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Spatial variations in wave transformation and sediment entrainment on a coral reef sand apron

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ABSTRACT

Waves are the main hydrodynamic force acting on coral reefs and are crucial in driving the evolution of reef systems. Previous research has mainly focused on wave breaking and transformation on the reef flat but often neglected the spatial variation of reformed wave characteristics once they have propagated into the back-reef environment. This study examines wave conditions on a reef flat and the adjacent back-reef sand apron specifically focusing on the transformation of wave height, period and spectra (including changes to long-period and incident wave height). The ability of reformed waves in the back-reef environment to entrain sediment is also investigated. Wave conditions were found to be distinctly different on the sand apron compared to the reef flat, with the majority of wave energy dissipated during initial breaking and transformation. Almost all incident waves are dissipated on the reef flat under a depth threshold of 0.5 m before reaching the back-reef with long-period motions dominating in the back-reef during these tidal stages. At higher tidal stages incident waves are capable of propagating into the back reef but they are very low energy with under 1% of all waves capable of entraining sediment. This suggests that higher energy events, such as high frequency storms, are required to significantly transport sediment and change reef geomorphology. Smaller scale spatial changes in wave height were observed on the sand apron that shows the influence of both cross- and along-reef attenuation processes. A distance parameter (X_{pd}) is introduced that combines the cross-reef distance from the reef crest (X_d) and the temporally specific along-reef distance from the first point of wave breaking on the reef rim (X_p, where $X_{pd} = X_d + X_p$). X_{pd} is shown to accurately describe the changes in wave height and sediment entrainment if deep water significant wave height, wave direction, and depth over the reef flat are known. The results in this study shows that wave conditions, sediment entrainment, and longer term trends in sediment characteristics can be predicted in back-reef environments from a few simple geomorphic inputs.

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1. Introduction

Coral reefs are complex and valuable coastal systems that have evolved to their present state due to the mutual interaction of biological, geological, and oceanographic processes (Kench and Brander, 2006; Montaggioni and Braithwaite, 2009). These processes create reefs that have a number of ubiquitous features that include; a fore-reef slope, reef flats, and back-reef sediment deposits (such as sand aprons and reef islands) (Fig. 1D). The majority of sediment production occurs on the fore-reef slope and reef flat (through the growth of coral and other benthic organisms), which is then broken down and transported to the back-reef environment mostly through wave breaking and transformation on the reef flats (e.g. Hopley, 1982; Macintyre et al., 1987). This results in hydrodynamic and sediment transport gradients, driven primarily by reef flat wave processes, which are responsible for the formation of back-reef sedimentary formations such as reef islands or sand aprons. As such, understanding the morphodynamics and interaction between reef flats and back reef systems is crucial in determining the response of coral reef sedimentary features to changing boundary conditions such as sea level rise and sediment production, which in turn has significant implications for the coastal evolution and protection of tropical coastlines and reef islands.

The morphodynamic evolution of these systems is dependent on intra-reef or autochthonous sediment dynamics, where the destructive force of waves and other biological and chemical processes is offset by the constructive effects of reef growth and sediment production (Stoddart et al., 1978; Cowell and Thom, 1994; Kench and Brander, 2006; Woodroffe, 2008). In order to better understand the processes driving geomorphic change many studies have focused on the transformation of swell waves as they break and propagate across reef flats (e.g. Young, 1989; Hardy et al., 1991; Gourlay, 1994; Nelson, 1994; Brander et al., 2004; Kench and Brander, 2006; Harris and Vila-Concejo, 2013). These studies have found that 60–99% of the wave energy is dissipated on the reef rim and that water depth over reef flat (d), distance from the

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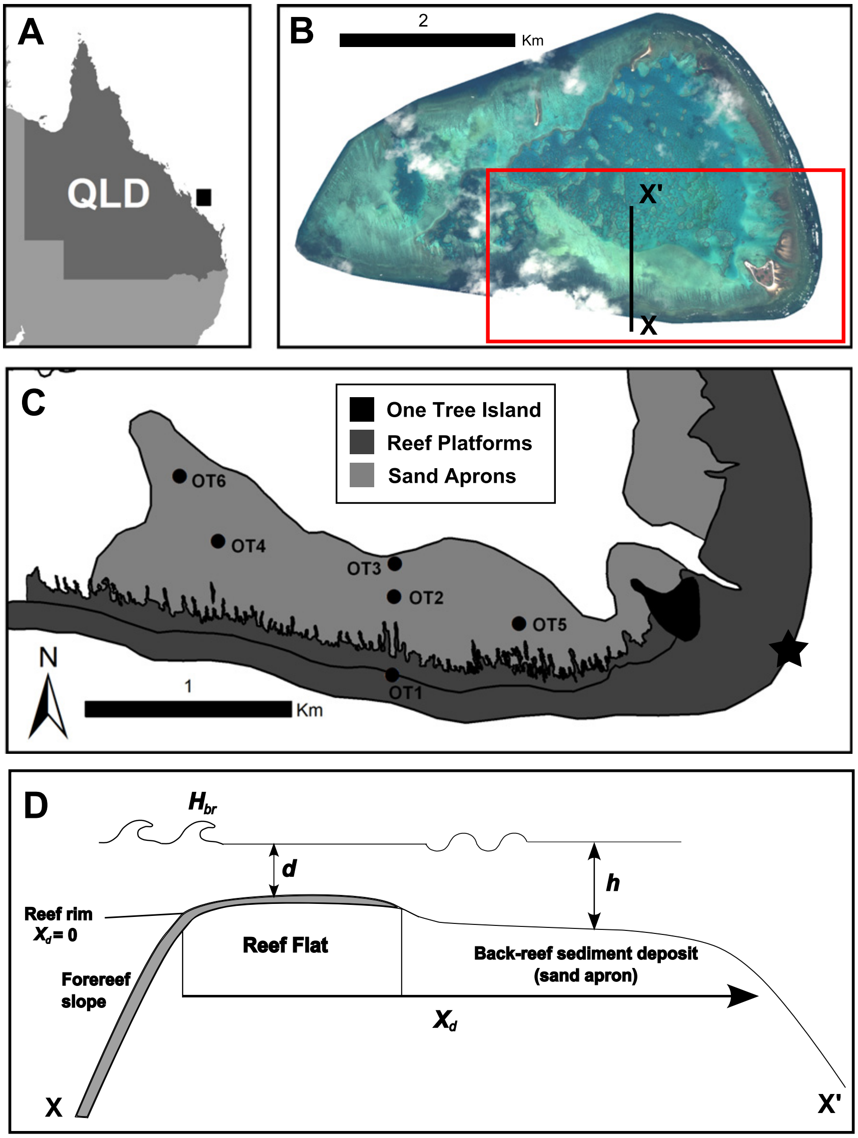

Fig. 1. (A) The location of the Capricorn Bunker group and OTR shown by the black square off the Queensland (QLD) coast of Australia; (B) satellite image (Worldview-2 2009) of OTR with the extent of panel (C) in red with the location of the example transect of the windward rim the black line; (C) schematic of OTR with the reef platform shown in dark grey, the sand aprons in light grey, and One Tree Island in black. The locations of the PT deployments are shown by the black circles and the location of $X_p = 0$ shown by the black star; and, (D) an example cross-section of the windward reef margin: the following parameters are shown in this profile: breaker wave height (H_{br}), width of the reef platform (W), cross-shore distance from reef rim (X_d), depth over the reef platform (d), and water depth (h).

reef rim (X_d), and wave height of the incident swell waves (H_{br}) regulates the energy that propagates into the back-reef environment. Depth over the reef flat has been shown to be the most important control in almost all studies on wave transformation (e.g. Gerritson, 1980; Hardy et al., 1991; Gourlay, 1994; Nelson, 1994; Hardy and Young, 1996; Kench and Brander, 2006). Comparatively, X_d has generally been shown to be of secondary importance and contributes to wave energy attenuation through bottom friction, with large X_d resulting in greater attenuation (Gerritson, 1980; Young, 1989; Kench and Brander, 2006). Most studies that have specifically examined wave transformation on coral reef flats have done so on a two-dimensional cross section of a windward reef flat (hence referred to as cross-reef, e.g., Fig. 1D), with the exception of a few studies (e.g. Young, 1989; Hardy and Young, 1996; Mandlier and Kench, 2012) which outlined the significant effects of three dimensional wave change due to refraction and diffraction processes. The wave refraction effects on coral reefs have also been shown in research examining reef wide wave exposure gradients (e.g. Hamylton, 2011) which were used to determine relative differences in breaker wave height on the reef flats and have proved effective in explaining changes in reef geomorphology in some settings. However, there is only sparse research examining the along-reef (parallel to the reef crest) spatial variation in wave transformation and sediment transport in the back-reef environment. This presents a significant gap in the current understanding of wave processes on reefs, since the majority of unconsolidated sediment and reef islands are found in such environments. In addition to an overall decrease in energy, the wave spectrum also changes during transformation over the reef flat (Young, 1989; Brander et al., 2004; Hardy and Young, 1996; Kench and Brander, 2006; Harris and Vila-Concejo, 2013). Incident or gravity waves (frequency (f) = 0.05–0.33 H_z) are primarily dominant in surf-zone wave spectra, with long period or infragravity waves ($f > 0.05\ H_z$) of secondary importance to incident wave processes (Aagaard and Masselink, 1999). In sandy beach studies long-period motions have been shown to increase in relative and absolute influence in the wave spectrum in the shoreward direction and also in shallow water (Aagaard and Masselink, 1999). As such, the swash motions on beach faces are usually dominated by long-period motion with most of the energy in the incident wave spectrum expended during breaking

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