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Numerical simulation of infragravity waves in fringing reefs using a shock-capturing non-hydrostatic model

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ABSTRACT

The shock-capturing non-hydrostatic model NHWAVE is used to study infragravity wave processes in the fringing reefs. The reef effects on the water column are modeled by using a drag force formulation. The model is calibrated and validated against flume observations in two laboratory experiments, which have different reef platforms. In both experiments, the model is shown to be capable of well predicting wave height, wave setup as well as energy density spectrum evolution at the reef flat. The results demonstrate that NHWAVE can be used to model wave processes in the reefs, including wave breaking and nonlinear wave dynamics. The model is finally applied to examine the effects of coral degradation on infragravity wave motions in the Taiping island, which is a fringing reef island in the South China Sea. It is found that the infragravity wave motions at the reef flat on the western island are possibly related to the fundamental mode of resonance. The coral degradation may greatly increase the infragravity wave energy at the reef flat. It would also lead to energy transfer to the lower-frequency waves, generating longer-period waves in the reef flat.

1. Introduction

Coral reefs are widely distributed in the tropical regions of the Pacific, Indian, and Atlantic Oceans, and provide habitat for a wide variety of marine species. The general reef platforms can be divided into three morphological zones: the forereef (or reef slope), which normally has a steep slope; the reef flat, which has a broad, horizontal, shallow and rough bottom extending to the island beach; and the reef edge, which connects the reef slope and the reef flat. As offshore waves propagate onshore to a reef platform, they initially break near the reef edge, and then continuously dissipate energy while passing through the shallow reef flat due to reef-induced friction. Numerous studies have demonstrated that up to 70–95% of wave energy can be dissipated during propagation onto the beach (Hardy and Young, 1996; Lowe et al., 2005; Massel and Gourlay, 2000). In this sense, coral reefs protect coastal areas from wave action. However, coastal damages have occasionally been reported along the low-lying reef coasts during typhoons (Nakaza and Hino, 1991). These damages are postulated to be caused by infragravity wave oscillations (Nwogu and Demirbilek, 2010). Infragravity waves may also affect sediment dynamics in the surf zone (Bowen and Huntley, 1984). Therefore, it is critical to study infragravity wave processes in the reef environment, which requires the development of sophisticated predictive models.

The generation mechanisms of infragravity waves have been extensively studied since the first report of low frequency motions on the sandy beach (Munk and Sargent, 1948). Longuet-Higgins and Stewart (1962, 1964) proposed that bound infragravity waves can be generated by groups of short waves through spatial gradients in radiation stress. Symonds et al. (1982) suggested that the temporal variation of the breaking position introduced by incident wave groups of varying amplitudes would lead to the generation of free long waves propagating both offshore and onshore within the surf zone. Later, nonlinear triad interactions accounting for energy transfer among the spectral peaks towards higher frequencies and lower frequencies were developed (Battjes et al., 2004; Herbers et al., 1994; Herbers and Guza, 1994; Janssen et al., 2003) and applied to explain infragravity waves observed in the field and laboratory experiments.

Although the platforms of sandy beaches and fringing reefs are physically different, the generation of infragravity waves on reefs is similar to that on sandy coasts. Both field and laboratory measurements have shown that the infragravity wave frequencies (typically 0.005–0.05 Hz) dominate the energy spectrum at the fringing reef flats (Brander et al., 2004; Hardy and Young, 1996; Young, 1989). These low-frequency motions are closely related to

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the fundamental mode of resonance at the flat (Lugo-Fernández et al., 1998; Nakaza and Hino, 1991; Péquignet et al., 2009). To understand these processes, various numerical models have been developed recently. For instance, Sheremet et al. (2011) applied both phase-resolving and phase-averaged wave models based on the extended nonlinear mild-slope equation to simulate swell, sea and infragravity waves in a laboratory fringing reef. After comparing with the measurements of Demirbilek et al. (2007), it was shown that the performance of the phase-resolving model was better than that of the phase-averaged model. Nwogu and Demirbilek (2010) developed a nonlinear Boussinesq equation model to investigate infragravity wave motions over the fringing reefs. Model results were verified against the laboratory data of Demirbilek et al. (2007) and showed a good agreement in wave height distributions as well as infragravity oscillations at the reef flat. Roeber and Cheung (2012) utilized a shock-capturing Boussinesq-type model to fringing reefs in both laboratory experiments and field environment in Hawaii. Their model well reproduced the development of infragravity waves. Although successful applications of Boussinesq equation models on reef environments have been reported, one major concern with these types of models is the relatively steep reef slope, which may violate the underlying bottom-slope assumption of weakly dispersive models (Nwogu and Demirbilek, 2010). Pomeroy et al. (2012) used the numerical model XBeach based on the wave action equation to predict infragravity waves in a field-scale fringing reef. The model results revealed that infragravity waves at the reef flat are dominantly shoreward propagating. The seaward propagating infragravity waves reflected from the shoreline were small due to the significant energy dissipation over the wide and hydraulically rough flat. This was further confirmed by Van Dongeren et al. (2013).

Except the above-mentioned models, the non-hydrostatic models introduced recently have shown great potential for resolving wave dynamics in the surf zone, including wave breaking (Zijlema and Stelling, 2008; Ma et al., 2012; Smit et al., 2013), nonlinear wave dynamics (Smit et al., 2014) as well as infragravity wave motions in sandy beaches (Rijnsdorp et al., 2014). Compared to the Boussinesq equation models, non-hydrostatic models are capable of simulating highly dispersive fully nonlinear wave processes, thus can be applied to steep slope environments. In addition, the shock-capturing numerical scheme recently introduced into the non-hydrostatic model (Ma et al., 2012) is capable of capturing wave breaking without relying on empirical formulations. In this study, we will show the capabilities of NHWAVE (Ma et al., 2012) in simulating infragravity waves in the fringing reefs. The reef effects on the water column are modeled by a drag force formulation. The model will be validated by laboratory measurements of wave heights as well as wave spectra in the reefs.

The remainder of the paper is organized as follows. In Section 2, the governing equations of NHWAVE are presented. The shock-capturing numerical schemes and boundary conditions are given in Section 3. In Section 4, the model is validated by the measurements in two laboratory experiments. In Section 5, the model is applied to study infragravity wave processes in Taiping Island, which is a fringing reef island in the South China Sea. Finally, the paper is concluded in Section 6.

2. Governing equations

NHWAVE (Ma et al., 2012) is a three-dimensional non-hydrostatic wave model that is capable of predicting instantaneous free surface and 3D flow structures. The model has been used to study tsunami wave generation by submarine landslides (Ma et al., 2013a) and wave damping by vegetation canopies (Ma et al., 2013b). It is based on the assumption that the free surface is a single value function of horizontal coordinates. Thus, the computational domain is bounded by the free surface $z=\eta(x,y)$ and the bottom $z=-h(x,y)$. The governing equations of NHWAVE are the incompressible Navier–Stokes equations in well-balanced conservative form, formulated in time-dependent surface and terrain-following σ coordinate, which is defined as

$$t=t^*, \quad x=x^*, \quad y=y^*, \quad \sigma=\frac{z^*+h}{D} \tag{1}$$

where the total water depth $D(x,y,t)=h(x,y)+\eta(x,y,t)$.

With σ coordinate transformation, the well-balanced mass and momentum equations are given by

$$\frac{\partial D}{\partial t}+\frac{\partial Du}{\partial x}+\frac{\partial Dv}{\partial y}+\frac{\partial \omega}{\partial \sigma}=0 \tag{2}$$

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}+\frac{\partial \mathbf{H}}{\partial \sigma}=\mathbf{S}_h+\mathbf{S}_p+\mathbf{S}_\tau+\mathbf{S}_c \tag{3}$$

where $\mathbf{U}=(Du,Dv,Dw)^T$. The fluxes are

$$\mathbf{F}=\begin{pmatrix} Duu+\frac{1}{2}g\eta^2+gh\eta \\ Duv \\ Duw \end{pmatrix}, \quad \mathbf{G}=\begin{pmatrix} Duv \\ Dvv+\frac{1}{2}g\eta^2+gh\eta \\ Dvw \end{pmatrix}, \quad \mathbf{H}=\begin{pmatrix} u\omega \\ v\omega \\ w\omega \end{pmatrix}$$

The first three source terms on the right-hand side of Eq. (3) account for the contributions from hydrostatic pressure, non-hydrostatic pressure and turbulent diffusion, given by

$$\mathbf{S}_h=\begin{pmatrix} g\eta\frac{\partial h}{\partial x} \\ g\eta\frac{\partial h}{\partial y} \\ 0 \end{pmatrix}, \quad \mathbf{S}_p=\begin{pmatrix} -\frac{D}{\rho}\left(\frac{\partial p}{\partial x}+\frac{\partial p}{\partial \sigma}\frac{\partial \sigma}{\partial x^*}\right) \\ -\frac{D}{\rho}\left(\frac{\partial p}{\partial y}+\frac{\partial p}{\partial \sigma}\frac{\partial \sigma}{\partial y^*}\right) \\ -\frac{1}{\rho}\frac{\partial p}{\partial \sigma} \end{pmatrix}, \quad \mathbf{S}_\tau=\begin{pmatrix} DS_{\tau_x} \\ DS_{\tau_y} \\ DS_{\tau_z} \end{pmatrix}$$

where $DS_{\tau_x}, DS_{\tau_y}, DS_{\tau_z}$ are diffusion terms. In this paper, we focus on wave propagation in the absence of strongly sheared currents, in which the effects of turbulence on the wave motion are marginal and can be neglected (Rijnsdorp et al., 2014). Therefore, the diffusion terms are omitted in the following simulations. The fourth term $\mathbf{S}_c$ accounts for the effects of coral reef on the water column. In a hydrodynamic sense, a coral reef is a complex array of obstacles that exerts a drag force on water moving over the reef (Rosman and Hench, 2011). The traditional approach to parameterize this drag is to increase the bottom friction coefficient (Lowe et al., 2009; Nwogu and Demirbilek, 2010), which is typically one order of magnitude larger than that over the bed without reefs. Following this approach, we model the drag force exerted by the coral reef on the water column as

$$\mathbf{S}_c=DF_c=\frac{1}{2}C_f|\mathbf{u}|\mathbf{u} \tag{4}$$

in which F_c is the drag force, C_f is the drag coefficient and $\mathbf{u}=(u,v,w)$ is the velocity vector. The drag coefficient will be calibrated using the laboratory measurements in the following sections.

In the above formulations, ω is the vertical velocity in the σ coordinate image domain, given by

$$\omega=D\left(\frac{\partial \sigma}{\partial t^*}+u\frac{\partial \sigma}{\partial x^*}+v\frac{\partial \sigma}{\partial y^*}+w\frac{\partial \sigma}{\partial z^*}\right) \tag{5}$$

with

$$\begin{aligned} \frac{\partial \sigma}{\partial t^*}&=-\frac{\sigma}{D}\frac{\partial D}{\partial t} \\ \frac{\partial \sigma}{\partial x^*}&=\frac{1}{D}\frac{\partial h}{\partial x}-\frac{\sigma}{D}\frac{\partial D}{\partial x} \\ \frac{\partial \sigma}{\partial y^*}&=\frac{1}{D}\frac{\partial h}{\partial y}-\frac{\sigma}{D}\frac{\partial D}{\partial y} \\ \frac{\partial \sigma}{\partial z^*}&=\frac{1}{D} \end{aligned} \tag{6}$$