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Source: Journal of Coastal Research, 85(sp1) : 511-515

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/SI85-103.1

Journal of Coastal Research	SI	85	511–515	Coconut Creek, Florida	2018

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ABSTRACT

Le Cozannet, G.; Duvat, V.; Salvat, B., Etienne, S.; Terorotua, H.; Garcin, M.; Lecacheux, S., and Montaggioni, L., 2018. Modelling the Response of Atoll Reef Islands to Multi-Millennial Sea Level Rise from the Last Glacial Maximum to the Coming 10kyr: the Case of Mururoa Atoll (Tuamotu, French Polynesia). *In:* Shim, J.-S.; Chun, I., and Lim, H.S. (eds.), *Proceedings from the International Coastal Symposium (ICS) 2018* (Busan, Republic of Korea). *Journal of Coastal Research*, Special Issue No. 85, pp. 511–515. Coconut Creek (Florida), ISSN 0749-0208.

www.JCRonline.org

Composed of biodetritic sediments and lying just a few meters above present sea-level, atoll reef islands are liable to be highly exposed to coastal flooding and shoreline erosion. Nevertheless, the analysis of multi-decadal shoreline change has shown that most reef islands either remain stable in area or are expanding within the context of current sea level rise. This article addresses the key issue of future atoll-island persistence using a simple morphodynamic model based on the computation of sediment production and fluxes, vertical coral growth and reef island accretion, with special reference to Mururoa Atoll (French Polynesia). The model parameters are calibrated from previously gained stratigraphic frameworks and sediment production rates. While a proper validation is a challenge with the scares data available, the model fits well with the atoll-rim and atoll-islands evolution schemes of Mururoa Atoll since the last glacial maximum. Multi-millennial projections of sea-level rise (Clark *et al.*, 2016) are used to examine future reef island response to rising sea-level. Assuming that all sediment volumes available on the atoll rim maintain in place and that the sediment production remains unaffected by ocean warming and acidification, the reef is interpreted as able to catch up sea level rise in the near future. Even in this very optimistic evolution scheme, the new reef edifice would be filnally drown in a high carbon emission scenario. The present study, along with others, strongly suggests that the persistence of reef islands in the future requires the conservation of already available sediments together with a continued production of coral detritus, not only from the outer slopes, but also on the atoll rim as water depths increase.

ADDITIONAL INDEX WORDS: *Atoll reef islands, sea level rise, climate change.*

INTRODUCTION

Without rapid decarbonisation of human activities, the levels of carbon dioxide concentrations in the atmosphere are expected to exceed those of the Eocene during the 21st century (Foster, Royer and Lunt, 2017). Among the consequences of this major event in the Earth history, one of the most striking will be the partial or total melting of ice sheets of Greenland and Antarctica (Clark *et al.*, 2015), regarded as able to cause a rise in sea level of 20 to 70m depending on human-induced greenhouse gas emissions over the next millennia (Figure 1).

Atoll islands are among the most vulnerable coastal environments to sea-level rise. However, available studies on multi-decadal shoreline change showed that at current sea-level rise, most atoll reef islands (74.6%) exhibit areal stability, while 14% increased and 11.4% decreased in size (McLean et Kench, 2015; Duvat et Pillet, 2017, Duvat, Salvat and Salmon, 2017; Duvat, 2018). Collectively, these observations suggest that the continued production of biogenic sediments (including coral sand, shingle, rubble and boulders) to date has been sufficient to compensate for the effects of a 15-to-30cm sea-level since the 1950s (Becker *et al.*, 2012).

This article examines the patterns of the atoll reef islands persistence in the face of sea-level rise, using a morphodynamic model based on the computation of biogenic sediment production and fluxes, and vertical coral and reef island accretion. Few morphodynamic models have been specifically developed for simulating the formation and evolution of atoll reef islands at different timescales: for example Montaggioni *et al.* (2015) implemented a stratigraphic model at Mururoa to examine the morphological changes of the atoll over the last 1.8 million years. Barry, Cowell and Woodroffe (2007) proposed a reduced complexity model applicable at multi-centennial timescales to

DOI: 10.2112/SI85-103.1 received 30 November 2017; accepted in revision 10 February 2018.
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represent atoll reef islands development during the late Holocene sea-level stand. Kench and Cowell (2002) proposed a variant of the Bruun rule to compute the response of beaches to sea-level rise. Finally, Storlazzi, Elias and Berkowitz (2015) used a full process modelling approach to estimate the response of islets to sea-level rise over the coming decades. However, the latter approach is only applicable where a sufficient amount of hydro-sedimentary data are available.

This article presents preliminary results from a morphodynamic model, which combines a sediment production module (as in Kench and Cowell, 2002) with the geomorphic development model of atoll-rim islets by Barry, Cowell and Woodroffe (2007), and include a stratigraphic model of outer-reef slopes similar to that provided by Montaggioni *et al.* (2015). The model performance is evaluated over the past 21kyr at Muruora atoll. Then, it is forced with multi-millennial sea level projections. The validity and limitations of the approach to provide guidances to the future evolution of atoll reef islands is then discussed.

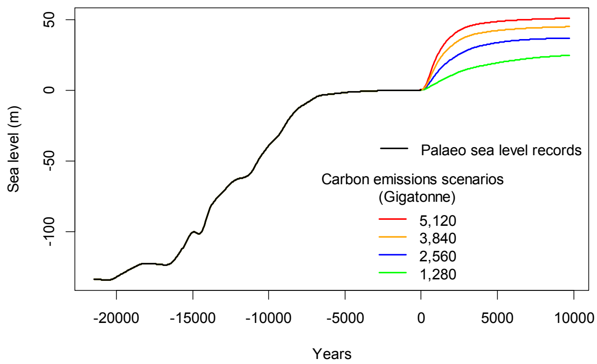

Figure 1. global multi-millennial sea level changes from the last glacial maximum to the present with projections for the coming 10,000 years (data from Clark *et al.*, 2015; reference 0 corresponds to 1950)

METHODS

The model developed herein reproduces the morphodynamic processes acting along a transect perpendicular to the atoll reef front. Each 1m-long cell of the profile contains information regarding the amount of cemented materials and non-cohesive biogenic sediments, and the coverage of living corals. The modelling follows an iterative process, whereby each cell of the atoll profile is updated at each timestep while considering the previous morphological state of the atoll, the production of new biogenic sediments by corals and their redistribution in different cells of the model (Figure 2). The timestep of the model is set as 50 years, which is a first order approximation to take into account the time of recovery for coral communities after major cyclonic events (Scoffin, 1993; Harmelin-Vivien et Laboute, 1986; Salvat *et al.*, 2008). In area subject to rare cyclones and extreme events such as the south-eastern Tuamotu atolls, this timestep may not be sufficient to average the effects of extreme storms and cyclones, and the model outcomes would thereby be expected to be smoother than in the real world.

The modelling approach presented here is necessarily simplified due to the scarcity of quantitative data available about the respective role of the different morphodynamic processes at the timescales considered. As a general principle, a "best case" scenario is selected, whereby the possibilities for reef islands to persist on the atoll rim are maximized.

Biogenic sediment production and allocation

In a first approximation, the model considers that the spatial distribution of living corals and the production of derived carbonate detritus are driven by the water depth only. The mathematical function used assumes that the skeletal productivity reaches a maximum of $10 kg.yr^{-1}m^{-2}$ for corals living between -1 and -20m depth (Woodroffe *et al.*, 2007; Montaggioni and Braithwaite 2009). Assuming a bulk density of $1.6.10^3 kg.m^{-3}$, this value corresponds to $6.2.10^{-3}.m^3.yr^{-1}m^{-2}$ (Figure 3.A), reflecting a high coral cover rate. However, the actual productivity should be expected to be lower in many cases.

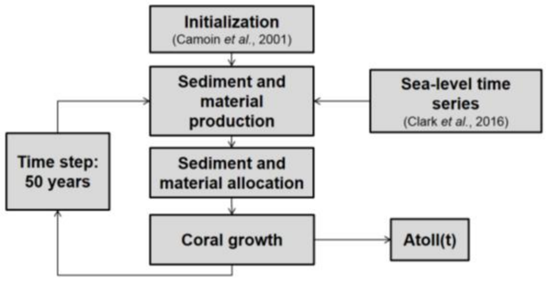

Figure 2. Atoll morphodynamics model presented in this study.

Then, the model estimates the amount of biogenic sediments potentially contributing to the sedimentary budget of reef islands. On the one hand, it optimistically assumes that all biogenic sediments produced on the atoll rim maintain in place and keep stabilized as soon as these are buried or flooded by a sufficient water depth; on the other hand, biogenic sediments produced on the outer slopes may either accumulate in-situ thus resulting in the accretion of the atoll outer slopes, or migrate to the atoll rim thus contributing to its sedimentary budget. In the latter case, the model assumes that (1) the proportion of biogenic sediments migrating from the outer slopes to the atoll rim is strictly controlled by the water depth (Figure 3.B), (2) biogenic sediments produced on outer slopes steeper than 40° can not migrate upwards and consequently are lost to the island system, and (3) biogenic material potentially contributing to the atoll-rim sediment budget can not exceed 25%.

Biogenic sediments remaining on the outer slopes contribute to accrete the reef outer slopes (Montaggioni 2005). In the model, this process is also parametrized as a function of changes in water depth, assuming that vertical accretion rates reach up to 2mm/yr (Figure 3.C). This value is based on those provided for reef margins by Montaggioni (2005, and references therein). However, this value is three times lower than-those used in the stratigraphic model of Montaggioni *et al.* (2015, Figure 4) during the last marine transgression. This is discussed in the next section.

The reef islands are built on the atoll rim according to the model of Barry, Cowell and Woodroffe (2007), which considers that islets grow oceanward from an initial position located close to the lagoon, as suggested by U/Th dating. This model assumes that during periods of stable sea level such as the late Holocene, the amount of biogenic sediment nourishing islets decreases over time, so that islets will progressively stretch out to their maximum accommodation size (e.g., 70% of the atoll rim). Standard parameters are selected for this component of the morphodynamic model: the sediment transport impedance term and the sensitivity to morphology values (Barry, Cowell and Woodroffe, 2007) are set to 200 and 5 respectively.

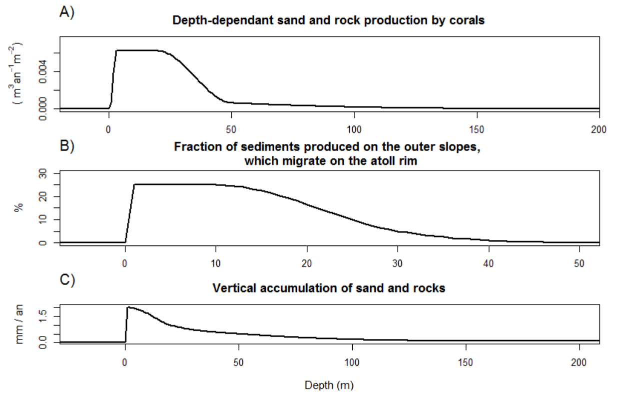

Figure 3. depth-dependant functions used in this study.

Test site: Mururoa, French Polynesia

The atoll chosen for this modelling study is Mururoa. This atoll is located in the south-eastern Tuamotu archipelago, in the Pacific (21°S,138°W). At present, the northern atoll rim is 150 to 350m in width (150m for the transect presented in Camoin *et al.*, 2001). The atoll reef islands are lying on a conglomerate platform dated 5 to 1 kyr BP, the altitude of which is about 0.4m above higher spring tide levels. During high tides, the atoll rim is partially inundated by water, and the reef flat is currently free from living corals. Depending on the sector considered, the islets cover 0 to 70% of the atoll rim and conglomerate substrates (note that higher values are found locally in the western and eastern parts of Mururoa). Hence, the observed highest values correspond to the accommodation size of 70% of the atoll rim as assumed in the islet development component of the model (Barry, Cowell and Woodroffe, 2007). Oceanward and beyond the reef crest, the profile of Mururoa atoll displays a gently-sloping terrace (to 20m depth) and steeper slopes basinwards (Camoin *et al.*, 2011; Montaggioni *et al.*, 2015).

In the modelling results presented herein, the atoll profile is initialized at the last glacial maximum (-21kyr) using the geological cross-sections interpreted by Camoin *et al.* (2001) from the four cores extracted from the northern rim of Mururoa. These cross sections provide a satisfactory reconstruction of the karstified Pleistocene basement down to about 20m depth. To complete the atoll profile at the maximum glacial age (-21 kyr), the lower section of the profile is extrapolated from 20 to 50m below current sea level, assuming that this tends to be is parallel to earlier interglacial surfaces. This profile could be improved by taking into account the unconformity surfaces shown in Montaggioni *et al.* (2015), but exploiting them would require more accurate stratigraphic modelling than needed for this study.

Sea level projections and reanalysis

The model is forced with global multi-millennial sea-level paleo-records and projections provided by Clark *et al.* (2015) (Figure 1; Section 2). These projections provide the response of sea level to four global warming scenarios, triggered by four different human-induced carbon emission scenarios. The sea-level response should not be significant for a timestep shorter than about 250 years. Furthermore, these projections relate to global eustacy, whereas regional to local sea level curves display deviations from the global average in the south-eastern Pacific. In particular, the Holocene sea-level high stillstand (Pirazzoli *et al.*,1988) was not integrated in the simulations. Considering the other approximations made in this study, neglecting the regional variability of sea level rise is assumed to be acceptable.

RESULTS

Figure 4 shows the modelled response of the atoll rim and margin along the defined profile to the last sea level transgression. Figure 5 displays the production and allocation of biogenic sediments from -21kyr to 10kyr in the future through the present, in relation to the projected sea level rise (Clark *et al.*, 2016). While a complete validation and an analysis of uncertainties is not possible with the data available, the simulations over the postglacial marine transgression and the late Holocene allow to verify that the model reproduces the key sedimentary processes.

Postglacial marine transgression (-21kyr to -6kyr)

From 21 to 11kyr BP, sea level rises from -130 to -60m (Clark *et al.*, 2016 and references therein). Since the atoll outer slopes are steeper than the 40° threshold, skeletal deposits are sliding downslope and consequently do not serve as source for the atoll-rim sediment budget. At around 11kyr BP, the sea level is 60m lower than today, reaching the zone of the outer reef profile typified by less steep slopes thereby allowing the biogenic sediments produced locally to start supplying the emerged upper surfaces of the atoll profile, especially during high-magnitude hydrodynamic events. As sea level continues to rise until 6kyr B.P., the atoll margins are progressively flooded (Figure 4) Accordingly, the production of coral-rich sediments increases in response to increasing accommodation space and available substrates for coral colonization (Figure 5, dotted red curves).

Late Holocene (-6kyr to present)

Six thousand years ago, sea level was close to its present position and the Pleistocene surface forms a 80m wide rim. Due to deposition of skeletal detritus supplied from the upper outer reef slopes, the rim extends oceanward to reach a width of 180m. This value compares well with the current width of the rim (about 150m in Camoin *et al.*, 2001). However, the modelled profile of the atoll displays a major difference with the field observations: the oceanward limit of the submerged sloping terrace (abscissa 500m) lies at 50m depth in the model while at 20m in the reality. Several explanations can be provided to account for this discrepancy, including poor initialization of the Pleistocene profile, underestimated of vertical accretion rates at the outer slope sites and limited validity of the function controlling depth-dependent biogenic sediment production (Figure 3.C). However, such a limitation does not affect significantly the results as this study focuses primarilly on atoll reef island developement. Hence, the most important point is to ensure that the model performs well in reproducing an atoll rim width comparable to the field observations, as shown by Figure 4.

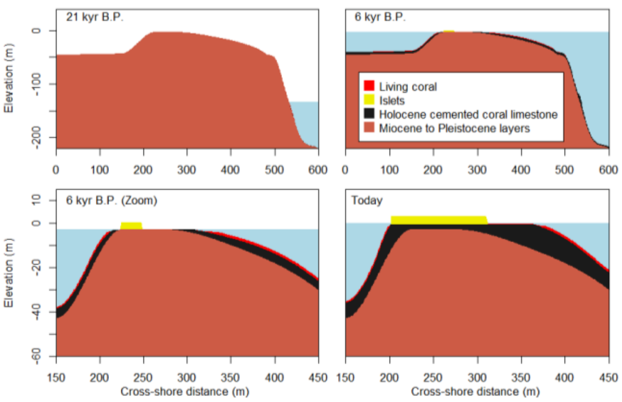

Figure 4. modelled response of Mururoa atoll to the last sea level transgression (from -21kyr to present).

As the modelled atoll rim extends oceanward from -6kyr to present, the space available for the settlement of living corals is decreasing. Correlatively, the amount of biogenic sediments migrating from the outer slopes to the atoll rim decreases from 0.2 to 0.1$m^3m^{-1}yr^{-1}$ (dotted red lines in Figure 5). These values are consistent with those previously published (Barry, Cowell and Woodroffe, 2007; Kench and Cowell, 2002). Furthermore, as assumed in these previous studies, the source of sediments nourishing the islets remains essentially the outer slopes until today (Figure 5). This result fits well with the fact that the reef flat of Mururoa is currently devoid of living corals. However, the input sea level data does not include the late Holocene higher sea-level stillstand, during which the water depth was possibly high enough to allow corals to colonize the atoll rim.

Projections : present to +10kyr

Assuming that processes operate similarly over time, the model is run forward into the next 10kyr, using the sea-level projections of Clark *et al.* (2006). As sea level rises above the current levels, the model predicts that the reef flat is fully covered by living corals as soon as the sea level exceeds 1m. This new source of biogenic sediment is made available for the islets sediment budget, and rapidly exceeds the contribution of sediments produced from the adjacent outer slopes. In the model, these large amount of sand accumulate, forming a smaller edifice over the modern atoll rim. This new rim succeeds in catching up with sea level. Such an evolutionary scheme is conditional to very optimistic assumptions. In this modelling experiment, all the biogenic sediments available on the atoll rim remain in place and contribute to build the smaller edifice, whose slopes are set to the threshold of 40°, thus allowing for newly released sediments to migrate upwards.

Both high and low carbon emission scenarios lead to approximately the same storylines. However, the 1280Gt emission scenario allows a wider edifice to be built up on the atoll rim. These results are sensitive to assumptions relative to the vertical accretion rates (Figure 3.C), especially in the case of the low carbon emission scenario. However, in the high emission scenario, the rates of sea level rise exceed the higher vertical accretion rates estimated by Montaggioni *et al.* (2015) for more than one millennium.

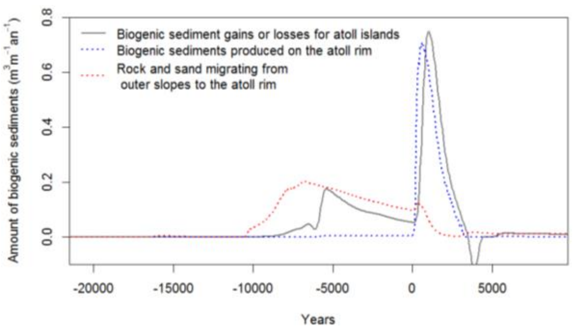

Figure 5. production and allocation of biogenic sediments from -21kyr to present, extended to the coming 10kyr. The projections are forced by the sea level projections resulting from the emission of 5,120Gt carbon.

Despite these assumptions, the new atoll rim is totally flooded by +4kyr, with the possibility of convertion of sediments into a conglomerate to ensure the stability of the new edifice erected on the present-day atoll rim. Furthermore, the model assumes that the coral productivity is comparable to that of the past 21kyr, thus neglecting any impact of ocean warming to coral productivity, despite well grounded concerns on this topic (Gattuso *et al.*, 2015; Wilkinson *et al.*, 2017). Hence, this scenario appears very optimistic and it should be not expected to occur everywhere.

DISCUSSION

There are large limitations to the modelling approach presented herein. Figure 4 suggests that despite biases in the vertical accumulation of sediments on the outer slopes at 20 to 50m depth, the model performs well in reproducing the evolution of the atoll islands and the oceanward extension of the reef flat over the late Holocene. Similarly, the model results appear not to be disturbed by the non-incorporation of algae, foraminifera and coral boulders as controlling variables in the input simulation. In first approximation, these sediment producers are regarded as providing an amount of detritus at least one order of magnitude smaller than those produced by corals. The uncertainties in the definition of depth-dependent functions would deserve more detailed attention and sensitivity analysis.

Despite its limitations, the modelling approach presented herein provides some insights into the fate of atoll rims, which can be useful for prospective studies beyond the next centuries. In a most favourable case in which corals are little affected by ocean warming, acidification and human activities, the reef flat is likely to be colonized by corals over the coming decades to centuries. Then, the atoll system could follow a catch-up mode, if the sediments accumulating on the reef flat and protected by an upward-growing reef crest, are not dispersed by waves and is cemented as sea level rises. Even in this case, the reef should be drowned finally at no specific end date within a high carbon world. The optimistic evolutionary scenario developed in the present study is based on highly favourable environmental conditions that can not be encountered in all tropical seas. In many locations, it can be expected that reef flat sediments will be dispersed due to higher wave energy, and that atoll islands will be drowned ultimately (Storlazzi, Elias and Berkowitz, 2015).

CONCLUSION

Such studies should be developed further, as determining when atoll reef islands are liable to become uninhabitable is crucial to design relevant adaptation pathways for atoll countries and territories. The capacities to adapt even in a worst case scenario should not be underestimated and may benefit from natural processes, for example if houses on stilts are reintroduced to allow reef island vertical accretion. Nevertheless, adaptation options allowing to maintain human activities on reef flats and islets constantly evolving upwards at rates exceeding 1cm/yr during millennia would deserve further studies.

ACKNOWLEDGEMENT

This work was funded by the ARN Storisk Project (ANR-15-CE03-0003). We thank Clark *et al.* for making their data available.

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