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Eco-geomorphic processes that maintain a small coral reef island: Ballast Island in the Ryukyu Islands, Japan

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ABSTRACT

Landform changes in Ballast Island, a small coral reef island in the Ryukyu Islands, were investigated by remote sensing analysis and a field survey. The area of the island almost doubled after a mass coral bleaching event in 1998. Coral branches generated by the mass mortality and broken by waves were delivered and stocked on a reef flat and accumulated to expand the area of the island. In 2012 high waves generated by typhoons also changed the island's topography. Overall, the island moved in the downdrift direction of the higher waves. Waves impacting both sides of the island piled up a large volume of coral gravels above the high-tide level. Eco–geomorphic processes, including a supply of calcareous materials from the corals on the same reef especially during stormy wave conditions, were key factors in maintaining the dynamic topographic features of this small coral reef island.

1. Introduction

Coral reef islands (reef islands), which have an elevation of one to three meters, are low-lying and form on coral reef flats or infilled lagoons. The islands are formed mainly of calcareous gravel and sand produced by reef-building organisms (Perry et al., 2011). Reef islands are extremely vulnerable to the ongoing sea-level rise induced by global warming (Hubbard et al., 2014; Pala, 2014; Weiss, 2015). Global warming also affects the process of reef island formation process through the degradation of corals by thermally induced bleaching, which reduces the production of calcareous materials (Perry et al., 2011). Additionally, the islands are often attacked by high waves from tropical cyclones, which often cause changes in reef geomorphology (Stoddart, 1971; Maragos et al., 1973). The globally averaged tropical cyclone intensity is expected to increase by between 2–11% by 2100 (Knutson et al., 2010). Based on this forecast, hydrodynamic disturbance will likely severely damage reef islands and change their landforms.

Large reef islands have a geological development history with a timescale of 10^3 years or less. They began to form during the late stage of post-glacial sea-level change over the last several thousand years, with their formation initially determined by the development of a rigid framework of coral reef or the aggradation of lagoons to platforms, followed by the accumulation of mainly coral, *Halimeda*, and molluscan gravel/sand along with foramiferal sand (Woodroffe et al., 1999, 2007; Woodroffe and Morrison, 2001; Kench et al., 2005, 2012, 2014b; Kayanne et al., 2011; Yasukochi et al., 2014).

In contrast to the relatively large atoll reef islands with a long geologic history, the processes by which some small reef islands (or coral sand cays or motu) form are more dynamic. The topography of small reef islands has been observed to change seasonally (Maragos et al., 1973; Kench et al., 2009) or interannually (Kench et al., 2014a, 2015). The formation process of these islands is controlled by the supply of calcareous materials and by prevailing wave regime (Yamano et al., 2000a, 2000b; Mckoy et al., 2010). To understand the maintenance of small reef islands, it is necessary to clarify the processes related to the supply of calcareous materials and their transportation by waves.

Perry et al. (2011) regarded the sedimentary traits and rate of supply of calcareous sediments on the reef to be a key factor in island development and resilience in the future and referred to their supply function as a "biological sediment factory." The degradation of coral reef ecosystems by processes such as coral bleaching limits the functioning of the

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factory, possibly leading to shrinkage of the island. Williams et al. (1999) predicted that the reduction in living corals by disease and bleaching would lead to the disappearance of reef islands. Hubbard et al. (2014) argued that unhealthy reefs prevent reef islands from keeping up with rising sea level. On the other hand, Perry et al. (2011) suggested that sediment yield may increase due to the dead coral substrate and may, at least temporarily, exceed that of the unbleached reef. However, the hypothesized relations between the degradation of corals and reef island geomorphology have never been substantiated in actual reef islands.

The growth of corals does not directly form islands. Branches of corals are broken and coral colonies are dislodged by heavy waves; these materials eventually become gravel (Hongo et al., 2012) that is then transported to form islands. Oceanic swells break at the edge of the reef flat and are converted into waves and current to transport the sediment (Gourlay, 1996a, 1996b; Hearn, 1999).

Tropical cyclones (typhoons in the NW Pacific, including Japan, with a maximum wind speed of more than 17 m s^{-1}, cyclones in the Indian Ocean and Australia, and hurricanes in the Atlantic Ocean and the east Pacific with a maximum wind speed over 32.7 m s^{-1}) are also known to be major driving forces in the topographic changes in reefs and reef islands (Stoddart, 1963). Tropical cyclones largely control the input of new sediment by direct breakage of reef material and rainfall-induced input of terrigenous detritus into the Great Barrier Reef system (Larcombe and Carter, 2004). In some cases, catastrophic erosion to reef islands has occurred; in other cases, the high waves generated by cyclones have delivered a large amount of gravel to accumulate on islands or even form new islands (Maragos et al., 1973; Baines and Mclean, 1976; Bayliss-Smith, 1988; Ford and Kench, 2014). Studies of some reef islands have attempted to determine the adjustment process following the large topographic changes caused by cyclones, which are equivalent to typhoons or hurricanes (Baines and Mclean, 1976; Ford and Kench, 2014). Due to the high waves generated by typhoons, a large volume of coral gravel is tossed up onto the reef and then moved toward the land. In Belize, for example, Stoddart et al. (1963) showed that a large amount of gravel was piled on the reef crest at Soldier Cay in the Turneffe Islands during Hurricane Hattie in 1961. Bayliss-Smith (1988) modeled the contrasting hurricane impacts of gravel motu accretion and sand cay erosion. However, time-series of topographic records for a single reef island in response to repeated tropical cyclones are poorly known.

Observations of topographic changes in reef islands have been conducted previously in the area of 7° to 25° in both hemispheres, which is where tropical cyclones form (Scoffin, 1993), although their intensity does not reach maximum levels. The peak intensities of tropical cyclones occur in the higher latitudes, from 15° to 30°, and are most densely distributed in the northwest Pacific, from the Philippines, Taiwan, and the Ryukyu Islands (Kossin et al., 2014). The southern Ryukyu Islands are located in this area, where the passage of typhoons at their peak intensity is a common phenomenon. An average of 7.6 typhoons approached the Ryukyu Islands every year from 1981 to 2010 (Japan Meteorological Agency; http://www.data.jma.go.jp/fcd/yoho/typhoon/statistics/average/average.html). Typhoons cause changes in both the coral distribution and the island topography in the Ryukyu Islands (Hasegawa, 1990; Kan et al., 1997; Onda, 1999; Yamano et al., 2000a). For example, Onda (1999) estimated that boulders deposited by typhoons contributed to vertical accumulation at a rate of at least 6.48 mm/year in the shallow lagoon on Kudaka Island. Additionally, the Hatenohama cays on Kume Island are mainly composed of sand and gravel (Hasegawa, 1990). A thickness of approximately 2 m of sediment was eroded from the cays by typhoon waves in 1986 (Hasegawa, 1990). However, no studies have observed time-series topographic changes in reef islands in the Ryukyu Islands or the effect of wave action on these reef islands during typhoons, so this has prevented the quantitative evaluation of the role of typhoons in the formation of reef islands.

In this study, we examined topographic changes in Ballast Island, a small reef island on an isolated reef in the southern Ryukyu Islands. A 30-year history of island landform (plan view) changes was reconstructed using aerial photographs and satellite images, during which time the 1998 mass coral bleaching event occurred and many typhoons passed near the island. An island topographic survey, together with wave observations, was conducted in 2012, when seven typhoons passed close to the island.

2. Study site and methods

2.1. Study site

Ballast Island is located 2.5 km northwest of Iriomote Island, the southernmost of the Ryukyu Islands, Japan (Fig. 1a). The island, which is about 200 m in length and 20 to 30 m in width, is located at the center of an isolated reef. The island has mostly been exposed above the high-tide level. Local people claim that it has existed predominantly in the same location for at least the last 50 years, yet its elevation and shape have changed with time, particularly after typhoons and winter monsoons.

The dominant wave direction is from the NNW, with wave height sometimes exceeding 3 m during the winter monsoons from November to February (GPV data obtained 5 km north of Hatoma Island). During spring and summer, relatively calm conditions prevail except during the passage of typhoons. During typhoons, this area experiences significant wave heights of more than 3 m. Ballast Island is located between Iriomote and Hatoma Islands, and the dominant wave direction at the island is thus from the east or west, because wind and waves from the north and south are blocked by Hatoma and Iriomote Islands.

2.2. Methods

Changes in the island plan view were reconstructed by aerial photographs for four periods from 1979 to 2006 and by satellite remote sensing images for 17 periods from 1998 to 2009 (Table 1 and Fig. S1). Land–sea boundaries were traced from shorelines in aerial photographs by visual identification of white gravel above sea level, whereas those in satellite images were detected by density slicing of the near-infrared band following Yamano et al. (2006) and Yamano (2007). We assumed the error in shoreline determination in aerial photographs was less than 3 m based on Ford (2012), who analyzed shoreline changes in reef islands using aerial photographs and satellite images. The error in satellite images was calculated to be 0.534 times the spatial resolution (Yamano et al., 2006). Accordingly, error values of 16 m for Landsat TM, 8 m for Terra ASTER, and 5.3 m for ALOS AVNIR-2 were obtained. Because of the variation in the water level in each image due to tides, all of the shorelines detected were relocated to those at mean sea level (msl) based on the profiles measured in the topographic survey. Then, the area of the island was calculated based on the shorelines and errors.

In October 2011, we conducted a topographic survey of the reef flat. A topographic cross-section of the reef from 600 m west to 600 m east of the island was measured every 10 m along a transect by leveling at sites shallower than 3 m and by placing a depth gauge at sites deeper than 3 m. Coral taxa were visually recorded as having less than 5% cover (+) and were subsequently recorded at 5% cover intervals every 10 m along the transect over a width of 1 m. The coverage of corals was determined visually, and the average of three observers was taken. This is a semi-quantitative method of estimating the coverage of corals, which applies the manta tow survey method more strictly (Kayanne et al., 2002; Harii et al., 2014). Each coral species was identified by sampling a minimal amount of the colony.

In March 2012 and July, August, and October 2013, cross-sections of the island were obtained using an auto level (AE-5: Nikon Corp., Tokyo, Japan) along one long axis and five short axes of the island. The measured depths and elevations were corrected to the altitude above msl with