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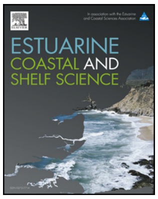

Holocene mangrove dynamics and relative sea-level changes along the Tanzanian coast, East Africa

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ABSTRACT

There is continued uncertainty regarding the rate, timing, duration and direction of Holocene sea-level for the Indian Ocean, and indeed the wider tropical realm. We present the first synthesis, and a new chronology, for Holocene relative sea-level (RSL) using a range sediment cores retrieved from mangrove ecosystems in three locations along coastal Tanzania. This study applies the relationship of ratios between the key mangrove taxa of *Sonneratia*:(*Bruguiera*/*Ceriops*) (S/BC) (ranging from 0 to 22.9) and *Sonneratia*:*Rhizophora* (S/R) (ranging from 0 to 2.29), vegetation and altitude to interpret mangrove dynamics and refine the vertical errors associated with relative sea level change. The variations in mangrove taxa ratios in the sediment cores obtained from each site shows mangrove development at different periods during the Holocene from around 7900 cal yr BP. An early to mid-Holocene RSL rise occurred from ~7900 to ~4600 cal yr BP that may have reached a higher level than present. A lower RSL occurred after 4600 cal yr BP, resulting in mangroves retreating seaward at all three study locations, before a low magnitude RSL rise occurred between 4400 and 2000 cal yr BP. Another RSL rise is recorded at ~500 cal yr BP before falling to a level lower than present at ~100 cal yr BP. There is evidence of a recent RSL rise recorded from mangrove ratios during the last century. In addition, the sedimentation rates among sites are relatively different due to different altitudinal ranges with freshwater input, sediment supply and progradation having significantly more effect in the Rufiji Delta (2.1–10.9 mm cal yr^{-1}) than at the Zanzibar sites (0.3–6.6 mm cal yr^{-1}).

1. Introduction

Relative sea-level (RSL) (the height of the ocean with respect to the surface of the solid Earth) has fluctuated over time that has resulted in geophysical and ecological changes (Pirazzoli, 1991). Far-field sites, located at a distance from the major ice sheets, are important locations for reconstructing RSL changes. Far-field locations can provide important constraints on global RSL change when combined with more intensively studied temperate areas, where coastal adjustments following removal of ice loading are most acute, especially during the mid and late Holocene (Milne and Mitrovica, 2008).

Holocene RSL changes in far-field locations result from eustatic changes, equatorial syphoning and hydro-isostasy (continental levering) (Mitrovica and Milne, 2002; Milne and Mitrovica, 2008). Equatorial ocean syphoning results from collapsing forebulges at the near-field continental margins that cause RSL fall to be recorded in far-field locations (Mitrovica and Peltier, 1991). Continental levering occurs when there is water loading due to deglaciation, that causes continental subsidence and an uplift of the adjacent continents, inducing RSL fall at areas distant from the continental margins (Lambeck and Nakada, 1990; Mitrovica and Milne, 2002; Gehrels and Long, 2008). RSL records from far-field locations have been produced from various locations including the Indian Ocean (Katupotha and Fujiwara, 1988; Banjeree, 2000), Southeast Asia (Hanebuth et al., 2000; Horton et al., 2005; Bird et al., 2007) and Australia (Lambeck and Nakada, 1990; Larcombe et al., 1995; Lewis et al., 2013). Holocene RSL changes have been reconstructed from Australia using a range of coastal and coral reef proxies; some studies suggest a highstand at ~6000 cal yr BP (Lambeck and Nakada, 1990; Larcombe et al., 1995), whereas others indicate a later highstand around 3900 cal yr BP (Baker et al., 2001). A review of geo-chronological data from along the southeast coast of Australia, indicates a highstand from 7700 cal yr BP that lasted until about 2000 cal yr BP, before falling to the present-day level (Sloss et al., 2007). In the northern Indian Ocean, two mid-late Holocene

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highstands, one at 7300 cal yr BP and another at 4300 cal yr BP, have been recorded from beach ridges and coral terraces along the east coast of India (Banerjee, 2000). These highstands were also recorded from corals and marine shells along the southwest and south coasts of Sri Lanka (Katupotha and Fujiwara, 1988) occurring at 6500 cal yr BP and 3200 cal yr BP.

Clearly far-field RSL records are of immense value for understanding and constraining sea level records but there is a range of timings and duration of these. In this paper we present evidence of RSL changes derived from three mangrove sediment records (Punwong et al., 2012, 2013a; 2013b) from sites on the Tanzanian coast. Combined, these data provide the first sea-level curve and a refined chronology for Holocene RSL and coastal changes for Tanzania. This study also uses the relationship between ratios of key mangrove taxa, vegetation and altitude to interpret mangrove dynamics and refine the vertical errors of RSL change. Holocene RSL changes are integrated with existing RSL reconstructions from the region to develop a reconstruction of Holocene RSL changes across the Southwest Indian Ocean.

1.1. *Sea-level history in the southwest Indian Ocean*

The record of Holocene RSL change along the East African coast, situated in the tectonically stable (Woodroffe and Horton, 2005) Southwest Indian Ocean, is poorly constrained (Pirazzoli, 1991; Camoin et al., 2004). Reconstructed RSL changes are available from only a few locations and use a range of different proxies (Fig. 1a). Previous studies of RSL change on the continental coasts of east and southeast Africa (Mozambique and South Africa) indicate that RSL rose rapidly during the early Holocene and reached the present level by the mid Holocene (Jaritz et al., 1977; Ramsay, 1995; Ramsay and Cooper, 2002; Norström et al., 2012). Mid Holocene highstands of up to 3.5 m above the present level were recorded by 5000 cal yr BP, followed by subsequent falls to the present level in the late Holocene. A different RSL reconstruction derived from coral from the offshore islands (Mauritius, Mayotte and Réunion Island) shows that a rapid RSL rise occurred during the early Holocene reaching present level at ~3000 cal yr BP with no evidence for a mid Holocene highstand (Camoin et al., 1997, 2004; Colonna et al., 1997; Zinke et al., 2003). Although all RSL studies within this region record an early Holocene RSL rise, there is considerable uncertainty on the amplitude and timing of this. The varied environmental settings and distances from formerly glaciated areas would result in different isostatic contributions to RSL changes. For example, it is thought that small offshore volcanic islands are less affected by hydro-isostatic adjustment than those studies from continental locations due to the effects of continental levering during the mid and late Holocene (Camoin et al., 2004; Lambeck and Nakada, 1990; Mitrovica and Milne, 2002; Milne and Mitrovica, 2008). The different proxies used make it likely that the sea-level index points may not be comparable and some sea-level index points may have large indicative ranges and different degrees of precision (Jaritz et al., 1977; Ramsay, 1995; Ramsay and Cooper, 2002; Woodroffe and Horton, 2005; Norström et al., 2012).

1.2. *Mangrove as sea-level indicators*

Research on RSL reconstruction from far-field locations has traditionally focused on coring and dating corals (Pirazzoli et al., 1988; Fairbanks, 1989; Colonna et al., 1997; Camoin et al., 1997, 2004). However, sediments that accumulate within mangrove ecosystems can also be used to reconstruct RSL and coastal changes. Mangrove ecosystems are found in coastal tropical regions along the margins of the sea and lagoons; they are characterised by evergreen trees and shrubs that are physiologically and morphologically adapted to grow in the sub-tropical to tropical intertidal zone between mean sea level and the high water of spring tide (Woodroffe and Grindrod, 1991; Blasco et al., 1996; Ellison and Farnsworth, 2001; Ellison, 2008). Mangrove ecosystems respond to changes in sea level by migrating landwards with a rise in sea level or seawards with a fall (Gilman et al., 2008). Mangrove community composition is able to keep pace with sea-level changes (McIvor et al., 2013). For mangroves to be able to withstand sea level rise, the rates of sedimentary accretion within the mangrove has to be equivalent to the rate of sea-level rise (Ellison, 2015), otherwise mangroves may undergo *in situ* drowning leading to weakened root structures, dieback and disappearance (Gilman et al., 2008).

Santisuk (1983) and Watson (1928) classified mangroves into a series of inundation class zones according to ecological preference to monthly inundation frequency. *Rhizophora mucronata*, *Avicennia marina*, *Sonneratia alba*, *Bruguiera gymnorrhiza* and *Ceriops tegal* are classified as true mangroves or mangroves. The term true mangroves are also defined as mangroves representing trees and shrubs growing in the areas inundated by the normal to all high tides. Back mangroves such as *Heritiera littoralis* and *Acrostichum aureum* are plants growing in the areas inundated by the sea only during spring high tides, exceptional high tides, or during cyclones. The dominance of mangrove species which occurs in zones throughout the mangrove ecosystem can thus be an indicator of sea-level fluctuations by comparing the relationships between contemporary vegetation assemblages and their inundation frequency with respect to sea level.

Mangrove pollen has previously been used to reconstruct compositional changes in mangrove ecosystems (e.g. Cohen et al., 2005; Horton et al., 2005; Vedel et al., 2006; Tossou et al., 2008; Hait and Behling, 2009) including in East Africa (Punwong et al., 2012, 2013a; 2013b). Engelhart et al. (2007) developed a transfer function from a modern analogue of mangrove surface pollen assemblages that has been used to predict the palaeo mangrove elevation with precision of ± 0.22 m. A contemporary study into the relationships between mangrove pollen in surface sediment samples and the composition of the vegetation indicated that majority of pollen was local in origin reflecting vegetation in close proximity to the sampling sites (Punwong et al., 2013a, 2013b). Pollen accumulated in sediments underlying mangroves, in combination with an understanding of the present relationship of mangrove composition to the altitude of present sea level, can be used to reconstruct RSL fluctuations (Ellison, 1989, 2005; 2008; Punwong et al., 2012, 2013a; 2013b).

2. Study sites

2.1. *Geology and geomorphology*

The three sites investigated are all characterised by mangrove forest and located in the northern Rufiji Delta (Tanzanian mainland), Makoba Bay and Unguja Ukuu (Unguja island, Zanzibar) (Fig. 1b–h). The Rufiji Delta consists of mangrove forest that grades into paddy fields at higher elevations and supports the largest expanse of estuarine mangrove along the East African coast (Nshubemuki, 1993; Fisher et al., 1994; Richmond et al., 2002; Masalu, 2003; Mangora et al., 2016). The deltaic area is covered by fluvial sand, silt and clay (Semesi, 1992) (Fig. 1c). A series of sand spit islands and submerged sand bars have formed parallel to the seaward margins (Fisher et al., 1994), while clayey silts and silty clays containing organic matter characterise the mangrove sediments. The average tidal range is 2–2.5 m and approximately 3.3–4.3 m on high spring tides (Francis, 1992; Fisher et al., 1994; Richmond et al., 2002).

Unguja Island (Zanzibar) is located on the continental shelf some 40 km from the mainland. The island has been periodically part of the mainland when sea level was 30–40 m below present sea level and the last separation from the mainland by sea-level inundation of the Zanzibar channel occurred at the end of the Pleistocene to early Holocene (Prendergast et al., 2016). Most of Unguja consists of Pleistocene reef limestone often outcropping on the east coast (Shunula, 2002) with alluvial deposits locally present (Schlüter, 1997; Arthurton et al., 1999) although there are no large rivers (Shunula, 2002). It is influenced by a semi-diurnal tide, ranging from 2 m on neap tide to 4 m