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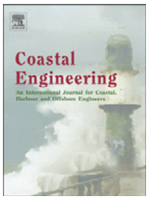

Numerical modeling of low-frequency wave dynamics over a fringing coral reef

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ABSTRACT

Low-frequency (infragravity) wave dynamics on a fringing coral reef were investigated using the numerical model XBeach (Roelvink et al., 2009). First, the skill of the model was evaluated in one- and two-dimensions based on its predictions of short waves (0.04–0.2 Hz), infragravity waves (0.004–0.04 Hz) and water level measurements (tidal and wave setup) obtained during a 2009 field study at Ningaloo Reef in Western Australia. The model calibration was sensitive to friction coefficients for short waves and current/infragravity bed friction, which were assumed independent in this model study. Although the one-dimensional cross-shore model captured the gradients in the dominant hydrodynamic processes at the site, a high current/IG bed friction coefficient was required. This resulted in an overestimation and a phase lag between the observed and predicted wave setup signal. In the two-dimensional model, a lower (more realistic) current/infragravity wave friction coefficient was required to achieve optimum performance due to the presence of significant reef and lagoon mean flows in the model, which led to reduced setup across the reef. The infragravity waves were found to propagate from the surf zone across the reef in a dominantly cross-shore direction towards the shore, but with substantial frictional damping. The infragravity waves were strongly modulated also over the reef by tidal depth variations, primarily due to the variability in frictional dissipation rates when the total water depth over the reef varied. Two mean wave-driven circulation cells were observed in the study area, with cross-shore flow becoming more alongshore-dominated before exiting the system via the two channels in the reef. The results reveal that short waves dominated bottom stresses on the forereef and near the reef crest; however, inside the lagoon, infragravity waves become increasingly dominant, accounting up to 50% of the combined bottom stresses.

1. Introduction

A large proportion of the world's coastlines, perhaps as high as 80% (Emery and Kuhn, 1982), contain a broad class of submerged reef structures, including tropical coral reefs, relic temperate limestone platforms and rocky coastal features. Abundant as these structures may be, comparatively little work (as compared to sandy beaches) has addressed the range of nearshore hydrodynamic processes in reef environments. A good understanding of these processes is important because waves and wave-induced currents on reefs ultimately drive sediment transport (e.g., Storlazzi et al., 2004), nutrient dynamics and uptake by benthic reef communities (e.g., Falter et al., 2004), as well as the transport and dispersal of larval fish and other organisms (e.g., Wolanski and Sarsenski, 1997) in these environments. Hydrodynamics are thus important for the morphological development of reef environments and their associated ecological zonation (e.g., Atkinson and Falter, 2003; Kench and Brander, 2006). While reefs protect the coast by dissipating wave energy offshore, severe coastal erosion and flooding may still take place during typhoons and hurricanes (e.g., Ogg and Koslow, 1978; Péquignet et al., 2009). Thus, the impact of environmental changes on a reef and the adjacent coastline (e.g. climate-induced sea level rise), extreme events and/or human interventions can only be accurately predicted with sufficient knowledge of nearshore processes.

Of the three main types of tropical coral reefs (barrier, atoll and fringing reefs), fringing reefs form adjacent to a mainland coast, and will therefore have the most direct interaction with it. Darwin (1842) first hypothesized that reef-building corals grow best in regions of a reef experiencing moderate wave energy, i.e., “It appears, […] that the action of the surf is favorable to the vigorous growth of the stronger corals, and that sand or sediment, if agitated by the waves, is injurious to them.” Darwin was also the first to refer to wave-induced mass flux and subsequent circulation: “a return stream

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must carry away the water thrown over the outer edge; and the current thus produced, would tend to prevent the channel being filled up with sediment." However, the detailed mechanisms controlling hydrodynamic variability over reefs were not elucidated at that time.

Munk and Sargent (1948) first quantified a mean wave set up of several decimeters relative to mean sea level over the reef at Bikini Atoll. This set up can be explained using radiation stress theory (Longuet-Higgins and Stewart, 1964) in which the decrease in wave energy flux due to wave breaking is (partially) balanced by a gradient in the mean water set up over the reef. Lee and Black (1978) and Hardy and Young (1996) observed the considerable transformation of incident short waves dominated by swell, in terms of wave heights and the spectral redistribution from higher to lower frequencies as the waves broke over the reef. Other field studies have specifically investigated how the transformation of short waves (e.g., swell) on reefs generates mean wave-driven currents across reef systems, primarily due to wave breaking (e.g., Hench et al., 2008; Jago et al., 2007; Lowe et al., 2009a; Symonds and Black, 2001; Taebi et al., 2011). Symonds et al. (1995) first formulated an analytical model based on a linearized set of momentum equations in order to demonstrate the relative importance of set-up and onshore wave-driven flow across an idealized 1D reef system (subsequent 1D analytical models were also formulated by Hearn (1999) and Gourlay and Colleter (2005)).

Despite physical differences between sandy coast and reef environments, simple 1D (cross-shore) wave transformation models developed for mildly-sloping beaches have been successfully used to investigate short wave transformation over some reefs. Gerritsen (1980) and Lowe et al. (2005) used a 1D wave-energy conservation model with the Battjes and Janssen (1978) breaker model, and both Massel and Gourlay (2000) and Sheremet et al. (2011) extended a mild-slope equation model with a correction for the steeper slopes of reefs.

More complex two-dimensional horizontal (2DH) and three-dimensional (3D) coupled wave-circulation numerical models have also been developed to predict the spatial distribution of mean wave-driven currents and water levels within reef-lagoon systems (Lowe et al., 2009b; Ranasinghe et al., 2006; Symonds and Black, 2001). These models are in essence based on the equation of mass conservation and the equations of 2D or 3D horizontal momentum conservation driven by radiation stress gradients, which are computed from the 2D quasi-steady conservation of short wave energy equation with dissipation terms for wave breaking and bottom friction dissipation.

Collectively, these field and modeling reef studies have shown that the physical processes on reefs do have some similarities to those on sandy coasts (e.g., having submerged bars), albeit with some important differences: the slope of reefs is generally much steeper than the foreslope of sandy shores, the reef bottom topography is much rougher and more inhomogeneous, and there is typically a larger distance between the breakpoint of the waves and the coastline.

Despite the historical focus on the dynamics of short wave energy (periods of 5–25 s) and mean (i.e. averaged over many wave periods) wave-driven flows on reefs, a relatively small number of field studies have identified the importance of lower frequency wave motions (periods of 25 s to tens of minutes), termed infragravity (IG) waves, to the overall water motion over coral reef flats and lagoons (e.g., Brander et al., 2004; Hardy and Young, 1996; Lugo-Fernandez et al., 1998). In particular, two recent field studies (Péquignet et al., 2009 and Pomeroy et al., 2012) have shown that mean currents and short waves accounted for only a small part of the total observed flow and surface elevation variance in the region between the reef crest and the shoreline of two fringing reefs with very different morphologies. Instead, the bulk of the water level variability was found to be contained within the IG frequency band, despite the response of the IG waves being somewhat different between systems. Péquignet et al. (2009) observed a cross-reef standing waves over a fringing reef flat in Guam while Pomeroy et al. (2012) observed dominantly shoreward propagating IG waves across the lagoon over a fringing reef in Western Australia.

Despite the importance of IG wave motions to reefs, process-based numerical models capable of predicting their dynamics have been lacking. Recently Nwogu and Demirbilek (2010) and Sheremet et al. (2011) each applied a 1D phase-resolving wave model to simulate both short wave and IG waves from laboratory flume experiments. They found that the models were capable of predicting the overall wave transformation and spectral redistribution (including IG waves) fairly well. However, these experiments used a scaled fringing reef prototype with smooth walls (no bottom roughness). Consequently, bottom friction in these models was either minimal (Nwogu and Demirbilek, 2010) or neglected entirely (Sheremet et al., 2011), so that IG wave decay was dominated by nonlinear momentum transfers (Henderson et al., 2006; Sheremet et al., 2011). 2DH or 3D numerical modeling studies of IG wave dynamics over real reefs (incorporating their full topographic complexity and importantly their large bottom friction coefficients) have yet to be conducted. Roeber and Cheung (2012) described an application of a 2D Boussinesq-type model to fringing reefs. They showed good model comparison to laboratory data of solitary wave incident on a 1D and 2D reef. The model was applied to a field site in Hawaii, showing for two steady-state conditions, the transformation of irregular incident waves, wave-induced setup and development of sub (infragravity band) and super-harmonics, but without conducting a detailed investigation into the dynamics. The objective of this paper was to investigate and understand the dynamics of IG wave motions across a fringing coral reef. This was done through an application of a recently-developed nearshore circulation model (XBeach) (Roelvink et al., 2009) that includes IG wave generation, propagation and decay, to a case study of Ningaloo Reef, a large fringing reef located on the northwest coast of Western Australia. In particular, attention is given to determining (a) the processes governing IG wave generation and decay over the reef, and (b) the relative importance of IG waves, short waves and currents on the spatial distribution of bed shear stresses, induced by water motion in the lee of the reef crest.

The paper is organized as follows. The field experiment is briefly described in Section 2. The XBeach model and the input parameters adopted for this study are discussed in Section 3. The results of the one- and two-dimensional model calibrations are then presented in Section 4. In Section 5, the validated 2DH model is used to investigate the dynamics of the IG waves under scenarios of different mean water levels, including their generation and dissipation, their propagation and finally the relative importance of IG waves, short waves and currents on bed shear stresses throughout the reef-lagoon system. The factors that affect the performance of the model are discussed in Section 6 along with the dynamics of IG waves that have been elucidated in this study. We finish with conclusions in Section 7.

2. Field study

This study focuses on the hydrodynamics occurring within an ~7 km section of Ningaloo Reef at Sandy Bay (Fig. 1a and b), which is composed of a shallow reef flat (~1–2 m depth) that is separated from the shore by a slightly deeper lagoon (~2–3 m average depth). The reef is broken to the north and south of the study area by channels, through which water exchange between the lagoon and the ocean occurs (Taebi et al., 2011). This present study employs data from a field experiment conducted in June 2009, which provided the offshore wave forcing and data on the forereef, reef flat and lagoon that was required to drive and validate the numerical models. A detailed description of the study site, the field experiment, and