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Spectral wave-driven sediment transport across a fringing reef

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ABSTRACT

A laboratory experiment was conducted to investigate the dynamics of cross-shore sediment transport across a fringing coral reef. The aim was to quantify how a highly bimodal spectrum of high-frequency (sea-swell) and low-frequency (infragravity and seiching) waves that is typically present on coral reef flats, influences the various sediment transport mechanisms. The experiments were conducted in a 55 m wave flume, using a 1:15 scale fringing reef model that had a 1:5 forereef slope, a 14 m long reef flat, and a 1:12 sloping beach. The initial 7 m of reef flat had a fixed bed, whereas the back 7 m of the reef and the beach had a moveable sandy bed. Four seven-hour irregular wave cases were conducted both with and without bottom roughness elements (schematically representing bottom friction by coral roughness), as well as for both low and high still water levels. We observed that the wave energy on the reef flat was partitioned between two primary frequency bands (high and low), and the proportion of energy within each band varied substantially across the reef flat, with the low-frequency waves becoming increasingly important near the shore. The offshore transport of suspended sediment by the Eulerian mean flow was the dominant transport mechanism near the reef crest, but a wide region of onshore transport prevailed on the reef flat where low-frequency waves were very important to the overall transport. Ripples developed over the movable bed and their properties were consistent with the local high-frequency wave orbital excursion lengths despite substantial low-frequency wave motions also present on the reef flat. This study demonstrated that while a proportion of the sediment was transported by bedload and mean flow, the greatest contributions to cross-shore transport were due to the skewness and asymmetry of the high and low-frequency waves.

1. Introduction

There is a growing body of literature on the hydrodynamic processes generated by the interaction of waves with coral reef structures, including the evolution of incident swell wave fields, the dynamics of low-frequency (infragravity) waves, and the generation of mean wave-driven flows (see reviews by Monismith (2007) and Lowe and Falter (2015)). Reef systems display very different bathymetric characteristics from sandy beaches; they usually have a steep forereef slope, a rough shallow reef crest (often located far from the shore) and are connected to the shoreline via a shallow rough reef flat and sandy lagoon. At the reef crest, high-frequency waves (i.e. sea-swell waves with periods 5–25 s) are dissipated in a narrow surf zone via wave breaking and bottom friction (e.g. Lowe et al., 2005a). In this region, low-frequency waves (i.e., infragravity waves with periods 25–250 s) are generated by the breaking of incident high-frequency waves (Péquignet et al., 2014; Pomeroy et al., 2012a). In some cases low-frequency wave motions with periods even larger than the infragravity band (i.e., periods exceeding 250 s) can also be generated at the natural (seiching) frequency of coral reef flats, which may also be resonantly forced by incident wave groups (Péquignet et al., 2009; Pomeroy et al., 2012b). This disparity between high and low-frequency waves often results in a bimodal spectrum of wave conditions on coral reef flats and lagoons, where wave energy is partitioned between distinct high-frequency (sea-swell) and low-frequency (infragravity) wave bands (Pomeroy et al., 2012a; Van Dongeren et al., 2013). Recent hydrodynamic studies have shown how these different wave motions interact with the

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rough surfaces of reefs, and cause rates of bottom friction dissipation to be highly frequency dependent (e.g. Lowe et al., 2007; Pomeroy et al., 2012a; Van Dongeren et al., 2013). The extent to which bimodal wave spectra on reefs affect sediment transport processes has yet to be investigated and is the focus of this paper.

It is customary to decompose the total sediment transport into two primary modes (bedload and suspended load), which enables a more detailed description of the physical processes involved, and can more readily be used to distinguish between the effects of currents and waves. For bedload transport, initial work focused on steady (unidirectional) flow in rivers and coastal systems where mean currents dominate (e.g. Einstein, 1950; Engelund and Hansen, 1967; Meyer-Peter and Müller, 1948). These descriptions relate the transport of sediment to the exceedance of a flow velocity or shear stress threshold. Current-driven suspended load is deemed to occur when the flow velocity (or bed shear stress) generates sufficient turbulent mixing to suspend particles in the water column (e.g. Bagnold, 1966). Traditionally, to incorporate these suspended load processes into predictive formulae, a vertically varying shape function describing the sediment diffusivity (e.g., constant, exponential, parabolic) is assumed, along with a reference concentration usually located near the bed (e.g. Nielsen, 1986; Soulsby, 1997; Van Rijn, 1993).

The extension of sediment transport formulae to wave-driven (oscillatory flow) conditions was initially considered within a quasi-steady (wave-averaged) framework analogous to current-driven transport formulations, albeit extended to account for the enhancement of the bed shear stress induced by the waves. This approach has also primarily concentrated on high-frequency waves, despite low-frequency waves (as well as wave groups) also being important in the nearshore zone (e.g. Baldock et al., 2011). The importance of the shape of a wave form on sediment transport (i.e., due to the skewness or asymmetry of individual waves) has also been considered using a half-cycle volumetric approach, where the separate contribution of shoreward and seaward wave phases to the net transport is considered (e.g. Madsen and Grant, 1976). In general, these suspended sediment transport formulations are all sensitive to how the sediment is distributed vertically in the water column, with a number of different shape functions and empirical diffusion parameters proposed that depend on the wave conditions (e.g. Nielsen, 1992; Van Rijn, 1993). It is also important to note that for rough beds, such as those with ripples, sediment suspension can be further enhanced by vortices generated at the bed (e.g. O'Hara Murray et al., 2011; Thorne et al., 2002, 2003). Finally, in contrast to the more widely-used steady or wave-averaged approaches, instantaneous (or intra-wave) sediment transport models have also been proposed that attempt to directly model the transport over each phase of an individual wave cycle (e.g Bailard, 1981; Dibajnia and Watanabe, 1998; Nielsen, 1988; Roelvink and Stive, 1989).

Irrespective of how the sediment transport is described, in wave applications these formulations tend to either assume that the transport can be described with properties of a single idealized monochromatic (regular) wave, or alternatively for the case of spectral (irregular) wave conditions, that the spectrum is narrow enough in frequency space that energy is concentrated near a well-defined (i.e., unimodal) peak and hence can be described by a single representative wave condition (height and period). For reef environments, there are distinct differences in how high and low-frequency waves transform across reefs, and hence in their relative importance over different zones of the same reef. As a result, sediment transport on reefs is still poorly understood and the applicability of existing sediment transport formulations to the distinct hydrodynamic conditions on reefs is not known. Consequently, an important first step is to understand the relative importance of suspended load and bedload to cross-shore transport, and more specifically how the mean flow and the distinct spectral wave conditions on reefs influence sediment transport.

Few detailed laboratory studies have been utilized to investigate physical processes on fringing reef systems, and all of those have exclusively investigated hydrodynamic processes and not sediment transport (e.g. Demirbilek et al., 2007; Gourlay, 1994, 1996a, 1996b; Yao et al., 2009). The objectives of this paper are thus to use a scaled physical model of a fringing coral reef to: (1) quantify the spectral evolution of high and low-frequency wave fields across a reef; (2) understand the mechanisms that drive suspension of sediment within the water column; (3) identify how high and low-frequency waves affect the magnitude and direction of cross-shore sediment transport processes; and (4) determine the relative importance of suspended load versus bedload to the overall sediment transport. As the characteristics of a reef flat can vary from reef to reef, in this study we focus on the impact of both the water depth over the reef flat and bottom roughness on these processes. In Section 2, we commence with an overview of the experimental design, instrument setup and the methods adopted to analyze the results. The results are presented in Section 3. Finally in Section 4, we assess the relative importance of the various sediment transport mechanisms, as well as the role of suspended versus bedload to changes in the overall cross-shore sediment fluxes. We conclude with a discussion of the implications of this study for the relative importance of different cross-shore transport mechanisms in fringing coral reef systems.

2. Methods and data analysis

2.1. Experimental design and hydrodynamic cases

The experiment was conducted in the Eastern Scheldt Flume (length: 55 m, width: 1 m, depth: 1.2 m) at Deltares (The Netherlands), which is equipped with second-order (Stokes) wave generation and active reflection compensation (Van Dongeren et al., 2001) (Fig. 1a). The laboratory fringing reef model was constructed to a scale ratio of 1:15, corresponding to a Froude scaling of 1:3.9. The latter represents the balance between inertial and gravitational forces, and was used to maintain hydrodynamic similitude of essential processes, such as wave steepness, shoaling and breaking (Hughes, 1993). The reef model (Fig. 1b) consisted of a horizontal approach, a 1:5 forereef slope from the bottom of the flume to a height of 0.7 m, a horizontal reef flat of 14 m length (7 m was a fixed bed and 7 m was a movable sediment bed) and a 1:12 sandy beach slope from the reef flat to the top of the flume. The forereef slope and fixed (solid) reef flat were constructed from marine plywood, while the movable bed consisted of a very well-sorted and very fine quartz sand with a median diameter $D_{50} = 110$ μm and standard deviation $\sigma = 1.2$ μm. This sand was chosen to be large enough to be non-cohesive (Hughes, 1993) and, when geometrically scaled, is equivalent to a grain size of 1.70 mm at prototype (i.e., field) scale – thus, comparable to the medium to coarse sand observed on many coral reefs (e.g. Harney et al., 2000; Kench and McLean, 1997; Morgan and Kench, 2014; Pomeroy et al., 2013; Smith and Cheung, 2002).

Four cases were simulated experimentally: a rough reef at low and high water, and a smooth reef at low and high water (Table 1). The low water condition consisted of a $h_r = 50$ mm still water level (SWL) over the reef flat, whereas the high water condition had a SWL of $h_r = 100$ mm. This corresponds to prototype SWLs of 0.75 m and 1.5 m, respectively. All four cases were conducted with a repeating ten-minute TMA-type wave spectrum (Bouws et al., 1985) with an offshore (incident) significant wave height H_{m0} of 0.2 m (prototype 3.0 m) and a peak period T_p of 3.2 s (prototype 12.4 s). These conditions were selected to be representative of relatively large (but typical) 'storm' conditions that most wave exposed reefs experience (Lowe and Falter, 2015). Each case was run for 7 h and was partitioned into three sub-intervals (A: 1 h, B: 2 h, C: 4 h).

To assess the impact of bottom roughness on the hydrodynamics and sediment transport across the reef, an idealized bottom roughness was used. Although it is not possible to capture the full complexity of natural three-dimensional roughness of coral reefs in a laboratory