The importance of low frequency waves in fringing reef environments

Andrew WM Pomeroy[123], Ryan J Lowe[3], Ap R van Dongeren[2], Jaap SM van Thiel de Vries[12], Graham Symonds[4], Jan A Roelvink[125]

[1]Delft University of Technology, Delft, The Netherlands
[2]Deltares, Delft, The Netherlands
[3]The University of Western Australia, Crawley, Western Australia, Australia
[4]Centre for Australian Weather and Climate Research, Floreat, Western Australia, Australia
[5]UNESCO I IHE, Delft, The Netherlands
Corresponding author: Andrew.Pomeroy@uwa.edu.au

Abstract. It is well recognized that hydrodynamic processes on coral reefs are complex, yet crucial drivers of a broad range of physical and biological processes. Short period swell wave transformation, wave setup and wave-driven flows over reefs have been the primary focus of most reef hydrodynamic studies to date. While low frequency (infragravity) waves have been identified on reefs for some time, their detailed dynamics have received relatively limited attention. Such infragravity waves have been shown to have an important contribution to the total sediment transport and morphological development of sandy coasts. However, their analogous importance to reefs (including top reef ecology) remains unknown. To investigate the importance of infragravity waves across a fringing reef-lagoon system, a three-week field experiment was undertaken at Ningaloo Reef in Western Australia. A synchronized cross-shore instrument array acquired pressure and velocity data, which was analyzed to assess the importance of the infragravity waves relative to other sources of water motion (i.e., swell waves and mean currents). The mechanisms responsible for the generation, propagation, and dissipation of these infragravity waves throughout the reef-lagoon system were quantified. In this paper the results of this study will be discussed along with the likely importance of infragravity waves on reefs to various processes that are known to rely on water motion (i.e., sediment transport pathways and nutrient dynamics).

Key words: coral reefs, infragravity waves, wave transformation, wave dissipation, bottom friction, Ningaloo Reef

Introduction

The influence of hydrodynamic processes on a wide range of ecological processes in coral reefs is well recognized. Whilst observations and measurements have quantified the hydrodynamic variability across reefs, many of the physical processes involved are still poorly understood. This is due to the much more complex and varied morphology of reefs (eg. due to their topographic complexity, steep slopes and large bottom roughness) when compared to the more intensively studied sandy beach environments. These complexities lead to a vastly different wave, current and water level response, despite similar offshore hydrodynamic forcing.

Previous studies have primarily focused on (1) swell wave energy transformation across reefs (eg. Hardy and Young, 1996; Massel and Gourlay, 2000) and (2) mean wave-driven circulation patterns and wave setup within reef-lagoon systems (eg. Hench et al., 2008; Lowe et al., 2009; Taebi et al., 2011). The detailed dynamics of low frequency waves, often referred to as infragravity (IG) waves, on reefs have only very recently been investigated. This is despite the recognition of the presence of IG waves on reefs for a decade or more (e.g., Hardy and Young, 1996; Lugo-Fernandez et al., 1998; Brander et al., 2004).

Péquignet et al. (2009) examined IG wave motions on a fringing reef in Guam and observed a significant resonant standing wave pattern during a tropical storm. The dynamics of IG waves have also been investigated in laboratory wave flumes using fringing reef prototypes (Nakaza and Hino, 1991; Demirbilek et al., 2007) and through numerical simulations of these same laboratory reef results (Nwogu and Demirbilek, 2010; Sheremet et al., 2011). These studies have suggested that IG waves can make an important (or even dominant) contribution to the overall water motion within coastal reef-lagoon systems.

IG waves are known to be generated by nonlinear interactions between groups of incident swell waves as ‘coupled’ bound long waves (Longuet-Higgins and

Stewart, 1964) that are released during breaking in the surf zone (e.g. Janssen et al., 2003), and/or variability in radiation stress gradients at the wave group forcing frequencies (Symonds et al., 1982). Whilst IG waves on coral reefs are likely to be generated by similar mechanisms, specifically how they propagate (seaward and shoreward), lose energy (via bottom friction and possibly nonlinear losses or breaking) and are reflected, remain largely unknown.

This paper presents a preliminary analysis of the results from a field study conducted at Ningaloo Reef (Western Australia) that specifically investigated IG wave dynamics.

Methodology

A field experiment was conducted at Sandy Bay (22 ° 13 ′ S, 113 ° 49 ′ E in Fig. 1) on an ~3 km section of Ningaloo Reef in Western Australia. At this site, the forereef slope rises at ~1:20 to the reef crest, which is located 1.4 km from the coastline. An ~500 m wide shallow reef flat, of between 1 m and 2 m deep, is covered by dense assemblages of corals (Wyatt et al., 2010). The 2-3 m deep lagoon separates the reef from the shore and is ~850 m wide. The lagoon primarily consists of sand and coral rubble. Channels (gaps) in the reef are located to the north and south of the study area.

Field study

During the austral winter of 2009 (9 June-1 July), a three-week field experiment was conducted with a synchronous array of ten moored instruments. Five were deployed at sites along the reef flat parallel to the coastline (sites A1-E1) and five were deployed along a cross-shore transect from offshore of the reef to near the shoreline (sites C1-C6) (Fig. 1). The instruments consisted of current meters/profilers recording 3D velocities, pressure and sea surface elevation. A full summary of the field experiment is presented in Pomeroy et al. (in prep.).

Data Analysis

One-dimensional wave and velocity spectra were estimated for each hourly burst of data. A Welch's averaged modified periodogram, with 50% overlap and Hanning windows applied, was used to reduce spectral leakage.

The surface elevation and velocity signals were separated into 'swell' (frequency 0.05-0.2 Hz or period 5-20 s) and 'infragravity' (frequency 0.005-0.05 Hz or period 20-200 s) components. Bandpass-filtering the raw data in frequency space using the IG band limits derived the IG surface elevation and velocity time series.

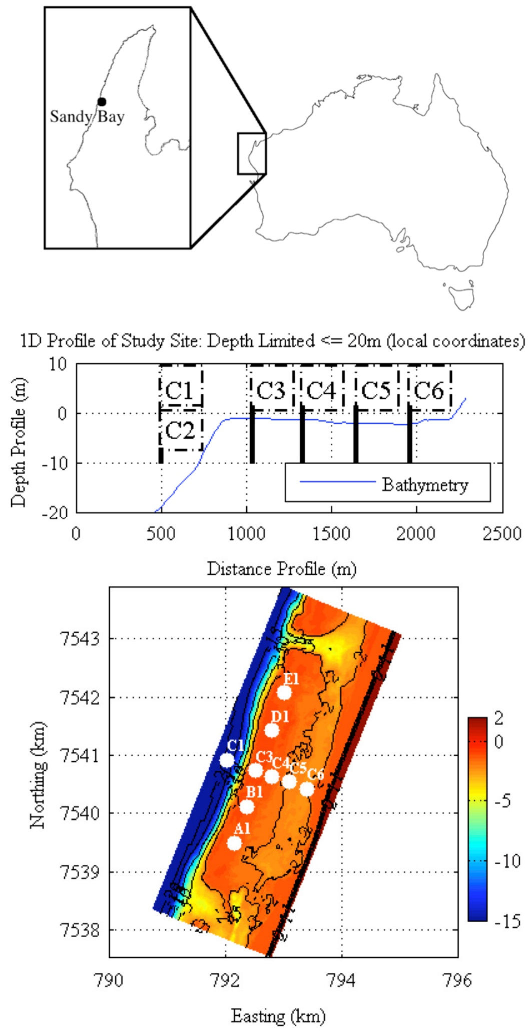

Figure 1: (a) Location of the site Sandy Bay (b) Cross-shore transect bathymetry and instrument location (c) Site topography and instrument arrangement. The bathymetric depth relative to the Australian Height Datum (AHD) is indicated by the colorbar.

The shoreward and seaward signals were then determined using the approach by Guza et al., (1984):

$$\eta_{IG}^{\pm} = \frac{\eta_{IG}\sqrt{gh} \pm Uh}{2\sqrt{gh}} \qquad (1)$$

where $\eta_{IG}^{\pm}$ denotes the shoreward (positive) and seaward (negative) IG surface elevation, U is the cross-shore flow velocity and h is the water depth.

The cross-shore energy densities *(E)* of the shoreward and seaward propagating waves (superscripts ± respectively) at frequency f and location x were estimated by analyzing the co-located velocity and surface elevation data in frequency space following Sheremet et al. (2002):

$$E^{\pm}(f,x) = \frac{1}{4}\left[S_{\eta\eta}(f,x) + \frac{h}{g}S_{uu}(f,x) \pm 2\sqrt{\frac{h}{g}}Co_{\eta u}(f,x)\right] \qquad (2)$$

where Eq. (2) has been normalized by the density ρ and the gravitational acceleration g. The cross-shore energy fluxes of the shoreward $\left(F^{+}\right)$ and seaward $\left(F^{-}\right)$ propagating waves, were then calculated as

$$F^{\pm}(f,x) = E^{\pm}(f,x)\sqrt{gh}\,. \qquad (3)$$

The energy fluxes were integrated over the IG and swell frequency bands to obtain the bulk swell $\left(F_{sw}^{\pm}\right)$ and IG wave $\left(F_{IG}^{\pm}\right)$ energy fluxes.

Rates of bottom friction induced energy dissipation within the IG wave band were specifically investigated on the reef flat shoreward of the surf zone (i.e. between sites C3 and C4) after wave breaking occurs. The rate of dissipation was parameterized with an empirical bottom friction coefficient (f_c) according to (e.g., Henderson and Bowen, 2002 in the formulation used by Van Dongeren et al., 2007):

$$D_{IG} = f_c\left(\frac{g}{h^3}\right)^{1/2}\frac{H_{rms}}{\sqrt{8}}\frac{H_{rms,IG}^2}{8} \qquad (4)$$

where H_{rms} is the total root-mean-squared wave height and $H_{rms,IG}$ is the root-mean-squared wave height for the infragravity band.

Results

The preliminary results presented in this paper focus on the cross-shore transect data obtained from instruments C1 – C6.

Low frequency wave generation and propagation

On the forereef (C1) the IG wave height $H_{rms,IG}$ did not demonstrate a significant dependency with changes in the tidal depth h measured on the reef at C3, i.e., when normalized by the forereef swell height $H_{rms,sw}$ this ratio was a roughly constant 8% (not shown). However, on the reef and in the lagoon, there were significant tidal modulations to this ratio ($H_{rms,IG}$ / $H_{rms,sw}$) (Fig. 2a), reaching values as high at 15 % near the reef crest when the tide was high (~2 m at C3). The amplitude of the swell waves did not significantly affect the ratio (Fig. 2b). However, the results indicate that for low tide water depths (i.e. smaller than 1.2 m as measured at C3) the height of the IG waves within the reef and lagoon were effectively zero. The physical process that results in the modulation of the height of the IG waves is investigated in greater detail by van Dongeren et al (in prep).

Decomposition of the swell and IG energy fluxes into shoreward and seaward contributions for sites

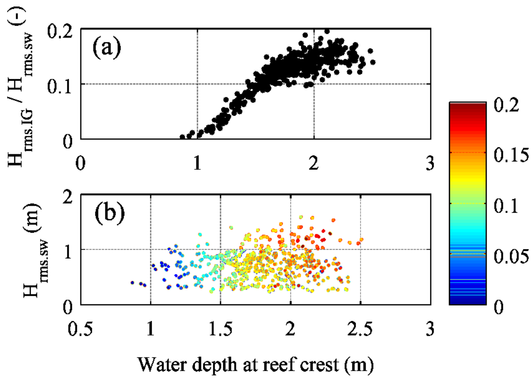

Figure 2: (a) Ratio of the IG and offshore root mean squared swell wave height against the water depth at instrument C3 (b) Offshore root mean square swell wave height against water depth a C3. The ratio of the IG and the offshore root mean squared significant wave heights is indicated by the colorbar.

where synchronous velocity and pressure measurements were made (i.e., C1, C3, C4, C5) elucidates the generation and propagation of IG waves in a reef environment. A correlation analysis of the separated IG wave signals at this site suggests that the IG waves were predominantly 'break point' generated (not shown).

On the forereef (C1), the cross-shore fluxes were dominated by the shoreward component of the swell waves. The shoreward and seaward components of the IG fluxes at C1 were comparable, albeit the shoreward fluxes were slightly higher but of considerably less magnitude than the swell wave fluxes (Fig. 3a,b).

At the reef crest (C3), a large reduction (relative to C1) in the shoreward and seaward swell fluxes of more than two orders of magnitude was observed (Fig. 3c). Conversely, at C3 the shoreward IG fluxes generally increased from C1, with the shoreward fluxes being much greater than the seaward fluxes (Fig. 3d). A net increase in shoreward IG flux results from a reduction in the observed seaward IG flux at this location. A tidal modulation of the local swell and IG fluxes was also observed.

On the back of the reef flat (C4), both the swell and IG fluxes in the shoreward and seaward direction were reduced (Fig. 3e,f) relative to C3. The IG flux was greater than the swell flux at this location and the shoreward flux continued to dominate over the seaward flux in both frequency bands. The cause of the reduction in the shoreward IG flux is investigated next.

Low frequency wave dissipation

The rates of IG wave dissipation D_{IG} over the reef flat due to bottom friction were investigated using Eq. (4). The bottom friction coefficient f_c associated with the

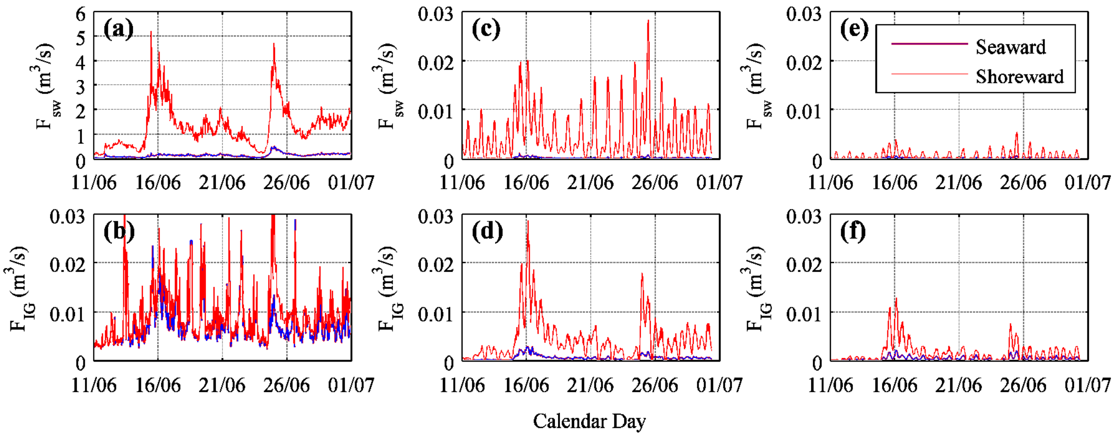

Figure 3: Shoreward energy flux for sea-swell frequency is indicated in the top panels and the IG frequency in the bottom panels. (a,b) are associated with instrument C1, (c,d) with instrument C3 and (e,f) with instrument C4. The seaward flux is near zero in plots (c) and (e).

IG wave decay was modulated by the variability in the tidal level over the reef (Fig. 4), with f_c increasing weakly as the depth (mean of C3 and C4) increased from 1 m to 2 m, albeit with significant scatter for depths < 1 m. The bottom friction coefficient f_c calculated in this study was approximately an order of magnitude greater than the equivalent values typically measured on sandy coasts. The influence of nonlinear energy transfers on the dissipation of IG wave energy was small (not shown) and was removed prior to conducting this analysis.

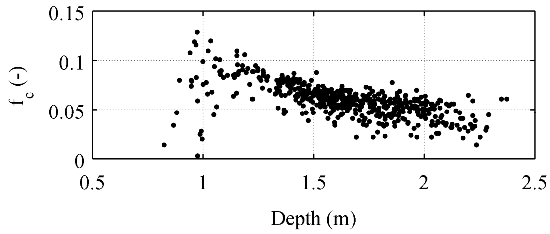

Figure 4: Estimated bed friction coefficient for each burst of data plotted against the mean water depth between C3 and C4 of the particular burst.

Discussion

The results of this study emphasize that IG waves are generated in coral reef environments and, depending on the depth of the water on the reef flat, could be as great as 15 % of the offshore wave height. Furthermore, IG waves were shown in this study to dominate the energy flux observed on the back of the reef and in the lagoon. The high friction coefficient calculated in this study is consistent with the higher roughness observed on the reef and lagoon bed due to the presence of coral.

Recently, the spatial importance of IG waves versus other processes was investigated using a calibrated XBeach (Roelvink et al., 2009) numerical model and by computing the percentage of the total bed stress explained by three key processes, mean flow, swell waves and IG waves. Evaluation of the spatial shear stress contributions by each of these three processes at the Ningaloo Reef site indicated that mean currents account for less that 20 % of the shear stresses on the reef and throughout most of the lagoon (Fig. 5a). However, in the southern side of the lagoon channel, near its connection with the cross-shore break in the reef, the contribution rose to ~40 %. This result is consistent with many studies that have demonstrated the importance of the lagoon the lateral flow and circulation.

Swell waves account for almost 100 % of the shear stress observed on the forereef and reef crest (Fig. 5b), a result also consistent with many previous studies. However, the influence of the swell waves dramatically decreases across the reef flat and within the lagoon (accounting for 40-60 % of the shear stresses) while penetration of the swell waves into the lagoon via the deep breaks in the reef enables these waves to account for >80 % of the shear stresses at these locations. Importantly, the contribution of IG waves to the balance of shear stresses is very significant (and even dominant) within parts of the lagoon near the shore, accounting for 40-60 % of the shear stress in this region.

The significant role played by IG waves in reef environments has important implications for the modeling of a number of processes that occur in reef systems such as sediment transport and nutrient uptake distributions. Further work is ongoing to investigate the influence of each of these key processes on the distribution of sediment and other particulates. It is anticipated that IG wave hydrodynamics play a significant role in these processes and therefore should be included in future hydrodynamic, morphological and biological modeling studies of reef systems.

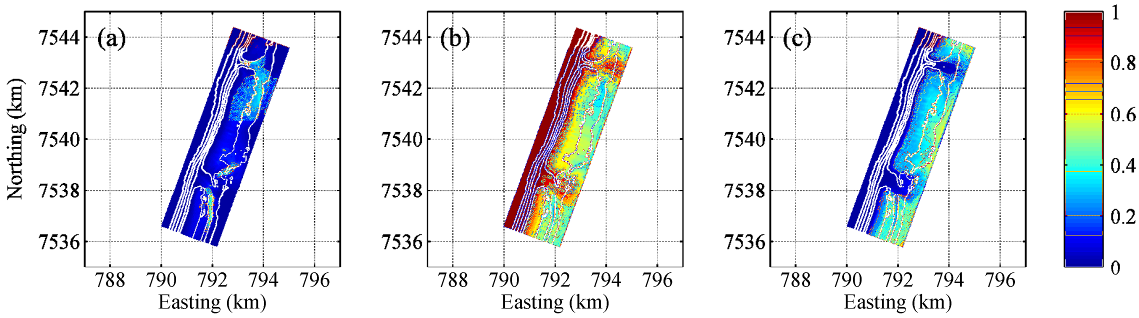

Figure 5: Proportion of (a) mean shear stress (b) swell wave shear stress (c) IG shear stress to total shear stress averaged over the duration of the 2D model of the peak storm event. The proportion is indicated by the colorbar.

Acknowledgements

Funding for this project was provided by an Australian Research Council Discovery Grant (DP0770094) to RJL and a CSIRO Flagship Collaboration Fund award to RJL, GS, JAR and AVD. AVD and JAR are supported by Deltares Strategic Funding 1202362. AWP acknowledges funding provided by the European Commission Erasmus Mundus Program. We thank Jim Falter and Nick Mortimer for assistance with the instrument deployment and recovery.

References

Brander RW, Kench PS, Hart D (2004), Spatial and temporal variations in wave characteristics across a reef platform, Warraber Island, Torres Strait, Australia, Marine Geology, 207(1-4), 169-184.

Demirbilek Z, Nwogu OG, Ward DL (2007), *Laboratory study of wind effect on runup over fringing reef, Report 1: Data Report*, ERDC/CHL TR-07-4, Coastal and Hydraulics Laboratory.

Guza RT, Thornton EB, Holman RA (1984), Swash on steep and shallow beaches, *Proceedings of the 19th International Conference on Coastal Engineering*, Houston, 708-723.

Hardy TA, Young IR (1996), Field study of wave attenuation on an offshore coral reef, *J. Geophys. Res.*, 101(C6), 14,311–14,326, doi:10.1029/96JC00202.

Hench JL, Leichter JJ, Monismith SG, 2008. Episodic circulation and exchange in a wave-driven coral reef and lagoon system. Limnology & Oceanography, 53 (6): 2681-2694.

Henderson SM, Bowen AJ (2002), Observations of surf beat forcing and dissipation, *J. Geophys. Res.*, 107(C11), 3193, doi:10.1029/2000JC000498.

Longuet-Higgins MS, Stewart RW (1964), Radiation Stresses in Water Waves - a Physical Discussion, with Applications, *Deep-Sea Research*, 11(4), 529-562.

Lowe RJ, Falter JL, Monismith SG, Atkinson MJ (2009), Wave-Driven Circulation of a Coastal Reef–Lagoon System. *J. Phys. Oceanogr.*, 39, 873–893. doi: 10.1175/2008JPO3958.1

Lugo-Fernandez A, Roberts HH, Wiseman Jr WJ, Carter BL (1998), Water level and currents of tidal and infragravity periods at Tague Reef, St. Croix (USVI), *Coral Reefs*, 17, 343-349.

Massel SR, Gourlay MR (2000), On the modelling of wave breaking and set-up on coral reefs, *Coastal Engineering*, 39(1), 1-27.

Nakaza E, Hino M (1991), Bore-like surf beat in a reef zone caused by wave groups of incident short period waves, *Fluid Dynamics Research*, 7(2), 89-100, ISSN 0169-5983, 10.1016/0169-5983(91)90062-N.

Nwogu O, Demirbilek Z (2010), Infragravity wave motions and runup over shallow fringing reefs, *J Waterw Port*, 136:295-305.

Péquignet ACN, Becker JM, Merrifield MA, Aucan J (2009), Forcing of resonant modes on a fringing reef during tropical storm Man-Yi, *Geophys. Res. Lett.*, 36, L03607, doi:10.1029/2008GL036259.

Pomeroy AWM, Lowe RJ, Symonds G, Moore, C Van Dongeren AR, (in prep.), Field observations of infragravity wave transformation over a fringing reef.

Roelvink JA, Reniers A, Van Dongeren A, Van Thiel de Vries J, McCall R, Lescinski J (2009). Modeling storm impacts on beaches, dunes and barrier islands. Coastal Engineering, doi: DOI: 10.1016/j.coastaleng.2009.08.006

Sheremet A, Guza RT, Elgar S, Herbers THC (2002), Observations of nearshore infragravity waves: Seaward and shoreward propagating components, *J. Geophys. Res.*, 107(C8), 3095, doi:10.1029/2001JC000970.

Sheremet A, Kaihatu JM, Su SF, Smith ER, Smith JM (2011), Modeling of nonlinear wave propagation over fringing reefs, *Coastal Engineering*, 58(12), 1125-1137, ISSN 0378-3839, 10.1016/j.coastaleng.2011.06.007.

Symonds G, Huntley DA, Bowen AJ (1982), Two-Dimensional Surf Beat: Long Wave Generation by a Time-Varying Breakpoint, *J. Geophys. Res.*, 87(C1), 492–498, doi:10.1029/JC087iC01p00492.

Taebi S, Lowe RJ, Pattiaratchi CB, Ivey GN, Symonds G, Brinkman R (2011), Nearshore circulation in a tropical fringing reef system, *J. Geophys. Res.*, 116, C02016, doi:10.1029/2010JC006439.

Van Dongeren A, Battjes J, Janssen T, van Noorloos J, Steenhauer K, Steenbergen G, Reniers A (2007), Shoaling and shoreline dissipation of low-frequency waves, *J. Geophys. Res.*, 112, C02011, doi:10.1029/2006JC003701.

Van Dongeren A, Lowe RJ, Pomeroy AWM, Trang DM, Roelvink JA, Ranasinghe R, Symonds G (in prep), A numerical study of low-frequency waves dynamics on a fringing reef.

Wyatt ASJ, Lowe RJ, Humphries S, Waite AM (2010), Particulate nutrient fluxes over a fringing coral reef: relevant scales of phytoplankton production and mechanisms of supply, *Marine Ecology-Progress Series*, 405, 113-130