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Multi-decadal shoreline changes in response to sea level rise in the Marshall Islands

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ABSTRACT

Low-lying reef islands are considered highly vulnerable to the impacts of climate change. Accelerating rates of sea level rise as a result of anthropogenic climate change are expected to destabilise islands and threaten to render entire nations uninhabitable. Using historic aerial photographs and recent high-resolution satellite imagery, shoreline changes on six atolls and two mid-ocean reef islands in the Republic of the Marshall Islands were analysed. Results reveal that since the middle of the 20th century more shoreline has accreted than eroded, with 17.23% showing erosion, compared to 39.74% accretion and 43.03% showing no change. The net result of these changes was the growth of the islands examined from 9.09 km^2 to 9.46 km^2 between World War Two (WWII) and 2010. Analyses of shoreline changes since the 1970s show that shorelines are accreting albeit at a slower rate, with rates of change between the 1970s and 2010 of 0.29 m/dec compared with 0.77 m/dec between WWII and 1970s. The observed shoreline changes occur in the context of locally rising sea level. As sea level continues to rise there is a critical need for regular monitoring of reef islands in order to better understand the spatio-temporal variability of reef island change and guide future adaptation efforts within atoll nations.

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1. Introduction

Atoll islands are coral reef associated sedimentary deposits found in subtropical and tropical oceans. The islands are comprised of unconsolidated or weakly lithified carbonate sediment derived from the skeletal remains of the reef framework and benthic organisms. Most chronologies of island development indicate islands are geologically young, having only formed in the mid-late Holocene, and were fully formed 5000–2000 years BP (Woodroffe et al., 1999, 2007; Woodroffe and Morrison, 2001; Kench et al., 2005; Kayanne et al., 2011; Kench et al., 2012, 2014a). However, recent chronologies and observations indicate some islands formed within the past 1000 years (Kench et al., 2014b; Ford and Kench, 2014). Once the islands have formed, reef island shorelines have been shown to be highly dynamic, with shoreline change driven by both local and distal storms (Stoddart 1963, 1971; Maragos et al., 1973; Ford and Kench, 2014; Smithers and Hoeke, 2014), tsunami (Kench et al., 2006), as well as seasonal and decadal variations in wave climate (Flood, 1986; Kench et al., 2006; Kench and Brander, 2006). Despite their relatively recent formation, atoll islands have been sites of human habitation since the first few centuries AD (Weisler, 2001; Kayanne et al., 2011). Today, atoll islands provide the bulk of habitable land in the atoll nations of the Maldives, Tuvalu, Kiribati and the Marshall Islands. In addition, several other countries in the Pacific and Indian Oceans have substantial populations residing on atoll islands.

Due to their limited land area, low elevation and limited economic and technical capacity atoll islands are considered vulnerable to the impacts of climate change, particularly sea level rise (SLR) (Barnett and Adger, 2003; Woodroffe, 2008). A suite of sea level rise impacts are considered likely to manifest on atoll islands including: increased marine inundation, increased groundwater salinity and chronic coastal erosion (Mimura, 1999; Barnett and Adger, 2003; Woodroffe, 2008). Sea level rise is commonly expected to destabilise island shorelines and lead to widespread loss of land as a result of erosion (Dickinson, 2009). Accounts and projections of islands being 'washed away' are a mainstay of political discussions and popular media reports of climate change impacts on atolls (Johnson, 2014; Lewis, 2015). Despite the widespread attention of the plight of atoll islands, there has been a paucity of evidence presented to underpin such assertions. Recently, the popular narrative of reef islands 'disappearing' has been considered overly simplistic and unhelpful for strengthening the resilience and adaptive capacity of island communities

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(Kelman, 2014; McCubbin et al., 2015). Likewise, evidence of the physical resilience of islands has emerged showing a notable absence of widespread chronic erosion (Webb and Kench, 2013; Yates et al., 2013).

Relative to shorelines on continental landmasses, few studies have systematically examined changes to reef island shorelines over multi-decadal time scales, coincident with records of rising sea level (McLean and Kench, 2015). Pacific atolls are typically remote, and with the exception of a small number of densely populated urban islands, sparsely populated. As a result, field-based monitoring efforts of island erosion are limited (Kench and Harvey, 2003). Recently, remote sensing approaches, used for several decades along continental shorelines, have been applied in the study of reef island shoreline change (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013). Within this recently emerging body of shoreline change studies on atoll islands there is little evidence of widespread reef island erosion. To the contrary, several studies have documented noteworthy shoreline progradation and positional changes of islands since the mid-20th century, resulting in a net increase in island area (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013; Kench et al., 2015). Within densely populated urban atoll settings, such as Majuro in the Marshall Islands and Tarawa in Kiribati, human activities such as land reclamation and causeway construction have been recognised as a significant factor responsible for increasing island size (Ford, 2011; Biribo and Woodroffe, 2013; Duvat, 2013). A wide range of shoreline armouring strategies have been employed to effectively maintain a shoreline position within urban atoll settings. Likewise, land reclamation has led to the expansion of islands on both ocean and lagoon facing shorelines, while causeways have linked previously disconnected islands. In contrast, the sparsely populated "outer islands" have been subjected to few engineering interventions at the shoreline, with shoreline changes reflecting morphodynamic responses to changing boundary conditions.

The use of remotely sensed imagery to study reef island change is still in its infancy, with an active phase of research only emerging since 2010 (Webb and Kench, 2010; Ford, 2011; Rankey, 2011; Yates et al., 2013). McLean and Kench (2015) provide a review of recent reef island change studies. To date, studies of shorelines along sparsely populated and uninhabited islands have revealed a prevalence of shoreline accretion compared to erosion, leading to an increase in island size (Webb and Kench, 2010; Ford, 2013; Yates et al., 2013). However, this limited set of observations has been derived from relatively small datasets and it is still unclear if accretion of reef-islands has been the prevalent mode of shoreline change over recent decades. Here we present analysis of shoreline change on 127 islands on six atolls and two mid-ocean platform islands within the Republic of the Marshall Islands.

2. Setting

The Republic of the Marshall Islands (RMI) is comprised of 29 atolls and five mid-ocean platform islands (Fig. 1). Two parallel chains of atolls extend from 4°34′N (Ebon Atoll) to 14°43′N (Bokak/Taongi) and from 160°48′E (Ujelang Atoll) to 172°10′E (Nadikdik Atoll) forming an exclusive economic zone of ~2.1 million square kilometres. The 2011 census shows the population of the Marshall Islands was 53,158, with 74% residing on Majuro and Kwajalein atolls, both characterised by densely populated and highly modified islands (EPPSO, 2012). The remaining atolls have relatively low populations, with larger villages typically found on one island per atoll. The eight atolls in this study span a latitudinal range from Ebon Atoll in the south (4°34′N, 168°43′E) to Rongerik Atoll in the north (11°22′N, 167°27′E). The collection of islands in this study comprises both atolls and mid-ocean platform islands (Fig. 2, Table 1).

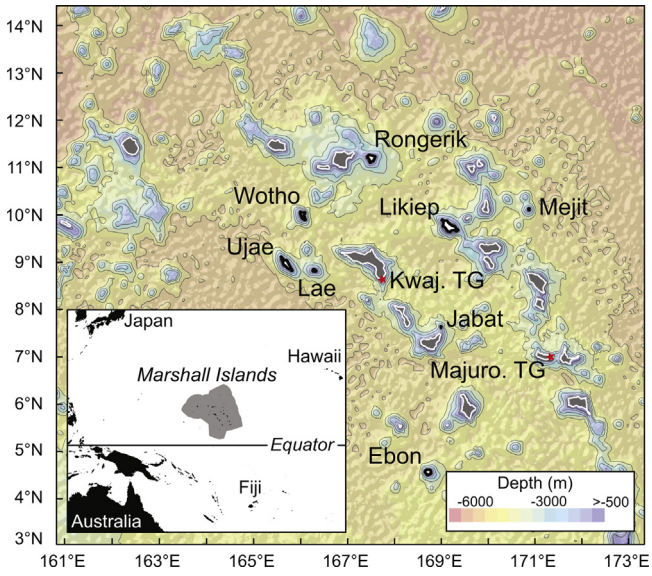

Fig. 1. The Republic of the Marshall Islands, including atolls examined in this study and the location of tide gauges on Kwajalein and Majuro Atolls (red stars).

2.1. Oceanographic setting

The Republic of the Marshall Islands (RMI) have among the lengthiest sea level records in the central Pacific (Becker et al., 2012). Currently tide gauges are operational at Uliga dock on Majuro Atoll and at the United States Army base on Kwajalein Atoll. The Majuro tide gauge record is comprised of two separate records collected by the University of Hawaii Sea Level Centre (UHSLC) from 1968 to 1999 and by the Australian National Tidal Facility from 1993 to present (Fig. 3). The Kwajalein tide gauge has been operating near-continuously since 1946 (Fig. 3). Sea level has risen at 2.2 mm/yr and 3.7 mm/yr at Kwajalein and Majuro respectively (Becker et al., 2012). Few long-term records of wave conditions exist for the RMI. However, Durrant et al. (2013) provide a hindcast of wave conditions at 4 arcmin resolution between 1978 and 2010. In general, there is a latitudinal and longitudinal gradient in average wave heights with atolls in the north and east of the archipelago characterised by higher average wave heights than in the southern RMI (Fig. 4).

3. Materials and methods

3.1. Image properties and processing

Remotely sensed assessments of shoreline change along shorelines within developed nations typically involve the use of temporally-rich collections of aerial photographs spanning several decades (e.g. Romine et al., 2009). However, atoll nations in the Pacific are remote and have limited collections of aerial photographs. Within the Marshall Islands the most active period of aerial photography was during the later stages of World War Two (WWII). WWII-era imagery was collected between 1943 and 1945. Following WWII, three aerial photograph surveys occurred in the Marshall Islands during the 1970s. The advent of high-resolution satellite sensors in the early 2000s has greatly increased the spatial and temporal coverage of imagery of the Marshall Islands. To study shoreline change we compare shoreline positions interpreted from historic aerial photographs captured between 1943 and 1978 with those interpreted from modern, high-resolution Worldview-2 satellite imagery collected since 2010, providing a window of analysis up to 68 years in length.

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