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Wave energy gradients and shoreline change on Vabbinfaru platform, Maldives

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ABSTRACT

This study examined coral reef platform wave processes and shoreline dynamics over short timescales. Wave energy gradients and shoreline change were measured over a 3-week period on Vabbinfaru platform, North Malé Atoll, Maldives, during the westerly monsoon in June 2010. Wave processes were measured using nine pressure sensors recording near continuous data for 19 days around the reef and shoreline of a small circular sand cay. Toe of beach position was surveyed before, during and after the deployment to map changes in shoreline configuration. Results show that wave height and direction on the windward reef are closely controlled by local wind activity inside the atoll lagoon. Wave transformation across the platform was found to exhibit strong tidal modulation and results in distinct cross-reef energy zonation. Results are presented by comparing two contrasting boundary wind conditions: the first 2 weeks characterised by moderate southwest winds, and the third week characterised by stronger northwest winds. Wave data was interpolated to platform scale and used to show spatial variations in energy exposure during the different boundary conditions. Under southwest winds, greatest wave energy was present on the western and leeward (eastern) reefs, driving an energy gradient towards the sheltered northern and southern shorelines. A net 4.5% increase in beach area was measured during this period. During stronger northwest winds, higher wave energy impacted the reef and was concentrated on the western reef, northern reef and northwest shoreline. An energy gradient formed around the island towards a low energy zone located at the southeast shoreline. Significant shoreline change occurred during this period with the toe of beach retreating landward by more than 10 m on the northwest, northeast and southwest of Vabbinfaru Island. Beach area was reduced by 3761 m^2 (17%) as the shoreline was forced to adjust in response to a new hydrodynamic regime. Results show that the coral reef platform is able to modify and filter the incident wave climate, resulting in marked spatial differences in wave spectra. Spatial differences in wave energy are sensitive to local wind activity, resulting in rapid alteration in wave energy distribution around the platform. Results highlight that reef island shorelines are morphologically sensitive to short-term changes in boundary wind and wave conditions. Wave energy gradients driven by local wind activity have the potential to drive alongshore fluxes of sediment around island shorelines. Therefore, changes to the process regime can result in disequilibrium of the shoreline, forcing rapid adjustment of island sediment.

1. Introduction

Coral reef islands are accumulations of biologically-produced carbonate sand and gravel deposited on the surface of reef platforms. These reef top landforms typically have a maximum elevation less than 5 m above mean sea level and sustain populations of small island nations throughout the world's tropical seas. As a consequence of their low elevation and unconsolidated sediment, reef islands and reef island communities are considered vulnerable to the threat of rising sea level (Woodroffe and Murray-Wallace, 2012). However, forecasting the physical response of reef islands to rising sea level is constrained by a limited understanding of the contemporary physical dynamics between islands and the hydrodynamic processes influencing them.

Reef island formation is influenced by a range of physical and biological processes, including sea level, sediment generation, wave climate and accommodation space (Kench et al., 2009a; Perry et al., 2011). However, contemporary island stability and change is primarily controlled by wave-driven hydrodynamic processes on the reef top (Samosorn and Woodroffe, 2008; Mandlier and Kench, 2012). The refraction and dissipation of ocean waves across the reef surface has been implicated as a primary control on the location and stability of reef islands (Gourlay, 1988; Mandlier and Kench, 2012). Gourlay (1988) presented a conceptual nodal point model showing how refracting waves converge on a reef platform, forming a focal zone for sediment accumulation and island formation. Flood (1986) suggested that shoreline dynamics on reef island beaches are controlled by migration of the nodal point due to changing incident wave conditions. This was confirmed by Kench and Brander (2006a) who showed that seasonal oscillations of shoreline sediment on reef islands in the Maldives

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were driven by reversing monsoon winds. Despite this conceptual understanding of wave-driven island change, there is a lack of knowledge regarding how island shorelines respond to short-term hydrodynamic variation. Very few field-based observations of hydrodynamic process and shoreline change exist.

Reef-top hydrodynamic processes are complex (Monismith, 2007; Taebi et al., 2012). Initial research focused on wave interaction with the reef edge, quantifying the attenuation of wave energy on reef flat and back-reef environments (Roberts et al., 1977; Lee and Black, 1978; Lugo-Fernandez et al., 1998). More recent studies have characterised wave transformation from the reef edge to the island shoreline, identifying strong tidal modulation of shoreline wave height (Brander et al., 2004; Kench and Brander, 2006b; Péquignet et al., 2011). Mathematical relationships between wave height and water depth have been examined to show that reef depth governs wave conditions that ultimately impact shorelines (Nelson and Gonsalves, 1992; Massel, 1996; Nelson, 1996). In addition, wave setup, driven by wave breaking at the reef edge, has been identified as a significant process driving variations in water level, reef-top currents, and controlling wave run-up at island shorelines (Symonds et al., 1995; Gourlay, 1996a, 1996b; Gourlay and Colleter, 2005; Jago et al., 2007).

Existing field studies have typically simplified complex 3-dimensional reef structures into single 1-line transects to evaluate wave transformation (Kench and Brander, 2006b), reef-top currents (Lugo-Fernandez et al., 2004) and wave setup (Jago et al., 2007). Laboratory and analytical modelling studies have also used simplified across-reef profiles to simulate wave setup and wave driven flow (Symonds et al., 1995; Gourlay, 1996a, 1996b). A full-scale understanding of wave and shoreline processes can only be attained through studies that represent the reefs spatial complexity. Recent studies have deviated from the single transect approach to examine spatial and seasonal characteristics in wave processes (Kench et al., 2009b) and circulation (Kench et al., 2009c) around reef islands in the Maldives. These studies evaluated the influence of reversing monsoon seasons on wave processes and resultant currents that drive an oscillation in shoreline position. However, the limited sampling duration (5 days) did not measure significant short-term variation in nearshore processes or shoreline dynamics. A longer sampling duration and increased instrument sampling density is needed to understand contemporary process-based dynamics.

This study examines spatial variations in reef platform wave processes and shoreline dynamics based on a 3-week experiment on Vabbinfaru Island, Maldives. Temporal and spatial variations in wave energy across Vabbinfaru platform are used to highlight the contemporary dynamics that exist between wave energy gradients and shoreline change.

2. Regional setting

The experiment was undertaken on Vabbinfaru platform, an oval-shaped coral reef inside North Malé Atoll, Maldives (Fig. 1). The Maldives archipelago is a double chain of atolls located in the central Indian Ocean (Fig. 1a), extending from 0°34′ S to 6°57′ N (Naseer and Hatcher, 2004). North Malé Atoll is located in the central section and eastern side of the atoll chain (Fig. 1b). The atoll perimeter is 161 km, of which 117.9 km comprised shallow reef and 43.1 km (26.8%) comprised deeper passages that allow oceanic tides, currents and waves to pass into the lagoon (Fig. 1c). The atoll covers a total surface area of 1568 km^2 of which 349 km^2 comprises 189 reef platforms (Naseer and Hatcher, 2004).

Vabbinfaru platform has a north to south length of approximately 500 m, an east to west length of 810 m and a circumference of 2.11 km. The platform has a total area of 0.31 km^2 comprising three main geomorphic environments: a) a ring of live coral around the outer platform; b) an inner shallow moat (<1.5 m) comprised sand and rubble; and c) a vegetated island with a mean elevation less than 1.5 m above sea level (Fig. 2). The reef platform is host to a productive marine ecosystem with 27% of the platform covered in live coral (Fig. 2a). The area of live coral cover is concentrated around the outer platform between water depths of 0.5 m below msl on the reef to depths greater than 40 m on the reef slope (Fig. 2b). The reef is generally subtidal, with corals only emergent during spring low tides. Within the zone of live coral, coral cover is 49–70%, composed predominantly of branching and tabulate *Acropora* species with a subordinate presence of massive and sub-massive *Porites* corals (Morgan and Kench, 2012). The live coral zone varies in width around the platform from 70 m on the west and east to 20 m on the north and south (Fig. 2a). Four shallow channels bisect the live coral cover, promoting water exchange between the moat and atoll lagoon. Channel depths range between 0.3 m to 0.5 m below the height of coral.

The inner moat covers 60% of the platform and comprised coral sand and rubble. Moat width varies around the island, ranging from 330 m (west), to 125 m (north) and approximately 105 m on the south and east. Moat depth ranges between 1 m and 1.5 m below msl, with a mean depth of 1.2 m below msl. There is an artificial, submerged coral and rip-rap breakwater approximately 40 m from the toe of beach on the eastern shoreline. The vegetated sand cay (Vabbinfaru Island) occupies 13% of the reef platform, located on the central east section of the reef surface (Fig. 2). Vabbinfaru Island comprised moderately well sorted sediment with a mean grain size of 1.34 phi (medium grain sand). Beach sediments predominantly consist of coral sand with an additional presence of Halimeda and coralline algae (Morgan, 2013).

3. Material and methods

3.1. Field experiment

Near-continuous field measurements of wave height and water level were collected over 19 days on Vabbinfaru reef platform, during the westerly monsoon in June to July 2010. Nine hydrodynamic instruments and one weather station were deployed around the reef and island shoreline for the duration of the experiment (Table 1). All instruments were synchronised to record every half hour, on the hour, with a sampling frequency of 2 Hz. The experiment commenced at 19:00 June 22nd (GMT + 6) and concluded at 09:00 July 10th, 2010. Each instrument recorded 845 synchronised bursts.

A total of five RBR-TWR 2050P data loggers (tide and wave recorders) were used to collect wave data around the reef. To characterise boundary wave conditions, one RBR was positioned at the westerly reef edge, at a water depth 1.7 m below msl (Fig. 2a). The four additional RBRs were positioned around the inner reef flats, at the boundary between live coral cover and the moat. These additional RBRs were deployed on the west, south, north and east to characterise wave energy transmitted over the reef (Fig. 2a). RBRs were secured to cement blocks. A full deployment summary is presented in Table 1.

To document wave energy reaching the shoreline, four Inter Ocean S4 electromagnetic current meters with pressure sensors were used in two deployment configurations (Table 1). From June 22nd until July 5th (Weeks 1–2) the S4s were positioned to the west, south, north and east of the island, 10 m seaward from the toe of beach (Fig. 2a). From July 5th–10th (Week 3) the S4s were rotated 45° clockwise around the island (W-NW; S-SW; N-NE; E-SE) to gain a higher resolution understanding of wave energy reaching different sections of the island. The S4s were deployed on stainless steel pods with the sensors 0.175 m above the bed. The S4s sampled 1024 data points per burst. Due to battery and memory limitations and instrument maintenance requirements, each S4 was retrieved to clean, service and transfer data. This was done twice during the experiment, giving two short periods (1–3 h) of missing data from each instrument.

A small tower located in the southwest moat section was used to mount a kestrel 4500 Weather Meter, 3.2 m above msl. The weather meter measured wind speed, wind direction, atmospheric pressure