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Physical modelling of reef island topographic response to rising sea levels

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ABSTRACT

Low-lying coral reef islands are considered extremely vulnerable to the impacts of climate change, particularly sea-level rise and increasing storm magnitude. Inundation and erosion are expected to destabilize reef islands and render them uninhabitable within decades. However, such assertions are founded upon the assumption that reef islands are geomorphologically inert landforms. Whereas, recent planform and cross-sectional analysis of reef island morphodynamics demonstrates that many islands are highly dynamic landforms changing in size, shape and position on the reef platform. This paper describes the first physical modelling experiments to model the whole-of-island morphodynamic response of reef islands to changes in sea level and wave regime. A wave basin is utilised to construct a 1:50 scale three-dimensional model of Fatato Island (Tuvalu) and document the whole-of-island response across a broad range of wave and water-level conditions. Whole-of-island results corroborate flume studies and provide new insights into the modes and styles of island change. Spit rotation, as well as lagoonward island recession and vertical oceanward crest accretion, are identified as the core island responses to increasing water level and wave conditions. However, results show that the rate and magnitude of physical adjustment is strongly dependent on the rate and magnitude of sea-level rise and wave conditions. Results challenge existing models of future island susceptibility to wave driven flooding, demonstrating that washover processes can provide a mechanism to build and potentially maintain island freeboard above sea level. These insights highlight an urgent need to incorporate island morphodynamics into flood risk models in order to produce accurate assessments of future wave-driven flood risks and better resolve island vulnerability.

Keywords: reef island, morphodynamics, sea-level rise, island vulnerability

1. INTRODUCTION

The future persistence and habitability of reef islands is widely considered to be at risk from the impacts of anthropogenic climate change, particularly eustatic sea-level rise (SLR) (Dickinson, 2009; Storlazzi et al., 2015, 2018). Projections of continued SLR (Kopp et al, 2014; Deconto and Pollard, 2016) and changing wave conditions (Nurse et al., 2014; Shope et al., 2016) are expected to destabilise reef islands through wave-driven erosion (Grady et al., 2013), and increase the frequency and magnitude of island flooding (Quataert et al., 2015; Storlazzi et al., 2015, 2018). Reef islands are comprised of unconsolidated reef-derived carbonate sediment, deposited and organised on atoll and platform reefs by wave and current processes (Stoddart and Steers, 1977; Flood, 2011). Often located in remote mid-ocean settings, within tropical and sub-tropical oceans, low-lying reef islands provide the only habitable land for island nations such as the Republic of the Marshall Islands, Kiribati, Tuvalu and the Maldives. Consequently, the ongoing future and security of these island nations is closely aligned with the physical stability and persistence of reef islands (Nurse et al., 2014).

In an attempt to predict future flood impacts on reef islands, numerical models have been used to simulate island inundation and flooding in response to anticipated SLR and wave-driven flooding (Storlazzi et al., 2015, 2018; Beetham and Kench, 2018). Both simple bathtub-type models, considering only SLR, and dynamic models, which include the combined impacts of SLR, wave run up and overtopping, indicate that predicted SLR will render some islands uninhabitable within decades (Storlazzi et al., 2015, 2018). Such predictions of extreme island vulnerability are founded upon the assumption that reef islands are geomorphologically inert, unresponsive to changing environmental conditions (Mimura, 1999; Yamano et al., 2007; Dickinson, 2009; Grady et al., 2013; Storlazzi et al., 2015, 2018). However, recent studies have shown that many reef islands are in continual morphodynamic adjustment across different

spatio-temporal scales in response to shifts in both sea level and wave regime (Duvat et al., 2018; Kench et al., 2018).

To date, a number of studies have undertaken detailed analyses of different modes of morphodynamic behaviour such as planform or cross-sectional island change in response to shifts of a single boundary condition (e.g. Kench and Brander, 2006; Etienne and Terry, 2012; Ford and Kench, 2015). Using remote sensing approaches, several studies have examined the planform response of reef islands to changes in sea level and storm events across multiple timescales (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013; Ford and Kench, 2014; Kench et al., 2015; McLean and Kench, 2015; Ford and Kench, 2015, 2016; Albert et al., 2016; Aslam and Kench, 2017; Kench et al., 2018). Most studies that have examined reef island shoreline change since the mid twentieth century, a period of documented SLR, have found no evidence of widespread chronic erosion. Rather, most islands have been stable and, in many cases, increased in area, suggesting islands can persist on reefs exposed to rising sea level (Yates et al., 2013; McLean and Kench, 2015; Kench et al., 2015, 2018; Duvat, 2019). Despite observations indicating islands have persisted, and in many cases expanded over a period coincident with accelerating sea level rise, these studies provide no evidence as to any topographical changes of the island. Island freeboard (the height of the island above water level) is a critical measure of island susceptibility to inundation as island elevation, in part, controls the frequency and magnitude of flooding events (Storlazzi et al., 2018). Topographic field surveys of multiple reef islands have documented the addition of sediment to the island surface as a result of overwash driven by tsunami (Kench et al., 2006, 2008), long-period swell events (Smithers and Hoeke, 2014) and storms (Etienne and Terry, 2012).

Collectively, these studies provide useful insights into reef island morphodynamics, including evidence that wave overwash can episodically increase the elevation of islands. However, such studies are limited spatially and temporally and topographic analysis of whole island

geomorphic change to a range of environmental conditions is yet to be undertaken. Consequently, the future geomorphic state and trajectories of reef islands remain uncertain. Understanding how islands physically respond to increasing sea level is essential to inform understanding of reef island trajectories and the future persistence of islands.

This study utilises a physical model to examine the responses of reef islands to SLR and storm events in order to improve understanding of reef island morphodynamics. As simplified replications of a real system, models can further the understanding of systems that are too complex or develop too slowly to be analysed in field experiments (Frostick et al., 2011; Hughes, 1993). In coastal geomorphology, physical models have provided valuable insights into the behaviour of complex systems by bridging the gap between numerical model simulations and real-world observations (Frostick et al., 2011). Physical models have been used extensively to explore both the hydrodynamics and morphodynamics of coastal systems, from early studies exploring the motion of waves in shallow water (Bagnold and Taylor, 1946) to gravel and sandy barrier morphodynamics (Williams et al., 2012; Masselink et al., 2015). Within coral reef science, physical modelling approaches have been adopted to study reef platform hydrodynamics since the 1970s (Gerritson, 1979; Seelig and Asce, 1983; Gourlay, 1994, 1996a, 1996b; Masselink et al., 2019). However, physical modelling of sediment transport on reef platforms has only recently been attempted (Pomeroy et al., 2015) and the geomorphic response of reef islands to increases in sea level and changes in wave conditions has yet to be resolved. The use of physical modelling allows landforms such as reef islands to be downscaled and studied in a controlled setting where a range of environmental conditions can be simulated with an immediate qualitative and quantitative analysis of the physical adjustments (Frostick et al., 2011).

Tuck et al., (2019) present the results of a physical modelling experiment conducted in a wave flume to explore reef island profile changes in response to SLR. Results of these cross-sectional

experiments provided new insights into the modes and styles of island change, particularly, the first experimental evidence that reef island surfaces can accrete vertically in response to rising sea levels (Tuck et al., 2019). Here we present results of a physical modelling investigation conducted within a wave basin in order to explore the morphodynamic behaviour of the entire island in response to changing sea level and wave conditions. The geomorphic responses of the whole island to controlled shifts in water level and wave conditions are discussed in the context of the future state and trajectories of reef islands.

2. METHODOLOGY

2.1 Experimental setup

Physical experiments to examine the geomorphic response of gravel reef islands (*motu*) to changes in sea level and wave regime were undertaken at the COAST (Coastal, Ocean and Sediment Transport) lab (University of Plymouth, UK). Experiments were conducted within a wave basin (15 m long x 10 m wide x 1 m deep) equipped with 20 absorbing piston wave paddles (Fig. 1). Fatato Island, a gravel *motu* located on the eastern, windward side of Funafuti atoll, Tuvalu, was chosen as the prototype island to construct the scale model for the laboratory flume experiments. Fatato was selected as several studies have examined the geomorphic and sedimentary characteristics of the island as well as wave processes on the reef platform and surrounding reefs (McLean and Hosking, 1992; Beetham et al., 2015; Kench et al., 2017). Results of these detailed field investigations were used to guide model construction to closely match prototype conditions. The reef platform and island model was constructed at a 1:50 scale. The reef platform (8 m long and 7 m wide), was constructed out of marine plywood and consisted of a horizontal reef surface 0.47 m above the flume floor with a 12° forereef and backreef slope (Fig. 1). A thin layer of the fine sand was glued onto the marine plywood to simulate the roughness of the reef surface. The oceanward reef crest was located 5 m from the wave paddles with the island shoreline positioned 2.4 m from the reef crest (Fig. 1). The island

144 was composed of fine sand (median = 1.5 ϕ ; 0.35 mm), which when geometrically scaled is
145 equivalent to a grain size of 17.5 mm at prototype, and comparable to medium gravel sediment
146 found on Fatato (Ryan, 2012).

147 All wave conditions simulated were irregular and generated according to a JONSWAP wave
148 steering signal specified by significant wave height (H_s) and peak period (T_p), using a peak
149 enhancement factor of 3.3 (i.e. narrow banded spectrum). Wave conditions during all
150 experiments were based on H_s , T_p and direction extracted from a 30 year hindcast from a point
151 35 km offshore of Funafuti atoll (8°42'7.20"S 179°23'49.20"E) (WaveWatch III hindcast data;
152 Hemer et al., 2013). Only onshore directed waves, approaching between 60° and 120°, were
153 included within the wave climate record when extracting wave parameters for Fatato Island.
154 To ensure the physical model accurately simulated wave processes across the reef platform
155 hydrodynamic verification tests were conducted (see Tuck et al., 2018), which found close
156 correspondence between simulated wave processes in the flume and field observations at Fatato
157 (Beetham et al., 2015).

Fig. 1. Schematic of the experiment set up A) Planform view, B) cross section of the wave basin. Experiment set up including 14 capacitance wire wave probes, a FARO Focus 3D s 120 Laser Scanner. C) View of island set up and island templates from the lagoon side of the basin. D) Side view of the island after templates have been removed. E) Three-dimensional model of Fatato Island created in the wave basin, central island and island spits are denoted. Grey lines illustrate the location of the central island and island spit profiles used to calculate geomorphic parameters.

2.2 Island morphology

The morphology of Fatato Island is typical of *motu* islands located on windward reefs throughout the Pacific Ocean (Stoddart and Steers, 1977; Richmond, 1992; Woodroffe, 2008; Fig. 2). An elongate, narrow island, Fatato Island is approximately 90 m wide, at the widest

point and 860 m long. Consistent with *motu*, Fatato is composed primarily of coarse gravel-sized carbonate sediment (-4.2 to -6.4 phi, 18.4 mm to 84.4 mm, Ryan, 2012; Kench et al., 2017; Fig. 2).

Fatato Island's oceanward beach face, composed of coarse gravel-sized sediment, has a 12° gradient and an elevated berm that reaches 3 – 4 m above mean sea level (MSL). The central island depression is densely vegetated and is 1.5 – 2 m above MSL. The lagoonward beach face is composed of finer pebble to sand-sized sediments and is of lower elevation than the oceanward berm (Ryan, 2012). Fatato Island also exhibits alongshore morphological differences where the central section of the island is of higher elevation, up to 4.5 m above MSL, than the island spits which are approximately 2 m above MSL (Ryan, 2012; Fig. 1E). The elevation of the island spits is not homogenous and reduces alongshore towards the ends of the island.

The across-shore morphology of Fatato Island is closely replicated by the scaled model (Fig. 1 E). However, alongshore island morphology is slightly truncated where only a 100 m section of the 400 m central island is reproduced between the island spits in order to fit the model into the wave basin (Fig. 1E; Fig. 2). As a result, the aspect ratio of the island is altered such that the spits take up a larger portion of the model island relative to their proportions on Fatato. Due to large variations in island elevation between the central island and the island spits, the morphologic adjustments of each section of the island are examined separately.

Fig. 2: A) Location of Fatato Island, Funafuti Atoll, Tuvalu. B) Fatato Island. C) Aerial photograph of Fatato Island taken by Paul Kench, February 2013.

2.3 Scale effects

The typology described by Paola et al., (2009) indicates that this physical model demonstrates geometric and kinematic similarity. Like many laboratory experiments this model does not achieve dynamic similarity as perfect similitude between all force ratios in the model and prototype is impossible (Kamphuis, 1985). However, the absence of dynamic similarity between model and prototype does not detract from their usefulness (Paola et al., 2009). Many physical modelling experiments do not achieve dynamic similarity under the principals of classical dynamical scaling. However, such models have proven useful for examining and predicting landscape change as they demonstrate ‘unreasonable effectiveness’ where experiments simulate many important processes observed in natural systems despite not exhibiting dynamic similarity (Paola et al., 2009). The experiments presented in this paper aim to examine the general modes and styles of geomorphic response of gravel reef islands to changing water level and wave conditions. The model does not attempt to simulate specific futures (scenarios of wave climates or sea level) and therefore the results do not represent site-

specific morphologic predictions but rather highlight the likely modes and styles of island response to changing water level and wave conditions.

One of the key challenges in physical modelling is minimising scale effects to ensure up-scaled modelling results are geomorphologically meaningful. As a result of not achieving dynamic similarity, scale effects are inherent in reduced scale models (Kamphuis, 1985). Therefore, scale relationships must be carefully chosen making sure the most critical parameters are kept in similitude (Dean and Dalrymple, 2004). Morphological evolution is governed by the sediment transport rate and direction, which applies equally at model and prototype scale (Frostick et al., 2011). Therefore, preservation of sediment transport mode and rates are considered important parameters for this study to ensure the modelled morphological evolution represents the prototype situation (Frostick et al., 2011). Consequently, these experiments were designed to satisfy the recommendations of Hughes (1993) with regards to hydrodynamic Froude scaling, which represents the balance between inertial and gravitational forces. In regard to sediment transport, it was attempted to achieve similitude for the dimensionless fall velocity, as well as the Shields and the Rouse numbers, the former indicates whether sediment will be set in motion and the latter is related to the mode of transport (Hughes, 1993). Relative sediment density could not be kept in similitude as carbonate sediment comprising reef islands has a lower density, $\sim 1.85 \text{ g/cm}^3$, than the quartz sand, $\sim 2.65 \text{ g/cm}^3$, available for use in the physical model. It is important to note that scaling of our experiments has been designed focusing on maintaining a similar dimensionless fall velocity, Shields and Rouse number but the effect of a difference in the relative density remains difficult to quantify and might affect sedimentation.

2.4 Instrumentation and data acquisition

An array of fourteen resistance wave probes, positioned along the centre of the wave basin (Fig. 1), was used to measure water level across the basin at a frequency of 128 Hz. The

resistance wave probes have a measurement error of 0.1 mm. The morphology of the reef island was surveyed using a FARO Focus 3D s 120 Laser Scanner at 1 mm point spacing. Five reference spheres situated within the scan were used to register each scan to a common coordinate system. The water was drained below the reef platform before each scan allowing the morphology of the whole island to be surveyed. The morphology of the island was surveyed before and after every run from four locations above the reef platform to ensure complete coverage of the island (Fig. 1).

2.5 Experimental programme

Experiments were designed to investigate the geomorphic response of a reef island to both mean and extreme wave and water level conditions and comprised five test series (A – E), including a total of 17 separate runs and 30 hrs of experimental work in the basin (Table 1).

Test Series A consisted of five 90-min runs in which the island was exposed to 0.026 m waves, representing H_s of 1.3 m at prototype, which closely match mean wave conditions offshore of Fatato Island. The water level was increased 0.02 m in 0.005 m increments every 90 min, representing a 1 m increase in water level in 0.25 m increments at prototype scale. Wave period (T_p) was kept constant at 1.4 s, representing 9.9 s at prototype (Table 1). Test A5 ran for 360 min in order to explore the effects of extended relaxation time on the island's morphology. The water level on the reef initially represented high tide (0.04 m) followed by four SLR scenarios resulting in water levels above the reef platform of 0.045, 0.05, 0.055 and 0.06 m, respectively, representing 0.25, 0.5, 0.75 and 1 m of SLR.

Following Test Series A, which examined the island response to mean wave conditions in tandem with SLR, Test Series B – E exposed the island to more extreme wave conditions and larger increases in sea level. Before each test series the island was remoulded to the initial island morphology using the island templates. Test Series B – E each comprised three 90-min

runs and exposed the island to significant wave heights (H_s) of 0.04, 0.06, 0.08 and 0.1 m, respectively, representing H_s of 2, 3, 4 and 5 m at prototype (Table 1). The water level on the reef platform (h_{reef}) initially represented high tide (0.04 m) and was increased 0.02 m in two 0.01 m steps, resulting in water levels on the reef platform of 0.05 and 0.06 m respectively representing 0.5 and 1 m of SLR at prototype.

Table 1. Parameters used during Test Series B – F: H_s = significant wave height, h_{reef} = water level on reef platform, T_p = wave period, T_{test} = test time. The prototype values are given in brackets.

Test	Run	H_s (m)	h_{reef} (m)	T_p (s)	T_{test} (min)
A	1	0.026 (1.3)	0.040 (2)	1.4 (9.9)	90
A	2	0.026 (1.3)	0.045 (2.25)	1.4 (9.9)	90
A	3	0.026 (1.3)	0.050 (2.5)	1.4 (9.9)	90
A	4	0.026 (1.3)	0.055 (2.75)	1.4 (9.9)	90
A	5	0.026 (1.3)	0.060 (3)	1.4 (9.9)	360
B	1	0.040 (2)	0.040 (2)	1.4 (9.9)	90
B	2	0.040 (2)	0.050 (2.5)	1.4 (9.9)	90
B	3	0.040 (2)	0.060 (3)	1.4 (9.9)	90
C	1	0.060 (3)	0.040 (2)	1.4 (9.9)	90
C	2	0.060 (3)	0.050 (2.5)	1.4 (9.9)	90
C	3	0.060 (3)	0.060 (3)	1.4 (9.9)	90
D	1	0.080 (4)	0.040 (2)	1.4 (9.9)	90
D	2	0.080 (4)	0.050 (2.5)	1.4 (9.9)	90
D	3	0.080 (4)	0.060 (3)	1.4 (9.9)	90
E	1	0.100 (5)	0.040 (2)	1.4 (9.9)	90
E	2	0.100 (5)	0.050 (2.5)	1.4 (9.9)	90
E	3	0.100 (5)	0.060 (3)	1.4 (9.9)	90

2.6 Test procedure followed during each test series

Each test series commenced with the reef island manually moulded to the same initial morphology using a series of island templates, followed by the procedural sequence summarised in Fig. 3 applying the wave and water level scenarios summarised in Table 1.

Fig. 3. Experiment procedure followed in the Wave Basin during Test Series A and B – E.

2.7 Data analysis

Each scan of the island consisted of four separate point clouds captured from the four scanner locations (Fig. 1). The point clouds were combined and analysed using CloudCompare software (CloudCompare 2.10, 2018). Each point cloud was manually checked to remove aberrant points (noise) and rasterised to create a Digital Elevation Model (DEM) with a resolution of 1 mm. In order to evaluate characteristics of morphologic island change, island volume, width, length, crest height, lagoonward movement and displacement of the island centre of mass (COM) were calculated for each DEM (Table 2). Analysis was undertaken using ArcGIS Spatial Analyst and 3D Analyst tools (ESRI, 2011).

Table 2. Details of the methods used to calculate each geomorphic island parameter.

Parameter	Calculation method		
		Island above reef platform	Island above sea level
Island volume		Volume of the entire island above the reef platform.	Volume of the entire island above simulated water level.
Average crest height	crest	Maximum height of the oceanward crest averaged from seven profiles taken across the central island.	Maximum height of the oceanward crest above simulated water level averaged from seven profiles taken across the central island.
Maximum island length	island	Maximum alongshore extent of the island above the reef platform	Maximum alongshore extent of the island above simulated water level
Planform area	island	The area of the island at the reef platform	The area of the island at simulated water level.

Average island width	Island width at the reef platform averaged from seven profiles taken across the central island.	Island width at simulated water level averaged from seven profiles taken across the central island.
Oceanward shoreline recession	Lagoonward distance migrated of the oceanward shoreline	
Island migration	Lagoonward distance migrated of the lagoonward shoreline	
Centre of mass	Mean position of the island above the reef platform	Mean position of the island above simulated water level

3. RESULTS

3.1 Island response to mean wave conditions

Test Series A examined the geomorphic response of the island to offshore wave conditions which closely match mean conditions at Fatato island ($H_s = 1.3$ m) coinciding with 1 m SLR in 0.25 m increments.

3.1.1 Planform and vertical island adjustments of the central island

The central island section exhibited minimal planform change when exposed to mean wave conditions and present-day water level (Fig. 4B). However, after water level was increased the oceanward shoreline migrated 18.5 m after 1 m SLR (T_{450}) and a further 16.9 m during the extended run (T_{720}). Despite lagoonward adjustments of the ocean shoreline the central island remained within the original island footprint throughout the experiment as the lagoon shoreline remained stable (Fig. 4).

The average height of the oceanward crest increased from 3.6 to 4.5 m when exposed to 1.3 m wave conditions and 1 m SLR (T_{450}). Crest height increased cumulatively by 0.94 m after 1 m of SLR (T_{450}), therefore island freeboard was reduced by 0.06 m (Figs. 5, 6). However, during the extended run when the island was exposed to 1 m SLR for a further 270 min, the average crest height increased by 0.11 m, thereby increasing island freeboard to 1.65 m, 0.05 m greater than at T_0 (Fig. 5).

Fig. 4. Three-dimensional geomorphic island changes in response to 1.3 m (Test Series A) wave conditions with coinciding SLR in 0.005 m (0.25 m at prototype) increments. The black dashed line illustrates the initial island shoreline; the white line illustrates the water level simulated in each run.

Fig. 5. The morphodynamic response of the central profile (upper panel) and spit profile (lower panel) to 1.3 m waves with coinciding SLR. The red circles represent the progressive displacement of the centre of mass of the whole island. The black arrows depict average vertical crest change and lateral island migration.

3.1.2 Planform and vertical island adjustments of the island spits

The island spits exhibited greater dynamism than the central island and migrated an average 27.2 m further lagoonward in response to mean wave conditions and 1 m SLR (T_{450}) (Figs. 4, 5). Spit migration increased alongshore towards the lower elevated ends of the island resulting in lagoonward rotation of the spits. The more rapid lagoonward spit migration increased the curvature of the oceanward ridge and resulted in an increasingly crescentic shaped island under rising water levels (Fig. 4).

The elevation of the island spits reduced when exposed to 1.3 m wave conditions and 1 m SLR (Fig. 5). Island spit elevation initially increased at present day water level (T_{90}) but subsequently reduced by 0.40 m when sea level was increased to 1 m at T_{450} and further reduced by 0.46 m when the experiment was run for a further 270 mins (Fig. 5).

3.1.3 Volumetric changes of the whole island

The volume of the island only by 10% when exposed to 1.3 m waves and 1 m SLR (T_{450}) (Fig. 6E). However, the volume of the island above water level exhibited a substantial 56% reduction from 6651 m³ at T_0 , to 2954 m³ when sea level was increased to 1 m (T_{450}). Island area above the reef platform was also reduced (68%) in response to simultaneous reductions in the length and width of the island as sea level was increased (Fig. 6). The length of the island reduced from 290 m at T_0 , to 208 m (28 %) at T_{450} and the width of the island decreased from 116 m at T_0 , to 80 m (31%) after exposure to 1 m SLR (T_{450}). However, the rate of planform island adjustment slowed as water level was increased and island area and volume above water level only reduced by a further 187 m² and 58 m³ (2% and 0.87% between T_{450} and T_{720}), respectively, when exposed to 1.3 m waves and 1 m SLR for an additional 270 min (Fig. 6).

Fig. 6. Island metrics of morphodynamic response to Test Series A simulating 1.3 m waves coincident with rising water levels at 0.25 m increments. A) Change in average crest height and, B) average crest height above wl (freeboard). C) Change in island area and, D) island area above wl. E) Change in island volume and, F) island volume above wl. G) Change in maximum island length and, H) maximum island length above wl. I) Change in average island width and J) average island width above wl. Note experiment time for Test Series A is 720 mins due to the 0.25 m steps in sea level and Test Series A5 extending for a further 270 minutes. The results are given at prototype scale. Shaded bars indicate water level simulated.

3.2 Island response to moderate and extreme wave conditions

Test series B – E exposed the island to more extreme wave and water level conditions in order to measure island response to a variety of storm conditions and more rapid increases of SLR. Test Series B – E simulated the geomorphic response of the island to 2 m (Test Series B), 3 m (Test Series C), 4 m (Test Series D) and 5 m (Test Series E) wave conditions as water level was increased in 0.5 m increments.

3.2.1 Planform and vertical island adjustments of the central island

When exposed to larger 2, 3, 4 and 5 m wave conditions (Test Series B – E), the central island exhibited substantial planform change where the ocean shoreline migrated increasingly lagoonward as water level and wave conditions were increased (Fig. 7). Lagoonward migration of the ocean shoreline ranged between 21.0 and 46.4 m when exposed to 2 – 5 m waves.

However, the central island only migrated out of the original island footprint when exposed to 5 m waves, where the lagoonward shoreline migrated 16.7 and 19.5 m lagoonward with 0.5 and 1 m SLR, respectively (Fig. 7 O,P).

The height of the oceanward crest increased under all water levels when exposed to 2, 3 and 4 m wave heights (Test Series B – D) (Fig. 8 A,B,C). However, the largest increases in crest height occurred under 2 and 3 m waves where crest height increased cumulatively by 1.07 and 1.02 m after 1 m (T₂₇₀) SLR, increasing island freeboard by 0.07 and 0.02 m, respectively (Fig. 8). Under 4 m waves average crest height only increased by 0.41 m reducing island freeboard by 0.59 m after 1 m SLR (T₂₇₀) (Figs. 8, 9). In contrast, when exposed to 5 m waves the height of the crest reduced to 0.70 m below water level by the end of the experiment (T₂₇₀) (i.e. the island was inundated) (Fig. 8).

Fig. 7. Three-dimensional geomorphic island change in response to 2 m (Test Series B), 3 m (Test Series C), 4 m (Test Series D) and 5 m (Test Series E) wave conditions with coinciding SLR at 0.01 m (0.5 m at prototype) increments. The black dashed line illustrates the initial island shoreline; the white line illustrates the water level simulated in each run.

Fig. 8. The morphodynamic response of the central profile (upper panels) and spit profile (lower panels) to 2m waves (A and E), 3 m waves (B and F), 4 m waves (C and G) and 5 m waves (D and H) with coinciding SLR. The red circles represent the progressive displacement of the centre of mass of the whole island. The black arrows depict average vertical crest change and lateral island migration.

3.2.2 Planform and vertical island adjustments of the island spits

Lagoonward migration of the island spits exceeded central island migration under all water level and wave conditions simulated during Test Series B – E. Spit migration increased alongshore towards the lower elevated ends of the spits resulting in lagoonward spit rotation and increased curvature of the oceanward ridge (Fig. 7). When exposed to 2 m waves, the island spits migrated an average 24.85 m, resulting in a crescentic planform island shape (Fig. 7 D). Spit migration increased under larger wave conditions, resulting in further curvature of the oceanward ridge and a spherical planform island shape (Fig. 7 F,J,N). The elevation of the island spits reduced between 0.37 and 1.17 m when exposed to 2 – 5 m waves and 1 m SLR (T_{270}), with a more rapid rate of spit erosion when exposed to higher wave conditions (Fig. 8 E,F,G,H).

3.2.3 Volumetric changes of the whole island

The volume of the island above the reef platform reduced between 7 and 31% when exposed to 2, 3, 4 and 5 m wave conditions and 1 m SLR (T_{270}) (Fig. 9). However, the largest reductions were observed in subaerial island volume where island volume above water level reduced by 100% under the largest 5 m wave conditions and 1 m SLR (T_{270}) as the island was destroyed and entirely inundated after 1 m SLR (T_{270}) (Fig. 9). The area of the island above the reef platform also exhibited substantial reductions (between 72% – 76 %) when exposed to 2 – 4 m wave conditions in response to simultaneous changes in island width and length (Fig. 9). In contrast, under 5 m waves the island sediment was spread across the reef platform as the island was destroyed under rising water levels (Fig. 9C).

Fig. 9. Island metrics of morphodynamic response to Test Series B – E simulating 2 m, 3 m, 4 m and 5 m waves coincident with rising water levels. A) Change in average crest height and, B) average crest height above wl (freeboard), C) Change in island area and, D) island area above wl. E) Change in island volume and, F) island volume above wl. G) Change in maximum island length and, H) maximum island length above wl. I) Change in average island width and J) average island width above wl. The results are given at prototype scale. Shaded bars indicate water level simulated.

3.3 Island centre of mass

The centre of mass (COM) provides a single measure of the change of the island as a whole and when analysed through time, can describe the net outcome of both the horizontal and vertical island adjustments. The COM of each island DEM was used as a measure of whole island response to changes in mean (Test Series A) and moderate to extreme (Test Series B – E) sea level and wave conditions (Fig. 10). The dominant shift of the centre of mass varied considerably between vertical increases when exposed to the mean and moderate wave conditions (Test Series A – C), and lagoonward horizontal change and vertical decreases when exposed to extreme wave conditions (Test Series D – E). The largest vertical increases (just over 0.5 m) in the position of the COM were observed when the island was exposed to 1.3 and 2 m wave conditions (Fig. 10). Although lagoonward migration of the entire island was minimal, ocean shoreline erosion and rotation of the island spits resulted in a 25.3, 28 and 32 m lagoonward shift of the COM when exposed to 1.3, 2 and 3 m wave conditions, respectively. When exposed to 4 and 5 m waves, significant lagoonward rotation of the island spits and migration of the entire island occurred, shifting the COM 50.9 and 77.2 m lagoonward, respectively. Simultaneously, the oceanward crest eroded and the COM increased only 0.23 m when exposed to 4 m waves and reduced by 0.89 m when exposed to 5 m waves (Fig. 10). Despite increases in crest elevation when exposed to 1.3 – 4 m wave conditions (Test Series A – D) the majority of the island surface did not keep up with sea level (Fig. 10B). As a result, the island's COM was 0.46, 0.48, 0.54 and 0.77 m below water level, after exposure to 1.3, 2, 3 and 4 m waves, respectively.

Fig. 10. Cumulative displacement of the centre of mass of the island when exposed to 2m, 3m, 4m, and 5m waves coincident with SLR. A) The black dot indicates the centre of mass of the initial island scan before each test series with each progressive point representing the COM after high tide, 0.5 m SLR and 1 m SLR for Test Series B – E and high tide, 0.25 m SLR, 0.5 m SLR, 0.75 m SLR and 1 m SLR for Test Series A. B) Cumulative displacement of the centre of mass relative to water level.

4. DISCUSSION

This study presents results from the first physical model used to simulate reef island morphodynamics in three-dimensions and provides new insights into the geomorphic response of reef islands to changes in sea level and wave regime. First, results highlight the three-dimensional morphological dynamics of reef islands, identifying vertical accretion of the island surface, lagoonward island migration and rotation of the island spits as the dominant geomorphic responses to changing wave and water level conditions (Figs. 4, 7). Second, modelling results suggest that optimal wave conditions exist to build islands and offset flooding events. These conditions, large enough to drive crest accretion through overtopping but not large enough to overwash and destroy the island, are expected to vary for different island and reef platform configurations. Third, results demonstrate that vertical island accretion is a mechanism through which islands may remain on reef surfaces despite SLR. When exposed to optimal wave conditions and a low rate of SLR, island building allows the island surface to

keep up with rising sea level. Collectively, these key insights improve understanding of the range of physical trajectories of reef islands in response to future climate change.

4.1 Three-dimensional reef island morphodynamics

Physical modelling of the morphodynamic behaviour of the entire island demonstrates that reef islands are physically dynamic landforms that change in size, shape and position on the reef platform in response to SLR and energetic waves. Results corroborate and expand upon earlier physical modelling experiments, undertaken within a wave flume, which examined island profile changes in response to SLR and a small range of wave conditions (Tuck et al., 2019). Tuck et al., (2019) identified vertical growth of the oceanward crest and lagoonward island migration as the two core geomorphic responses of islands to changing wave and water level conditions. Results of this study conducted in a basin closely matched the island behaviour observed in the flume (Tuck et al., 2019), as well as providing observations of island spit rotation, identified as the third core island response to SLR and changing wave regime. Three-dimensional island analysis also reveals disparate morphological adjustments between the higher elevation central island and lower elevation island spits. The morphological changes observed are driven by overtopping and overwash processes: overtopping processes mobilise shoreline sediments, transporting them towards the island crest increasing crest height. While island overwashing transports sediment landward onto the island surface contributing to lagoonward island migration, eroding the island crest and forming washover deposits (Matias et al, 2012). It is important to note that the modelling approach examines the general modes and styles of island response, rather than simulating site-specific morphological predictions. Furthermore, the more extreme scenarios simulated require major changes in sea level and wave conditions that currently sit at the upper bounds of future predictions.

4.1.1 Central island morphodynamics

4.1.1.1 Vertical increases in island elevation

Within the physical model crest accretion is identified as a key mechanism that enabled the island to adjust and keep up with SLR. Results confirm early theories of reef island preservation on the reef platform that consider reef islands able to accommodate rising sea levels (McLean, 1989; Hopley, 1997), as well as geometric modelling results (Cowell and Kench, 2001, Kench and Cowell, 2001; Lorenzo-Trueba and Ashton, 2014) which suggest that washover processes may allow the reef island surface to keep pace with SLR (Fig. 8). Despite observed increases in the elevation of the oceanward crest when exposed to 1.3 – 4 m waves (Test Series B – E), the crest height only kept pace with SLR (i.e. island freeboard maintained) when exposed to 2 and 3 m waves (Figs. 8, 9). The most rapid and greatest increase in the height of the oceanward crest was observed when the island was exposed to 2 m waves, and subsequently reduced in magnitude as wave height was increased. When exposed to 2 – 3 m waves overtopping caused substantial accretion of the oceanward crest, increasing island freeboard (Fig. 8). When exposed to 1.3 m waves less wave energy was available at the shoreline to drive overtopping processes and resultant increases in crest elevation were not substantial enough to maintain island freeboard. However, we observed that during the extended 270 min run the island freeboard recovered to 0.05 m above its initial position (Fig. 5). This observation suggests that variability in the rate of SLR has a critical control on the ability of the crest elevation to keep pace with rising sea levels. Further study is necessary to explore the changing pattern of SLR which may allow the island crest to maintain freeboard. For example, many islands may be able to keep up with rising sea levels if negative sea level anomalies associated with ENSO cycles allow adequate relaxation time for the island freeboard to recover after SLR.

4.1.1.2 Lagoonward island migration

Modelling outputs also identified lagoonward migration of the island as a characteristic mode of island response to increasing wave heights and water levels. Results suggest that *motu* will migrate lagoonward when exposed to rising water levels potentially reaching a new equilibrium on the reef flat, as suggested by Sheppard et al., (2005) and modelled by Kench and Cowell (2001), Shope and Storlazzi (2019). A lagoonward shift of the oceanward crest was observed under all wave conditions, where washover processes eroded the oceanward shoreline resulting in narrowing of the island. The entire island only migrated outside of its initial footprint when the island was exposed to 5 m waves, which generated complete overwash conditions and destroyed the island. Large wave conditions are required for overwash to impact the lagoonward shoreline thereby migrating the island lagoonward of its initial position.

Our results show that islands will decrease in width as the ocean shoreline erodes in tandem with increasing sea level and wave height. As the island narrows, the islands volume above sea level reduces and the centre of mass shifts upwards and lagoonward. However, when exposed to extreme wave heights, island narrowing is expected to be lessened as gravel *motu* are expected to exhibit a barrier rollover response where the whole island migrates lagoonward out of its initial footprint. These results are similar to outputs of numerical models which show islands to exhibit both oceanward shoreline erosion and total barrier rollover in response to rising sea levels (Kench and Cowell, 2001; Shope and Storlazzi, 2019).

Observations from experiments in both the wave flume (Tuck et al., 2019) and the wave basin highlight both wave height and the rate of SLR as key controls on the future geomorphic behaviour of *motu*. Our observations show that when exposed to 2 – 3 m waves, or extended periods of relaxation time, whole island migration is minimal and island freeboard is maintained under all sea level scenarios (Figs. 8, 9).

4.1.2 Island spit morphodynamics

Results of this study reveal there are substantial differences between the morphological responses of the lower elevation island spits compared to the central section of the island. First, in contrast to crest accretion exhibited by the central island, the lower elevation island spits experience a higher frequency of overwash processes that erode the oceanward crest under all wave and water levels conditions (Figs. 5, 8).

Second, our observations identify lagoonward rotation of the island spits as a key geomorphic response to increases in sea level and wave height. Spit rotation occurs under all wave and water level conditions (Figs. 4, 7). As sea level is increased the lower elevation ends of the island rotate lagoonward at a faster rate due to enhanced overwash frequency, decreasing the length of the island and resulting in an increasingly crescentic planform island shape. Islands exposed to larger wave conditions are expected to undergo a more rapid rate of spit rotation (Ashton et al., 2016; Fig. 7). The highly migratory spits observed during the experiments are consistent with remote sensing observations that report considerable migration of reef island spits over seasonal and decadal timespans (Webb and Kench, 2010; Rankey, 2011; Ford, 2013, Kench et al., 2015).

4.2 Modelling assumptions

The experiment program was designed in order to explore the modes and styles of island change in response to a range of wave conditions. As such, it is important to note that several other processes may also influence island morphodynamics and that the model simulations may reflect the more extreme morphological outcomes in comparison to field settings. In particular, the simulations do not account for the morphological response to changing rates of SLR or to smaller constructive wave conditions that likely occur inbetween storm events. Therefore, the results do not represent site-specific morphologic predictions but rather highlight the likely

modes and styles of geomorphological response of reef islands to changing water level and wave conditions.

Furthermore, this study does not simulate the role of sediment supply or coral reef growth with SLR on future island change. Changes in sediment supply are expected to have a large control over the development and stability of reef islands by altering the mode and rate of island adjustment (Perry et al., 2011). The physical modelling experiments presented here deal with a fixed volume of sediment and therefore cannot replicate increases in island volume observed in the field (Kayanne et al., 2016). Our results indicate a reduction of habitable island area with rising sea levels (Fig. 7). However, a supply of sediment produced on the surrounding reefs is expected to offset subaerial island width and volume reduction, potentially improving island habitability (Kench and Cowell, 2002).

Our experiments also maintained a fixed reef flat level, which did not account for the potential growth of the reef crest and reef flat, which geological records indicate is a typical response of reefs to SLR (Kleypas, 1996; Toomey et al., 2013; Woodroffe and Webster, 2014; van Woesik et al., 2015). The simulation of reef growth within modelling experiments may further reduce the changes observed in this study by altering wave energy attenuation across the reef platform and ultimately the amount of energy available at the shoreline to induce geomorphic change. Numerical modelling results simulating the effect of reef platform accretion with SLR on wave processes indicate that reef growth can significantly diminish the SLR associated increase in sea and swell wave height and resulting overwash volume (Beetham et al., 2017).

An inherent limitation of physical modelling studies is that facilities such as a wave basin or flume typically only generate unidirectional waves. Therefore, the physical model created for this study only considers ocean waves (from ocean to lagoon). As a result, any changes in the lagoon shoreline within the model are dependent on whether overwash processes can drive

sediments lagoonward. In reality, lagoon shoreline change is primarily influenced by lagoon energy (from lagoon to ocean), therefore, physical adjustment of the lagoon shoreline, particularly lagoonward berm development, as a result of lagoon energy is absent in the model (Shope and Storlazzi, 2019). In addition, the modelling experiments do not simulate the frictional and binding effects of dense vegetation, which is observed on many motu, and is expected to have an effect on island response. Future physical modelling experiments that simulate storm-derived sediment supply, reef growth and multi-directional wave energy sources are expected to provide more realistic trajectories of the future state of reef islands.

4.3 Future reef island trajectories

Along with studies analysing planform island change, physical modelling outputs suggest that many islands may remain on reef surfaces despite SLR as overwash processes provide a mechanism for island building that in turn enables the island to maintain freeboard and offset future flood events (Yates et al., 2013; Mclean and Kench, 2015; Kench et al., 2015, 2018; Duvat, 2019). However, continued morphodynamic adjustments of islands in response to changing wave and water level conditions is expected to result in different island configurations and possibly locations on reef platforms. A conceptual framework of island geomorphic responses to increasing sea level and changing wave heights is proposed, including island building and island migration, as well as limited response leading to island drowning and island destabilisation as the potential responses. The conceptual framework emphasises the importance of wave height on island building, identifying an optimal range of wave conditions that are conducive to island preservation on the reef platform (Fig. 11 G - L). Within the physical model 2 – 3 m waves are identified as optimal conditions for island building; however, these conditions are expected to vary for different islands depending on site-specific differences in reef width, island morphology and sediment size. Wave heights that are large enough to drive overtopping processes at the island shoreline promote island building and

573 preservation upon the reef platform by maintaining island freeboard. *Motu* exposed to wave
574 heights slightly beyond the optimal range are expected to exhibit substantial lagoonward
575 migration in response to the higher frequency and intensity of overwash processes (Fig. 11 M
576 - O). When exposed to extreme wave conditions, on the other hand, *motu* are expected to
577 destabilise and be destroyed as overwash processes erode the island with rising sea levels (Fig.
578 11 P - R).

579 The results of this study are highly instructive for future assessments of island vulnerability.
580 Current flood risk models that simulate future SLR on present day island geomorphology are
581 only applicable to the small number of islands where shorelines have been armoured and are
582 therefore unable to adjust to changing environmental conditions (Fig. 11 A - C). Incorporation
583 of reef island morphodynamics within predictive models is required to accurately predict the
584 future state of the majority of reef islands that will change in shape and position on the reef
585 platform with rising sea levels and increasing wave heights (Fig. 11). Further work is required
586 to ground truth the boundaries of the conceptual zones of island geomorphic response for
587 different islands and under different environmental conditions.

Fig. 11. Conceptual model of island geomorphic responses to changing sea level and wave height. A - C) No island response, D - F) limited island response (1.3 m waves), G - L) island building (2 – 3 m waves), M - O) island migration (4 m waves), and P - R) island destruction (5 m waves), observed during the modelling experiments.

To date, adaptation planning within reef island settings has been restricted by a lack of relevant information regarding contemporary and future island morphodynamics in response to changing wave and water level conditions. The results of the physical modelling experiments presented here provide new insights of whole island change to rising sea levels and changing wave conditions. Quantified modes and styles of island change provide a sound basis on which to develop new adaptation pathways sympathetic to the dynamic nature of islands. A better understanding of island morphodynamics allows island communities to make more informed land use planning decisions, as well as helping improve mitigation efforts to restrict future impacts of climate change on small island nations (Kench et al., 2018).

5. CONCLUSION

This paper presents the first physical modelling investigation of the whole-of-island morphodynamic response of reef islands to changing sea level and wave conditions. Our results demonstrate the dynamic nature of reef islands, identifying lagoonward rotation of the island spits as well as vertical island accretion and lagoonward migration as the core modes of island response to SLR. Challenging existing models of future island flooding which assume islands are geomorphologically inert, the present results demonstrate that washover processes provide a mechanism through which islands are able to accrete vertically in response to SLR, offsetting future flood events. Modelling results suggest that some islands may maintain island freeboard and remain on reef platforms despite SLR. However, island vulnerability to inundation is expected to be highly variable, dependent on site-specific variations in the rate and magnitude of SLR (relaxation time) and offshore wave conditions. The whole-of-island results provide new insights for evaluating the susceptibility of islands to inundation and highlight the urgent need to couple future SLR and wave conditions with likely geomorphic island responses to provide more realistic predictions of flood impacts and better resolve future island vulnerability.

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Data availability

The datasets reported in the paper are available from the corresponding author on reasonable request.

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