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Reef island dynamics and mechanisms of change in Huvadhoo Atoll, Republic of Maldives, Indian Ocean

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ABSTRACT

Planform changes in 184 reef islands in Huvadhoo atoll, Republic of Maldives are quantified in the context of global environmental change and anthropogenic impacts. Aggregated at the atoll scale, results show that, over the past four decades, total land area increased by 59 ha (2.4%). Land reclamation of 93.8 ha on 12 inhabited islands was the dominant factor in the increase in land area. Excluding reclaimed islands from the dataset reveals net erosion of atoll island area of 28.5 ha (1.5%). Erosion was prevalent on 45% of islands with remaining islands being stable (40%) or increasing in area (15%). A relationship between island size and planform change was identified. Small islands (<10 ha) were dominated by erosional responses whereas larger islands were dominated be accretion. Results indicate future transformation in atoll land resources to fewer smaller islands but an increase in size of larger islands. Results also indicate that all islands changed, underscoring the dynamic nature of islands on reef surfaces. Ten distinct styles of island adjustment were identified from the dataset. Direct human impact, through reclamation, was found to have a more significant impact on island change in the atoll than secondary factors such as sea level change and changes in reefal sediment supply. Implications for the Maldives are discussed and indicate that land resources for ongoing habitation will persist across the next century though the location of tourism activities on smaller islands places this valuable economic sector at risk. Analysis of historic island change provides a rich information source to reconsider landuse planning in the context of climate change adaptation.

1. Introduction

The future persistence and stability of atoll islands is of significant global interest as a consequence of anthropogenically forced sea level rise and climatic change (Pala, 2014). Low-lying reef islands provide the only land for habitation in atoll nations with some islands sustaining among the highest population densities on earth. These islands are expected to become inundated and erode as a consequence of anthropogenically induced rising sea levels (Kahn et al., 2002; Dickinson, 2009; Storlazzi et al., 2015; Albert et al., 2016). Numerous reports suggest entire islands will erode away rendering the people of atoll countries environmental refugees (Barnett, 2005; McAdam, 2010; Connell, 2013). While there is seldom quantitative information presented to validate such assertions it is apparent that understanding the future trajectories of island morphological adjustment to global environmental changes and the role of anthropogenic activities on island dynamics is critical for informing global discourses of the fate of islands and to support adaptation responses in atoll nations.

To date, there have been few studies undertaken to document and understand the morphological changes in reef islands, examine the drivers of such changes including past and present human impacts, or consider the implications of such changes for island communities. Webb and Kench (2010) undertook the first quantitative analysis of physical changes in 27 atoll islands in the central Pacific, in the context of sea level change, across a time window ranging from 19 to 61 years. The multi-decadal timeframe of analysis is a minimum requirement for the detection of responses to medium-term sea level change. Webb and Kench (2010) showed that despite sea level rise islands were persistent features on reef surfaces over this timescale, that land area had generally increased over the past few decades and that islands are geomorphically dynamic features that are in continual adjustment to changes in environmental boundary conditions (sea level,

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waves, sediment supply). Subsequently, a number of additional Pacific case studies have reported multi-decadal planimetric changes in mid-ocean atoll islands in the Marshall Islands (Ford, 2011, 2013; Ford and Kench, 2014, 2015; Kiribati (Rankey, 2011; Biribo and Woodroffe, 2013) and French Polynesia (Yates et al., 2013) and summarised by McLean and Kench (2015). Collectively, these studies further support earlier observations that atoll islands are dynamic landforms and highlight the physical response to anthropogenically-forced sea level rise is not simply erosional. Rather, the range of possible island responses includes island expansion (accretion) as well as erosion and island mobility on their coral reef platforms.

More recently, Kench et al. (2015) examined the physical changes of 29 islands in Funafuti atoll, Tuvalu over the past 118 years, a sea level rise hotspot where over the past 60 years sea level has been rising at 5 mm/yr in the western Pacific. Their results showed: all islands had undergone physical changes; the total land area over the past century had increased by 7.3%; no islands had eroded away, and; more than half the islands in the atoll increased in size. Inferred mechanisms for the observed changes include the frequency of storms that can have both erosional and accretionary impacts; changes in the nearshore process regime; alterations in the sediment supply generated from the surrounding reef flat; and human modification to shorelines, although this was negligible on the islands studied. Indeed, some studies have noted that these mechanisms may overprint any sea level change signal (McLean and Kench, 2015). In contrast to the studies of atoll reef islands, Albert et al. (2016) document an erosional response and loss of five reef islands in the tectonically active Solomon Islands. Such findings indicate that morphological response will vary spatially, heightening the need to further resolve differences in island dynamics between reef regions where island sedimentary structure, tectonics, sediment supply regimes, sea level rise and wave processes differ.

Despite the recent increase in studies examining the morphological changes of islands over the past century to decades, studies have been focussed in the Pacific Ocean and the sample size, in terms of number of islands examined, is small. In contrast, there have been few attempts to examine physical changes in islands in the Indian Ocean despite the existence of a number of atoll archipelagos (e.g. Chagos, Maldives and Lakshadweep). Hamylton and East (2012) examined shoreline adjustments on Diego Garcia atoll, Chagos, as part of a broader study of ecological and geomorphic changes in the atoll and identified variability in shoreline response. Purkis et al. (2016) re-examined the morphological changes in islands in Diego Garcia across a 50 year time window also highlighting spatial differences in erosion and accretion with net change in island area less than 1% but larger gross fluxes in shoreline behaviour over the short-term. Purkis et al. (2016) suggest both sea level rise and anthropogenic stressors are likely the main drivers of change and that increased dynamism of island shorelines can be expected in the future as sea levels rise. Purkis et al. (2016) also highlight that further exploration of island change in the extensive atoll systems north of Chagos is warranted as the Maldives contain a larger number of reef islands, which are located in an oceanographic and climatic setting distinct from the Pacific. For example, a number of studies have shown that in the Maldives the style of island evolution in response to historical sea level change (Kench et al., 2005, 2009) and the contemporary morphodynamics of islands in response to the contemporary process regime (climate and ocean processes, Kench et al., 2006; Kench and Brander, 2006) has distinct differences to other reef regions (Kench et al., 2009). Such differences may imply that future island adjustments to sea level change may also differ. Here we present an analysis of changes in 184 islands in Huvadhoo atoll, Maldives based on analysis of aerial imagery spanning four decades. Specific objectives are to: i) quantify planform changes in reef islands across the last four decades; ii) determine whether differences in physical change exist between islands of varied size; iii) examine spatial differences in island change within the atoll, and; iv) examine the drivers of island change in the context of anthropogenically driven environmental changes and direct human impacts. Results are used to discuss the likely future landform trajectories of islands in Huvadhoo atoll and implications for island communities.

1.1. Regional setting

The Maldives archipelago comprises a double chain of atolls and reef platforms located 700 km southwest of Sri Lanka and constitutes the central section of a submarine ridge that connect the Lakshadweep Islands (to the north) and Chagos Islands (to the South). The Maldives archipelago extends 868 km from Ihavandhippolhu atoll in the north (6°57′ N) to Addu atoll (0°34′ S) just south of the equator. The atoll chain is considered globally unique in terms of biodiversity, the diversity of reef structures it possesses and their mode of evolution (Kench, 2011). The reef system supports approximately 1200 low-lying reef islands, which are mid- to late Holocene in age (Kench et al., 2005; Kench, 2011; Perry et al., 2013). The Maldivian population of 351,000 inhabit 194 islands throughout the archipelago. As one of only four atoll nations on earth the Maldives is regarded as extremely vulnerable to future sea-level rise and climatic change (Kahn et al., 2002).

The focus of this study is Huvadhoo atoll situated in the southern part of the archipelago (0°32′ N, 73°17′ E), south of the one and a half degree channel (Fig. 1a). Huvadhoo is the largest atoll in the Maldives, has a perimeter of 261.4 km with an area of 3279 km^2 (Naseer and Hatcher, 2004). The atoll is 80 km along its North-South axis and 60 km at its widest point (West-East). The atoll periphery is fragmented with numerous passages in the atoll rim that allow the penetration of ocean swell and currents into the lagoon, which has a maximum depth of 80m. The atoll has 241 reefs with a total area of 437.9 km^2 (Naseer and Hatcher, 2004). Huvadhoo has 241 vegetated islands that have a total land area of approximately 2753.7 ha. Island size ranges from 0.01 ha to 238.1 ha. The majority of islands (200) are located around the atoll periphery, with 41 islands located on lagoonal patch reefs. Nineteen of the islands are inhabited including several lagoon islands. The islands on the western atoll rim are composed of a mix of gravel and sand size sediments. In contrast, most lagoonal islands and those on the eastern rim are dominated by sand-size sediments (East et al., 2016; Liang et al., 2016).

1.2. Sea level records

Over the past 130 yr there has been an unambiguous increase in averaged global mean sea level (GMSL) of approximately 200 mm, with 20th Century rates of 1.5–2.0 mm y^{-1} based on tide gauge records and faster rates detected from 1993 to 2009 of ~3.3 mm y^{-1} since the availability of satellite altimetry. Tide gauge records from Male' atoll central Maldives and Addu atoll in the south of the archipelago (Fig. 2) both show increases in mean sea level of approximately 3.2 mm y^{-1} and 4.0 mm y^{-1} respectively over the past 28 years. Such rates are consistent with global trends and also previous estimates from the Maldives (Kahn et al., 2002), although they are slightly below the rate of 5.0 mm y^{-1} identified by the IPCC for future planning purposes (also see Woodworth, 2005).

1.3. Process regime

The climate of the Maldives is characterised by marked transitions in regional wind patterns from the NE monsoon