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Physical modelling of the response of reef islands to sea-level rise

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ABSTRACT

Sea-level rise and increased storminess are expected to destabilise low-lying reef islands formed on coral reef platforms and increased flooding is expected to render them uninhabitable within the coming decades. Such projections are founded on the assumption that islands are geologically static landforms that will simply drown as sea-level rises. Here we present evidence from physical model experiments of a reef island that demonstrates islands have the capability to morphodynamically respond to rising sea level through island accretion. Challenging outputs from existing models based on the assumption that islands are geomorphologically inert, results demonstrate that islands not only move laterally on reef platforms, but overwash processes provide a mechanism to build and maintain the freeboard of islands above sea level. Implications of island building are profound as it will offset existing scenarios of dramatic increases in island flooding. Future predictive models must include the morphodynamic behaviour of islands to better resolve flood impacts and future island vulnerability.

INTRODUCTION

Sea-level rise (SLR) and increasing storm magnitude are major threats to the future existence of atoll nations (Cazenave and Le Cozannet, 2014; Dickinson, 2009; Nurse et al., 2014; Storlazzi et al., 2018). Located in remote mid-ocean settings, low-lying coral reef islands provide the only habitable land in atoll archipelagos of Kiribati, Maldives, Marshall Islands, Tokelau and Tuvalu. Comprised of the skeletal remains of reef dwelling organisms, islands are constructed on reef surfaces by wave and current processes (Gourlay, 1988). SLR projections of 0.5 to 2.0 m over the 21st century (Deconto and Pollard, 2016) and potential changing wave regimes (Nurse et al., 2014) are expected to have profound impacts on islands, including: (1) physical destabilization and erosion through increased wave attack (Dickinson, 2009), (2) an increase in the frequency and magnitude of wave-driven flooding (Quataert et al., 2015; Storlazzi et al., 2018) and (3) saltwater intrusion of fresh groundwater reserves (Connell, 2015; Marotzke et al., 2017).

To date, assertions of island vulnerability and loss of islands, and attempts to model flooding impacts, are founded on assumptions that the physical structure of islands is inert and nonresponsive to changing environmental conditions (Dickinson, 2009; Quataert et al., 2015; Storlazzi et al., 2018). However, recent studies demonstrate that islands are physically dynamic landforms that are in continual adjustment to shifts in sea level and wave regimes that drive changes in the planform configuration (area, shape and position) of islands on reef surfaces, across a range of timescales (Duvat and Pillet, 2017; Ford and Kench, 2016; Dawson and Smithers, 2010). At multi-decadal timescales these studies also show a prevalence of island expansion among island archipelagoes (Duvat, 2018). However, such planform adjustments arguably do little to increase the resilience of islands to rising sea-levels and increased storm flooding, unless processes are also able to modify island elevation (Storlazzi et al., 2018). To date, future changes in island topography (elevation) have been poorly resolved and remain a fundamental gap in studies of island vulnerability. Resolving future changes in island elevation, particularly the level of the seaward ridge, above sea level is critical, because it is this level that controls the frequency and magnitude of ocean wave-driven overwash and island flooding, and consequently future flood risk to island communities (Beetham et al., 2017; Ferrario et al., 2015).

This study develops a physical modelling approach to explore island change and presents the first experimental observations of the morphological dynamics of an island under increasing sea level (0.5 m, 1.0 m) and energetic wave conditions (3 m and 4 m). Experiments identify the modes and magnitude of change in island morphology, which provide new insights into future island change.

METHODS

Physical modelling experiments were undertaken in a wave flume (length: 20 m, width: 0.6 m, depth: 1 m) at the COAST (Coastal Ocean and Sediment Transport) Lab (Plymouth University, UK). The laboratory reef platform and island were constructed to a 1:50 scale, corresponding to a Froude scaling of 1:1, representing the balance between inertial and gravitational forces and hydrodynamic similitude. Fatato Island, a gravel '*motu*' located on the south-eastern rim of Funafuti Atoll, Tuvalu, was chosen as the prototype island as detailed field investigations of island morphology, sediment properties and wave boundary conditions were available to guide model construction and laboratory experiments (DRI Appendix 1).

The reef platform and island morphology were based on topographic surveys of Fatato Island (DRI Fig.1). A horizontal reef platform (8 m x 0.6 m) was located 0.47 m above the flume floor, providing a 1:2.3 forereef and back reef slope measuring 1.13 m long. The oceanward reef crest was located 9 m from the face of the wave paddle and 2.4 m from the reef crest. The effects of rugosity are not considered in these experiments as the full complexity of reef platform roughness is difficult to capture in a laboratory model. However, a layer of the fine sand was glued onto the marine ply to reduce the smoothness of the plywood surface. The morphology of the gravel island was replicated in the flume using a template based on island field surveys. The island was formed out of fine sand (median = 1.5 φ; 0.35 mm), which geometrically scaled to an equivalent grain size of 17.5 mm, comparable to medium gravel sediment found on Fatato. Perfect similitude between model and prototype is impossible, therefore the scale relationships were carefully chosen to make sure the most important parameters were kept in similitude (Dean and Dalrymple, 2004). Using 0.35 mm sediment, the corresponding Shields and Rouse numbers scaled between 1:2.06 and 1:2.36 respectively.

Waves simulated during all experiments were produced by an absorbing piston paddle. All wave conditions were irregular and generated using a JONSWAP wave steering signal based on hindcast wave conditions offshore of Fatato generated from WaveWatch III modelling (Hemer et al., 2013) with atmospheric forcing provided by CFSR (Tolman, 2009). Only waves approaching between 60° and 210° were taken into consideration when extracting wave parameters for Fatato Island. Reef platform water levels were recorded using 15 capacitance wire wave probes at a frequency of 32 Hz.

Experimental programme

To ensure the physical model simulated wave processes across the reef platform hydrodynamic verification tests were conducted (see Tuck et al., 2018), which found close correspondence between simulated and observed wave conditions at Fatato (Beetham et al., 2015).

Island morphological response to changing incident waves and SLR was examined in six experimental runs (DRI Table 1). At the beginning of each experiment (Exp 1.1 and Exp 2.1) the scaled island was constructed on the reef platform using the template. Experimental runs were undertaken to simulate current spring high tide level, and SLR at prototype scale of 0.5 m and 1.0 m. Water level was increased in the flume at 10 mm increments every 90 minutes to achieve sea level increases of 0.5 m and 1.0 m above high tide, respectively (DRI Table 1). Island morphology was measured along the central profile using a laser beam profiler at 0.05 m horizontal increments. Surveys were captured before and after each experiment and at 30-minute intervals during each test. Island volume of a 30 m section of the island encompassing the transect, as well as island width, crest height, crest lagoon movement and centre of mass were examined for each profile to assess characteristics of morphological change. Morphodynamic tests were conducted to examine the repeatability of the results and validity of the model simulations (DRI Appendix 2).

RESULTS

Flume experiments all showed physical changes in island structure, including both vertical adjustments that influence island topography and planform movement that governs island position on reef surfaces (Table 1). Vertical increases in the ocean ridge were observed in all experiments. Under SLR of 0.5 m, the ocean ridge exhibited a 0.47 m and 0.31 m increase in elevation under the 3 m and 4 m wave conditions, respectively (Fig. 2). Maximum increases in ridge elevation occurred under the 1.0 m SLR experiment, increasing to 0.68 m and 1.13 m for the 3.0 m and 4.0 m wave conditions, respectively (Fig. 2).

Significantly, while the absolute ridge level increased, the rate of change in elevation of the island ridge lagged sea-level change, resulting in temporary reduction of the island ridge above water level (Fig. 2A, B). However, as shown in the extended experimental run, the island ridge was able to regain its relative elevation with respect to water level (Fig. 2F, G). Ultimately, the magnitude of increase in crest elevation was of a similar magnitude to sea-level change, suggesting sea level as it influences wave runup processes as an important controlling factor on island elevation.

Lagoonward translation of the island shoreline was also evident in each experiment. Shoreline displacement ranged from 5.25 m under 0.5 m SLR and the 3 m wave condition, to 43.5 m under the 1.0 m SLR and 4.0 m wave condition (extended run, Fig. 2). Changes in crest elevation and lateral displacement of the island margin resulted in modifications to secondary aspects of island configuration with respect to water level (Fig. 2). First, while physical adjustments allow the island to conserve the sediment volume at 189 m^3 and 185 m^3 when exposed to the 3 m and 4 m wave conditions, the island volume above water level decreased with SLR by 55% and 54%, respectively. However, island volume was able to recover 17.5% in the extended experimental run (Exp 2.3x). Second, there was an 11.3 % decrease in mean island elevation above sea level, despite absolute crest level increasing (Fig. 2I). Third, the centre of mass of the island migrated landward and upward (Fig. 2A, F). Fourth, island width decreased in each experimental run reducing by 14.9 and 23.7 m when exposed to 3 m and 4 m wave conditions, respectively.

DISCUSSION

The collective mode of geomorphic response in experiments was physical rollover of the island, whereby the island moved upward through sediment transfer to the island surface and the shoreline migrated away from the reef edge. Such a rollover response has previously been reported in sand barrier systems (Kraft et al., 1987; Orford et al., 1991). The mechanism driving the rollover response is wave overtopping and overwash processes; overtopping processes mobilise shoreline sediments and transport them to the island crest governing ridge accretion. Whereas, overwash processes transport sediment landward on to the island surface forcing lateral shoreline displacement by eroding the crest and depositing washover sheets that facilitate broader island aggradation (Matias et al., 2012). The proportion of island surface that directly responds to individual washover events is controlled by both sea level and wave energetics. Notably, under the lowest energy wave conditions and SLR scenarios overtopping events that drive crest accretion dominate, while overwash events are limited to higher water levels resulting in partial rollover and narrowing of the island (Fig. 2A). In contrast, under higher wave and SLR conditions, complete washover processes initially dominate, driving entire island rollover. Consequently, as the island migrates lagoonward wave energy dissipation increases across the reef flat, and overtopping processes begin to dominate resulting in an increase in crest elevation (Fig. 2F).

Our results present the first experimental evidence that reef island surfaces and, in particular, island oceanward crests are able to accrete vertically in response to rising sea levels, confirming earlier geometric modelling attempts (Kench and Cowell, 2001) and similar to the response of gravel barriers to SLR (Kraft et al., 1987; Orford et. al., 1991). These results, combined with previous studies of the island planform changes underscore the three-dimensional morphological dynamics of islands and suggest that many islands may remain on reef surfaces over the coming century. Significantly, as islands migrate and change position on reef surfaces (Kench et al., 2018), overtopping and overwash processes provide a physical mechanism for vertical island building that affords islands the potential to keep pace with sea level and offset future flood events. Results also suggest that the rate and magnitude of island building will be spatially variable dependent on site specific differences in the rate of sea-level change and whether SLR is uniform or, as is most likely, episodic, which would allow for island ridge recovery through overtopping processes.

Confirmation of the modelling results can be found in detailed field observations of island building through overwash sedimentation, as observed in this study, in response to high energy episodic events (Etienne and Terry, 2012), long period swell events (Smithers and Hoeke, 2014) and tsunami (Kench et al., 2006). In Fiji, Tropical Cyclone Tomas deposited coral boulders as well as gravel sheets up to 0.55 m thick along Taveuni Island shoreline (Etienne and Terry, 2012). Further evidence of constructional and accretionary impacts from long period swell events have been observed in Takuu Atoll where storm generated washover processes deposited a 0.05 – 0.22 m thick sand sheet over Nukutoa Island, increasing average island elevation above water level by 10% (Smithers and Hoeke, 2014). Similar sand sheet deposits and resultant vertical island building have been observed as a result of tsunami events (Kench et al., 2006). For example, in the Maldives sand sheets up to 0.3 m thick were documented on islands in South Maalhosmadulu atoll, in response to the December 2004 tsunami.

The results do not represent site specific morphologic predictions but rather highlight likely modes and styles of geomorphological response of reef islands to changing water level and wave conditions. As such, the implications of this work must be considered in context that observed morphological responses are expected to reflect more extreme morphological outcomes in comparison to field settings where a number of factors could potentially offset morphological change. First, our model scenarios represent instantaneous 0.5 m shifts in sea level, when in reality such changes would be gradual, limiting the sharp increases in wave height at the shoreline, and punctuated by periods of sea-level fall and stability allowing increased response time, similar to experimental run 2.3. Second, the physical model tests do not account for the effect of reef-derived sediment supply, which may offset both the rate of lateral migration and reduction in subaerial island volume and width (Perry et al., 2011). Third, experiments did not allow reef growth response, or account for the spatial variation of reef platform rugosity, which may mitigate changes in wave energy at island shorelines (Beetham et al., 2017). Fourth, the physical experiments subjected the island to persistent extreme and destructive waves operating at high tide. Finally, the island morphology and hydrodynamics closely match those of Fatato. However, the island was constructed using homogenous sediment, rather than trying to faithfully replicate the complex stratigraphy of Fatato, and devoid of the binding and frictional effects of vegetation, which may alter the island response.

Our findings have profound implications for understanding the physical vulnerability of reef islands to future environmental change. Results challenge existing simplistic analyses of future island flooding that assume that islands are geomorphically inert and will be inundated with rising seas and wave-driven flooding. While such assumptions may be appropriate in the small number of islands where shorelines have been armoured, our data shows this assumption fails on the majority of islands where wave-shoreline interactions are unmodified. In these latter settings, islands can maintain their relative freeboard and migrate on reef platforms, thus providing a physical platform for island communities (Kench et al., 2018).

Recognition that islands move on their reef platforms and have the potential to accrete at the same pace as SLR provide new insights for evaluating the susceptibility of islands to wave-driven flooding. First, all experiments showed an increase in the level of the seaward island ridge which is expected to offset future increase in flood inundation, projected under static island topography scenarios. Second, the rate of sea-level change is critical for the ability of the island crest to keep pace with SLR. The step-change in sea level of 0.5 m in experiments caused vertical accretion of the crest to lag sea-level change, due to the time dependency of individual overtopping events to deposit washover sheets on the island surface. This lag created a temporal window in which island freeboard above water level decreases and temporarily exposed the island to increased flooding. These insights highlight an urgent need to incorporate island morphological dynamics into reassessments of future wave-driven flood risk projections for reef islands.

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REFERENCES CITED

1. Beetham, E., Kench, P.S., and Popinet, S., 2017, Future reef growth can mitigate physical impacts of sea level rise on atoll islands: Earths Future, v. 5, p. 1002–1014, doi: 10.1002/2017EF000589.

2. Beetham, E., Kench, P.S., O'Callaghan, J., and Popinet, S., 2015, Wave transformation and shoreline water level on Funafuti Atoll, Tuvalu: Journal of Geophysical Research: Oceans, v. 121, p. 311–326, doi: 10.1002/2015JC011246.

3. Cazenave, A., and Le Cozannet, G., 2014, Sea level rise and its coastal impacts: Earth's Future, v. 2, p. 15–34, doi: 10.1002/2013EF000188.

4. Connell, J., 2015, Food security in the island Pacific: Is Micronesia as far away as ever?: Regional Environmental Change, v. 15, p. 1299–1311.

5. Dawson, J.L., and Smithers, S.G., 2010, Shoreline and beach volume change between 1967 and 2007 at Raine Island, Great Barrier Reef, Australia: Global and Planetary Change, v. 72, p. 141–154, doi: 10.1016/j.gloplacha.2010.01.026.

6. Dean, R.G., and Dalrymple, R.A., editors, 2004, Coastal processes with engineering applications, Cambridge, UK, Cambridge University Press.

7. DeConto, R.M., and Pollard, D., 2016, Contribution of Antarctica to past and future sea-level rise: Nature, v. 531, no. 7596, p. 591, doi: 10.1038/nature17145.

8. Dickinson, W.R., 2009, Pacific atoll living: How long already and until when: GSA Today, v. 19, p. 4–10, doi: 10.1130/GSATG35A.1.

9. Duvat, V.K.E., 2018, A global assessment of atoll island planform changes over the past decades: Wiley Interdisciplinary Reviews: Climate Change, v. 557.

10. Duvat, V.K.E., and Pillet, V., 2017, Shoreline changes in reef islands of the Central Pacific: Takapoto Atoll, Northern Tuamotu, French Polynesia: Geomorphology, v. 282, p. 96–118, doi: 10.1016/j.geomorph.2017.01.002.

11. Etienne, S., and Terry, J.P., 2012, Coral boulders, gravel tongues and sand sheets: Features of coastal accretion and sediment nourishment by Cyclone Tomas (March 2010) on Taveuni Island, Fiji: Geomorphology, v. 175, p. 54–65, doi: 10.1016/j.geomorph.2012.06.018.

12. Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., and Airoldi, L., 2014, The effectiveness of coral reefs for coastal hazard risk reduction and adaptation: Nature Communications, v. 5, p. 3794, doi: 10.1038/ncomms4794.

13. Ford, M.R., and Kench, P.S., 2016, Spatiotemporal variability of typhoon impacts and relaxation intervals on Jaluit Atoll, Marshall Islands: Geology, v. 44(2), p. 159–162, doi: 10.1130/G37402.1.

14. Gourlay, M.R., 1988, Coral cays: products of wave action and geological processes in a biogenic environment *in* Proceedings of the 6th international coral reef symposium, Townsville, Great Barrier Reef Committee, v. 2, p. 491–496.

15. Hemer, M.A., Fan, Y., Mori, N., Semedo, A., Wang, X.L., 2013, Projected changes in wave climate from a multi-model ensemble: Nature Climate Change, v. 3, p. 471–476, doi: 10.1038/nclimate1791.

16. Kench, P.S., and Cowell, P.J., 2001, The morphological response of atoll islands to sea-level rise. Part 2: Application of the modified shoreface translation model (STM): Journal of Coastal Research, v. 34, p. 645–656.

17. Kench, P.S., McLean, R.F., Brander, R.W., Nichol, S.L., Smithers, S.G., Ford, M.R., Parnell, K.E., and Aslam, M., 2006, Geological effects of tsunami on mid-ocean atoll islands: The Maldives before and after the Sumatran tsunami: Geology, v. 34, p. 177–180, doi: 10.1130/G21907.1

18. Kench, P.S., Ford, M.R., and Owen, S.D., 2018, Patterns of island change and persistence offer alternate adaptation pathways for atoll nations: Nature Communications, v. 9, p. 605, doi: 10.1038/s41467-018-02954-1.

19. Kraft, J.C., Chrzastowski, M.J., Belknap, D.F., Toscano, M.A., and Fletcher, C.H., 1987, The transgressive barrier-lagoon coast of Delaware: morphostratigraphy, sedimentary sequences and responses to relative rise in sea level, *in* Nummedal, D., Pilkey, O.H., and Howard, J.D., eds., Sea-Level Fluctuation and Coastal Evolution: SEPM Special Publication, v. 41, p. 129-143.

20. Marotzke, J., Jakob, C., Bony, S., Dirmeyer, P.A., O'Gorman, P.A., Hawkins, E., Perkins-Kirkpatrick, S., Le Quéré, C., Nowicki, S., Paulavets, K., and Seneviratne, S.I., 2017, Climate research must sharpen its view: Nature climate change, v. 7, p. 89–91, doi: 10.1038/nclimate3206.

21. Matias, A., Williams, J.J., Masselink, G., and Ferreira, O., 2012, Overwash threshold for gravel barriers: Coastal Engineering, v. 63, p. 48–61, doi: 10.1016/j.coastaleng.2011.12.006.

22. Nurse, L.A., McLean, R.F., Agard, J., Briguglio, L.P., Duvat-Magnan, V., Pele-sikoti, N., Tompkins, E., and Webb, A., 2014, Small islands, *in* Barros, V.R., et al., eds., Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, UK, Cambridge University Press, p. 1613–1654.

23. Orford, J.D., Carter, R.W.G., and Forbes D.L., 1991, Gravel barrier migration and sea level rise: some observations from Story Head, Nova Scotia, Canada: Journal of Coastal Research, v. 7, p. 477–488.

24. Perry, C.T., Kench, P.S., Smithers, S.G., Riegl, B., Yamano, H., and O'Leary, M.J., 2011, Implications of reef ecosystem change for the stability and maintenance of coral reef islands: Global Change Biology, v. 17, p. 3679–3696, doi: 10.1111/j.1365-2486.2011.02523.x.

25. Smithers, S.G., and Hoeke, R.K., 2014, Geomorphological impact of high-latitude storm waves on low-latitude reef islands: Observations of the December 2008 event on Nukutoa, Takuu Papua New Guinea: Geomorphology, v. 64, p. 223–234, doi: 10.1016/j.geomorph.2014.03.042.

26. Storlazzi, C.D., Gingerich, S.B., van Dongeren, A., Cheriton, O.M., Swarzenski, P.W., Quataert, E., Voss, C.I., Field, D.W., Annamalai, H., Piniak, G.A., and McCall, R., 2018, Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding: Science Advances, v. 4, p. eaap9741, doi: 10.1126/sciadv.aap9741.

27. Tolman, H.L., 2009, Usermanual and system documentation of WAVEWATCH III version 3.14. NOAA/NWS/NCEP/MMAB Technical Note 276, p. 19.

28. Tuck, M.E., Ford, M.R., Masselink, G., and Kench, P.S., 2018, Physical modelling of reef platform hydrodynamics: Journal of Coastal Research, v. 85, p. 491–495, doi: 10.2112/SI85-099.1.

29. Quataert, E., Storlazzi, C., van Rooijen, A., Cheriton, O., and van Dongeren, A., 2015, The influence of coral reefs and climate change on wave-driven flooding of

tropical coastlines: Geophysical Research Letters, v. 42, p. 6407–6415, doi: 10.1002/2015GL064861.

Figure 1. Surveyed cross-section of Fatato (A), longitudinal schematic of scale physical model in flume (B), and oblique photo of flume looking toward island beach (C).

Figure 2. Results of flume experiments of a 0.5 m and 1.0 m SLR (sea level rise) under 3m (A) and 4.0m wave conditions (F). Changes in island crest level (B,G), island volume (C,H), mean island height (D,I) and island width (E,J) across the simulations is presented. Note the lag between sea level and crest level in the extended experimental run (G).

Table 1. Vertical change in crest height and horizontal oceanward and lagoonward shoreline change as a result of each physical modelling test. Results are given at prototype scale.

[1] GSA Data Repository item 201Xxxx, Appendix DR1 (Island setting), DR2 (Model Validation), Figures DR1, DR2 and DR3, and Tables, DR1, is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.