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Wave characteristics and morphological variations of pocket beaches in a coral reef–lagoon setting, Mayotte Island, Indian Ocean

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ABSTRACT

Pocket beaches are common worldwide but documentation on their hydrodynamics, sediment transport processes and morphodynamics is sparse compared to open beaches. Studies of headland-bound pocket beaches in coral reef environments are even more sparse notwithstanding an increasing number of studies of coral reef shorelines. Mayotte Island, in the Indian Ocean, is characterised by a coral reef–lagoon complex and numerous pocket beaches nested between volcanic headlands. Field experiments were conducted in order to: compare wave attenuation from the outer barrier reef to the inner reef flat fronting three pocket beaches, analyse attenuation patterns across an inner reef flat fronting one of the beaches, and document beach morphological changes. Wave attenuation exceeded 90%, and increased as wave heights increased, with maximum attenuation of moderately large waves (significant wave heights > 1.8 m) generated by a category 1 cyclone (Jokwe). Further attenuation across the inner reef flat was neither related to reef width nor correlated with water depth, but the correlation was slightly better with relative wave height. Attenuation increased as relative wave height decreased.

Patterns of beach morphological change driven by residual wave energy following reef attenuation were strongly affected by the degree of beach embayment. Mtsanga Gouela and Trevani beaches are characterised by a low bay indentation conducive to longshore sediment mobility, and provide rare examples of inferred rotation of reef-fronted beaches, similar to rotation of drift-aligned beaches in non-reef settings. In contrast, Dapani beach, nested in a strongly indented bay, was dominated by seasonal cross-shore sand exchange. In addition to reef-driven wave attenuation, an important factor differentiating pocket beaches in coral reef settings and non-reef settings is the inner reef flat. The historical stability of the beaches suggests that the outer limits of cross-shore seasonal or cyclone-induced sediment movements are set over these reef flats. Further studies of reef-fronted pocket beaches will require better elucidation of the effect of the fronting reef flats on sediment transport and storage, and of the role of heterogeneity in sediment grain size and density common in reef environments in volcanic settings.

1. Introduction

Pocket beaches refer to short (100 m to a few kilometres long), more or less embayed beaches. The morphological behaviour of embayed and pocket beaches has received attention in the literature in terms of: (1) cross-shore and longshore sediment mobility and their effects on plan-form configuration, and (2) the impact of morphological context, such as the degree of indentation, on wave incidence and plan form. The headlands that bound pocket beaches may act as barriers to longshore sediment transfers between adjacent beaches (Short and Masselink, 1999; Storlazzi and Field, 2000; Dolique and Anthony, 2005; Bowman et al., 2009; Dehoucke et al., 2009). Longshore sediment fluxes may also be limited as a result of significant refraction as these beaches commonly absorb incident wave energy from a limited directional window (Bowman et al., 2009). Individual pocket beaches may vary, therefore, in terms of their sediment dynamics, from typical swash-dominated to drift-dominated configurations; these configurations denoting, respectively, propensity for the absence and dominance of longshore drift (Davies, 1980). The sediment transport condition and consequent morphological change have largely been linked to the degree of bay indentation and exposure to the wave field, especially wave incidence angle (Hsu and Evans, 1989; Hsu et al., 1989), and the importance of beach indentation has been reiterated in a recent spate of studies (Bowman et al., 2009; Hsu et al., 2010; Uda et al., 2010; Schiaffino et al., 2011).

Although pocket beaches are common worldwide along rocky coasts, documentation on their hydrodynamics, sediment transport processes and morphodynamics is sparse compared to open beaches. Studies of bedrock headland-bound pocket beaches in coral reef environments

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are even more sparse, although such beaches are frequent on reef-fringed volcanic islands, such as Hawaii (Norcross et al., 2002). Studies of reef-fringed shorelines have essentially concerned wave energy gradients and their implications for island shoreline geomorphology (e.g., Brander et al., 2004; Kench and Brander, 2006a,b; Kench et al., 2006, 2009). The dissipation of incident wave energy through friction against the rough bottom of coral reef systems can play a significant role in natural coastal defence (Hearn, 1999; Sheppard et al., 2005; Zawada et al., 2010), the reefs acting as submerged offshore breakwaters (e.g., Gourlay and Colleter, 2005). Several of these studies have also highlighted a critical control by water level over reefs, generally modulated by topography, and by tidal range, with low-tide conditions in meso- to macrotidal settings being likely to preclude onshore wave transmission, whereas energy transmission can be significant during high water stages (Brander et al., 2004; Storlazzi et al., 2004), and under conditions of minimum wave breaking (Kench and Brander, 2006a). The seasonal pattern of wave energy on many coral reef shorelines and differences in wave energy between windward and leeward sides of reef islands may also induce differentiations to which reef shoreline geomorphology must adapt (e.g., Kench and Brander, 2006a,b; Kench et al., 2009).

Reef shorelines are extremely diverse, ranging from open coast beaches, through islands developed on top of reef flats in the open ocean, to shorelines sheltered behind reef–lagoon systems. While the wave energy exposure and dissipation conditions evoked above may be relevant to all types of reef shorelines, the way the morphology and dynamics of pocket beaches, locked between bedrock headlands and protected against open-ocean waves by reef–lagoon systems, react to residual incident wave energy is not known. In such settings, over space and time, both the amount of residual wave energy and the influence of bay indentation on incident energy must be considered as critical controls on beach morphological variations.

Mayotte Island, in the Indian Ocean, is characterised by a vast, highly diversified barrier reef–lagoon complex (Fig. 1) and numerous pocket beaches that show variable exposure to waves in space and time. These variations and the morphological behaviour of the reef-fronted beaches have been characterised from four experiments on barrier reef, fringing reef and beach hydrodynamics and five beach topographic surveys conducted from 2005 to 2008. More specifically, the experiments were aimed at: (1) highlighting temporal patterns in the wave regime, (2) comparing wave attenuation from the outer barrier reefs to the inner reef flats fronting two pocket beaches, (3) showing attenuation patterns across an inner reef flat fronting a pocket beach, and (4) interpreting the morphological behaviour of three variably embayed pocket beaches in response to the incident wave conditions.

2. Study area

Mayotte is located north of the Mozambique Channel 300 km northwest of Madagascar and 450 km away from the African continent. With a total area of 374 km^2, Mayotte is composed of a main Island (Grande Terre), a smaller one (Petite Terre), and about 30 islets, of volcanic or coral material, spread out in the lagoon. Grande Terre culminates at a peak elevation of 660 m (Mount Bénara). Mayotte is ringed by about 270 km^2 of reefs (Fig. 1). These include a largely continuous barrier with a circumference of 157 km. The barrier reef bounds a 3–15 km-wide, and up to 80 m-deep lagoon with an area of nearly 1500 km^2, one of the largest reef lagoons in the Indian Ocean.

Mayotte experiences a humid tropical climate comprising two seasons, a hot rainy monsoon season, and a cooler, dry trade wind season. Mean annual rainfall is about 1500 mm. Pressure gradients between the Intertropical Convergence Zone and anticyclones in the Indian Ocean generate, respectively, hot and humid monsoon winds from a north to northwest sector during the southern hemisphere summer (December to March) and cool, dry trade winds from south to southeast during the southern hemisphere winter (May to August). The latter form the dominant winds (Fig. 2a). Winds from SE to SSW account for 50% of all winds, followed by the SW to WSW (16.5%). Winds from NW to NNE account for only about 19%, while winds embracing both the north and south sectors, from NE to ESE account for 14.5%. Mean wind speeds are relatively weak, attaining maximum values of 4.3 m s^{-1} for the SE to SSW sector while maximum speeds are associated with winds from SW to WNW and from NE to ESE. The maximum wind speeds occur during the passage offshore, along NE–SW tracks north and south of Mayotte, of tropical storms or cyclones between January and April.

Voluntary Observing Ship (VOS) wave observations (sector: 11–15°S, 43–47°E) over the period 1960–2000 and AVISO data from spatial altimetry show that the offshore wave climate of Mayotte is dominated by moderate waves with characteristic periods of 5 to 6 s that denote a regional fetch (Fig. 2b, c). The wave climate is closely related to the seasonal wind regime. Monsoon winds from NW to NE generate moderate waves, with a tendency towards relatively calm conditions at the end of the monsoon season. The highest and most frequent waves are from S to SE (60%), in response to the highly regular and sustained trade winds from May to September. Forty to 44% of all wave heights are between 1 and 2 m, while heights above 2 m account for 8 to 15%. The highest waves occur in July, at the height of the trade wind season, with 75% of wave heights exceeding 1 m. The directional frequency of waves from NE to ESE (30 to 45%), a window characterised by low waves, increases in August and especially September. The wave heights show a cyclic pattern of increases and decreases over periods of 5 to 10 days (Fig. 2c) that are hinged on strengthening or weakening of the trade winds caused by changes in the position of anticyclone activity in the Indian Ocean. Mayotte also lies on the track of tropical storms and cyclones, two of which approached close to the island over the study period (Fig. 2c). Tides affecting Mayotte are semi-diurnal and the tidal range mesotidal, with a mean spring range of about 3.2 m.

The total shoreline length of Mayotte is 265 km, and is an intricate alternation of cliffs separating variably indented pocket beaches of sand and sandy mud, the sheltered low-energy backshores of many of which have been colonised by mangroves. Table 1 summarises a number of ‘embayment’ parameters of the 35 longest pocket beaches of Mayotte, three of which – Dapani, Mtsanga Gouela and Trevani (Fig. 1) – were selected for this study. These parameters, the use of various ratios of which enables an objective comparison of the degree of beach shoreline indentation from poorly to highly indented (e.g., Hsu et al., 1989; Spagnolo et al., 2008; Bowman et al., 2009), include:

Ro	the distance between two bounding headlands,
α	the degree of bay indentation relative to the Ro control line,
S1	the length of the embayed shoreline between the two headlands, and
S2	the length of the embayed beach.

Mtsanga Gouela and Dapani beaches represent the two extreme ends of indentation, from very low in the case of the former, to very high in the case of Dapani beach (Table 1). Trevani beach may be considered as representative of a moderately indented beach, although closer in the range to Mtsanga Gouela than to Dapani beach. The beaches are all fringed by a reef flat ranging in width from about 50 to over 800 m (Table 1) and lying at an elevation of −1.8 to −2.2 m IGN 50 (French national geodetic reference for Mayotte), i.e., between MLWN (mean low water neaps) and MLWS (mean low water springs). This fringing reef flat is linked to the lagoon by abrupt submarine slopes ranging from 45° to vertical cliffs several metres high. The lower beach is sometimes separated from the reef flat by a >0.5 m-deep trough visible at low tide.

Trevani beach is up to 50 m-wide intertidally (Fig. 3a), and is fringed by a 170 m-wide reef flat. The beach consists of poorly sorted medium sand ($D_{50}=1.74$–$1.51\ \Phi$) formed of volcanic clasts and alterites, and less than 10% of bioclasts. The intertidal beach shows two distinct segments: a moderately steep upper beach (tanx=