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Impact of sea-level rise and coral mortality on the wave dynamics and wave forces on barrier reefs

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ABSTRACT

A one-dimensional wave model was used to investigate the reef top wave dynamics across a large suite of idealized reef-lagoon profiles, representing barrier coral reef systems under different sea-level rise (SLR) scenarios. The modeling shows that the impacts of SLR vary spatially and are strongly influenced by the bathymetry of the reef and coral type. A complex response occurs for the wave orbital velocity and forces on corals, such that the changes in the wave dynamics vary reef by reef. Different wave loading regimes on massive and branching corals also leads to contrasting impacts from SLR. For many reef bathymetries, wave orbital velocities increase with SLR and cyclonic wave forces are reduced for certain coral species. These changes may be beneficial to coral health and colony resilience and imply that predicting SLR impacts on coral reefs requires careful consideration of the reef bathymetry and the mix of coral species.

1. Introduction

Reefs protect the shore of many tropical islands and beaches from waves, and also provide valuable ecosystem services and economic benefits (Moberg and Folke, 1999). Many of the physical and biological processes on coral reefs are strongly dependent on the reef top hydrodynamics, which control flushing, mixing processes and nutrient supply, and govern destructive forces under extreme conditions. The effective assessment and management of reefs as ecological, social and economic resources requires the ability to assess how these physical and biological processes will be impacted by climate change. The potential impacts of climate change, including sea-level rise (SLR) and the mortality of coral during warm conditions (Hoegh-Guldberg et al., 2011), may reduce the effectiveness of fringing and barrier reefs as protection for islands, and directly change the hydrodynamics, nutrient supply and forces on reefs and corals (Sheppard et al., 2005; Webb and Kench, 2010; Perry et al., 2011; Storlazzi et al., 2011; Grady et al., 2013). This paper investigates the effects of SLR on the physical hydrodynamic processes occurring on barrier coral reefs. We ask how current reef environments may change as water depths change over reefs, and which reef bathymetries and zones are likely to experience the greatest changes. Modifications to the present environment by SLR could have significant impacts on the functioning of coral reefs. Firstly, wave-orbital velocities underpin the rate at which essential dissolved gases (e.g., oxygen, carbon dioxide) and nutrients are both delivered to and removed from benthic organisms (Monismith, 2007). Such fluxes play an important role in driving primary production in corals (Jokiel, 1978; Tribble et al., 1994), algal turfs (Carpenter and Williams, 1993, 2007), and fleshy algae (Renken et al.. 2010). Flow can also influence the response of corals to thermal stress either by influencing the rate of temperature rise directly, through increased mixing between surface and cooler, deeper waters (Skirving et al., 2006), or potentially by reducing the risk of local anoxia that can cause coral mortality (Wangpraseurt et al., 2012). Wave action also plays a key role in damaging or dislodging corals, particularly during storm conditions (Massel and Done, 1993; Storlazzi et al., 2005; Madin and Connolly, 2006). SLR also potentially slows growth as reef flats become subject to erosion by larger waves (Buddemeier and Smith, 1988). Wave action additionally plays a role in overall reef surface geomorphology, with reef width and depth controlling changes in geomorphology (Kench and Brander, 2006). The interaction of these multiple processes suggests the potential for feedback between the biological and physical processes.

A number of recent studies (Grinsted et al., 2009; Merrifield et al., 2009) point out that not only is global sea level rising, but the rate is increasing in response to global climate change.

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Syntheses by Grinsted et al. (2009) and Nicholls and Cazenave (2010) suggest that global mean sea level in 2100 may exceed the 2000 level by two times the average IPCC (2007) projection of approximately 60 cm above 2000 levels (Storlazzi et al., 2011). The impact on coral reefs from predicted sea level rise has been addressed by number of studies (e.g. Graus and Macintyre, 1998; Sheppard et al., 2005; Ogston and Field, 2010; Storlazzi et al., 2011; Grady et al., 2013). SLR creates deeper water over reefs and lagoons, potentially allowing larger waves, with possibly a different wave period to that of the locally generated wind waves, to reach the leeward reef edge, reef lagoons and reef island shorelines. This may induce beach erosion, turbidity (Storlazzi et al., 2011) and greater damage to reefs under storm or cyclonic conditions as the forces exerted on the coral structure change, potentially leading to greater rates of breakage (Massel and Done, 1993) and an increase in the average depletion of coral populations (Mumby et al., 2011), increasing the vulnerability of reef islands and atolls (Roy and Connell, 1991; Khan et al., 2002). Buddemeier and Smith (1988) note that predicted rates of SLR are significantly greater than the maximum vertical accretion rates of coral reefs and therefore reefs are unlikely to keep up with SLR.

Typical wave induced flows, in addition to currents, are governed by the particular morphology of the reef-lagoon itself, and subject to changes in wave climate (Lowe et al., 2009). However, in the absence of detailed knowledge of changes in wave climate, if any, we limit the modeling to investigate the impact of SLR only and therefore the results are not region specific. For deep and/or open lagoon systems, the wave dynamics are largely controlled by the morphology and physical roughness properties of the fore-reef and reef flat, and the morphology of the lagoon plays a minor role in the overall momentum dynamics (Gourlay and Colleter, 2005). In this case, the water depth over the reef flat determines the wave energy dissipation and is a controlling parameter for the wave dynamics (Sheppard et al., 2005, Madin and Connolly, 2006, Storlazzi et al., 2011). Further, wave conditions vary across the reef (e.g. Brander et al., 2004), with reef width and surface roughness also influencing wave dissipation, and therefore different reefs and their ecological process have varying – and context dependent – sensitivity to SLR.

This paper studies the effects of SLR on the flow environment on coral reefs under both average and cyclonic climates (defined in Section 2). We use a wide range of barrier reef profiles and a 3rd generation wind-wave model to investigate and obtain insight into the sensitivity of the wave induced velocity and forces on branching and massive corals to SLR for different reef geomorphology and surface roughness. The changes in wave height, wave-orbital velocity and wave induced forces are presented and discussed in terms of their potential impacts on coral health. The paper is organized as follows. Section 2 presents an overview of the numerical model, together with the selected environmental conditions adopted for the model input. Results are given in Section 3, which provides a summary of the model predictions, with a focus on the changes in key parameters (wave height, wave-orbital velocity, wave forces) under SLR. The implications of the results for predicting ecosystem health and for future modeling of reef colonies under SLR are discussed in Section 4. Final conclusions follow in Section 5.

2. Methodology

2.1. Wave dynamics model selection

The SWAN (Delft University of Technology) and MIKE 21 SW (Danish Hydraulic Institute) third-generation wave models were considered for use in this study. Comparison of SWAN with MIKE 21 SW shows that both models give very similar results. However, as MIKE21 SW is designed for wider application and not specifically for application as a 1D model, it is more computationally expensive than SWAN. Similarly, SWAN 1D provides wave setup as an output based on an explicit solution; therefore there is no need to run a hydrodynamic model to calculate wave setup, again reducing computation time. Consequently, the SWAN 1D model was selected due to the extensive number of simulations required to cover the range of bathymetric conditions. The SWAN model has been used for prediction of waves over coral reefs in a range of locations (Vitousek et al., 2007; Storlazzi et al., 2011), and extensively tested for wave propagation in a wide variety of coastal environments (Ris et al., 1999). The inputs required for the model are bathymetry, water level, surface roughness and wind and wave conditions at the offshore model boundary.

2.2. Bathymetry

The idealized cross section of a barrier reef adopted for the modeling includes a sloping fore-reef, a horizontal reef flat, a sloping back-reef, a deeper lagoon, and the shoreface (Fig. 1). It is assumed that the fore-reef and back-reef have slope of 1:2 (26°), the beach has slope of 1:10 (6°), and that the water depth on the outer fore-reef is 50 m. A range of values for the width (50–1200 m) and depth (0.5–3 m) of the reef flat and the width (50–2000 m) and depth (5–20 m) of the lagoon were combined to create 540 different reef profiles. In addition, the roughness of the reef was varied, resulting in a total of 1080 different reef bathymetries (Table 1). A base bathymetry was also chosen for more detailed investigations and model testing or where comparison is required with a particular control case. This profile has a reef flat width of 400 m, a reef flat depth of 1 m, a lagoon width of 1000 m, a lagoon depth of 10 m, and a surface roughness of 0.1 m. This profile is representative of the main reef at Lizard Island, Great Barrier Reef (GBR) Australia (as outlined below), which was selected as a representative location for the selection of appropriate climatic wind, wave and tide data for the model study. The range of the bathymetric parameters (reef flat depth and width, lagoon width and depth, and surface roughness, representing coral cover and dead carbonate) was selected based on typical values for reefs in the GBR and worldwide. In the present study, the reef flat depth is a key parameter; for ease of reference we refer to reefs with reef flat depths in the range 0.5–1 m and 2.5 m–3 m as shallow reefs and deep reefs, respectively. While tides are not included, the range of water levels considered encompasses typical tidal ranges. Hence, results for different water levels are also representative of conditions at different stages of the tide.

2.3. Environmental conditions

Met-ocean data was used to identify different climate scenarios. Wind and wave data from the European Centre for Medium Weather Forecast (ECMWF) global atmospheric and oceanic models (C-ERA-40 spanning 1958–2002 and ERA-Int spanning 1989–2009) with spatial resolution of 1.5° and time resolution of 6 h were extracted. However, because of their coarse resolution, these models do not resolve reef and reef islands very well. Hardy et al. (2001) have run a local wind-wave model for the GBR with temporal resolution of 1hr and spatial resolution of 1500 m covering 1996–2003. With this resolution, Lizard Island is as a whole reasonably well resolved and data are available inside and outside of the lagoon, although detail is limited within the lagoon. However, the duration of this hindcast model is only for 8 years (1996–2003) which is insufficient for predicting statistical extremes, but sufficient to estimate typical conditions for the present modeling. To check the Hardy et al. results, synoptic wind data

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