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Original article

Shoreline changes in a rising sea level context: The example of Grande Glorieuse, Scattered Islands, Western Indian Ocean

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ABSTRACT

This paper provides baseline data on absolute and relative sea level variations and shoreline changes in the Scattered Islands region of the Indian Ocean, based on aerial image analysis, satellite altimetry and field observations and in situ measurements from the 2009 and 2011 TAAF scientific expeditions. The analysis shows the importance of regular observations and monitoring of these islands to better understand reef island responses to climate stressors. We show that Grande Glorieuse Island has increased in area by 7.5 ha between 1989 and 2003, predominantly as a result of shoreline accretion: accretion occurred over 47% of shoreline length, whereas 26% was stable and 28% was eroded. Topographic transects and field observations show that the accretion is due to sediment transfer from the reef outer slopes to the reef flat and then to the beach. This accretion occurred in a context of sea level rise: sea level has risen by about 6 cm in the last twenty years and the island height is probably stable or very slowly subsiding. This island expansion during a period of rising sea level demonstrates that sea level rise is not the primary factor controlling the shoreline changes. This paper highlights the key role of non-climate factors in changes in island area, especially sediment availability and transport. We also evidence rotation of the island, underscoring the highly dynamic nature of reef islands.

1. Introduction

Long-term global sea level variability is a subject of major importance, due to its direct societal impact and to its association with climate change. Great efforts have been undertaken to better understand the mechanisms driving this variability, and numerous works highlight the complexity of the response both over temporal and geographical scales (Church et al., 2008). The global estimated rate of sea-level rise for 1993–2009 is 3.2 $\pm$ 0.4 mm year^{-1} using satellite data and 2.8 $\pm$ 0.8 mm year^{-1} using tide gauge data (Church and White, 2011). This rate is near to the upper end of the sea level projections of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 2014). Even though satellite altimetry has proven to be a very powerful technique for deriving a global overview of variability, it only provides a picture since the start of satellite altimetry records in 1993, and is only valid for the open ocean. Accurate information about sea level variations in coastal regions and over longer periods is therefore of critical importance.

Among coastal zones, reef islands are widely acknowledged to be highly vulnerable to climate change, in particular to sea level rise (Woodroffe, 2008; Nurse et al., 2014), and to extreme climate events, such as tropical and non-tropical cyclones (Baines and McLean, 1976; Hoeke et al., 2013) and El Nino Southern Oscillation (ENSO) (Rankey, 2011), the frequency and intensity of which might be affected by climate change. Sea level rise is often perceived as casting doubt on their future habitability (Barnett and Adger, 2003; Mimura et al., 2007). In addition to hazards directly related to sea-level, the high vulnerability of these low-lying islands to climate change is augmented by other factors such as

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the high sensitivity of corals to climate stressors (Hoegh-Guldberg et al., 2007), the instability of the sediments composing them (Woodroffe, 2008; McLean and Kench, 2015) and the high exposure of underground freshwater lenses to saline intrusion (White et al., 2007).

Beyond the general statement that reef islands are threatened by climate change, it is widely recognized that the impact of climate change on reef islands is under-researched and that future research efforts should focus, first, on measuring environmental changes, especially shoreline changes, at the scale of specific islands and, second, on attributing observed changes to specific factors, either climate-related or anthropogenic. Up to now, most studies have focused on inhabited islands where anthropogenic disturbances mask the climate change signal (Nurse et al., 2014). This is especially true for reef islands: until recently, most studies dealt either with atoll capitals that are considered to be at high risk because they concentrate human assets (Yamano et al., 2007; Webb and Kench, 2010; Ford, 2012; Duvat et al., 2013), or with rural islands where human disturbances, although more limited and localized, have been shown to contribute to shoreline changes (Rankey, 2011; Ford, 2012; Hamylton and East, 2012). Although measuring and understanding ongoing environmental changes in these urban and rural settings is a key priority for the next decades, it is important in parallel to isolate the climate change signal by investigating uninhabited reef islands with natural shorelines.

Investigating uninhabited reef islands is especially important for better understanding the impact of sea level rise on island area and elevation. One of the key questions regarding the future habitability of these low-lying islands is their capacity to morphologically adjust to rising sea levels through vertical and horizontal accretion (Woodroffe et al., 1999; Woodroffe, 2008). This question remains highly controversial, as highlighted by recent papers (Pala, 2014; Hubbard et al., 2014).

In this context, baseline environmental studies in the remote French Scattered Islands - from north to south the Glorieuses Islands, Tromelin Island, Juan de Nova Island and Europa Island (see Fig. 1) - should help to understand the impacts of climate change, and more particularly sea level rise, on the physical characteristics of natural reef islands[1] (i.e., island area and island planform characteristics). First, the Scattered Islands provide information on the impacts of climate change in one of the least investigated regions of the tropical zone, the southwestern Indian Ocean. Second, the distribution of these islands from 11 to 22°S might allow the differentiation between contributions of various climate-related drivers of environmental changes, i.e., extra-tropical and tropical cyclones (the influence of which decreases northward), ENSO and climate change induced sea level rise.

The geodynamic context of the Scattered Islands region is complex and the exact number and limits of the active tectonic units is still debated. The kinematics of the region are mainly controlled by the East African Rift, which divides the African continent into two main tectonic plates: Nubia and Somalia, which encompass other smaller blocks, such as Victoria and Rovuma (e.g., Fernandes et al., 2013). The eastern segment of the East African Rift is considered to continue into the Indian Ocean along the Davie Ridge, south of the Kenya coast. The Davie Ridge is a major submeridian fracture zone that is considered to be the tectonic boundary between the Rovuma block and the Somalia plate. Some authors postulate the existence of a third tectonic block (Lwandle), between Mozambique Channel and a diffuse area in Madagascar, to better fit indirect observations (Stamps et al., 2008). In this case, the Glorieuses Islands and Juan de Nova Island would be on the Somalian tectonic block whereas Europa Island would be on Rovuma/Nubia blocks. The existence of the Lwandle block is not completely accepted and, in any case, tectonic vertical displacements on the Eparses Islands are expected to be almost negligible because they are far from highly active plate boundaries. Observed vertical motions should therefore mainly be caused by local processes.

The sea level in the Scattered Islands is clearly under-observed compared to others islands of the region, where permanent tide gauges have been installed for twenty years or more (La Réunion, Mayotte, Madagascar). Madagascar also benefits from a large amount of historical sea level observations. Very few historical sea level observations were found for the Scattered Islands. The only in situ sea level observations found for Europa and Juan de Nova islands date from the mid-1950 (Poujol, 1957) and consist of a few days of tide staff readings during a SHOM[2] field trip to infer the tidal regime. The first detailed geomorphological studies of the Scattered Islands are also very recent, coming from TAAF[3] scientific expeditions, both specifically on Tromelin Island in 2008 and 2009 (Marriner et al., 2012) and on the whole archipelago as part of the Scattered Islands Expedition of 2009.[4] Before then, knowledge of the morphology of these islands was very limited, mainly consisting of brief and imprecise descriptions made by coastal geomorphologists and marine ecologists who visited the islands in the 1960s and 1970s (Battistini, 1965, 1966; Stoddart, 1967; Berthois and Battistini, 1969; Battistini and Cremers, 1972). The only published detailed geomorphological studies are for Tromelin Island (Marriner et al., 2010, 2012) and Glorieuses Island (Guillaume et al., 2013).

This paper provides baseline data on sea level and shoreline changes based on recent measurements and formulates first hypotheses on the potential future impact of sea level rise on island persistence and morphology. The key questions addressed here are: (1) To which extent is sea level rising in the Glorieuses islands area of the Scattered Islands, and what are the respective contributions of vertical motion and climate-induced sea level rise? (2) Is Grande Glorieuse Island mainly undergoing erosion, stability or accretion? (3) What are the key factors controlling shoreline changes on this island and, among them, what is the role of sea level rise?

2. Materials and methods

2.1. Sea level observations

During the 2009 Scattered Islands Expedition, two bottom pressure gauges (RBR Ltd) were successively installed at Europa (40.339667°N, 22.340583°S) and Juan de Nova (42.741667°E, 17.040733°S) on the coral reef at about 15 m depth (Calzas, 2009), in order to estimate the sea level variation. These two islands are of interest for sea level studies; firstly because they are located in the middle of the Mozambique channel, which is known for its high spatial and temporal sea level variability mainly due to the transit of numerous eddies (Schouten et al., 2003); and secondly, because these two sites are directly under the tracks of satellite altimetry missions (namely, SARAL/AltikA and Jason-2). The idea behind the project was to study the possibility of installing a permanent tide

[1] Since the 1950s, the Scattered Islands have been equipped with weather stations. Since the 1970s, they also serve as military bases and labelled as nature reserves. As a result, they only host a limited number of people and exhibit limited human modification and have non-modified shorelines.

[2] Service Hydrographique et Océanographique de la Marine.

[3] Terres Australes et Antarctiques Françaises (www.taaf.fr).

[4] Two authors of this paper participated to this expedition that took place from April 18th to May 13th 2009.