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Invited review

Drivers of Holocene sea-level change in the Caribbean

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ABSTRACT

We present a Holocene relative sea-level (RSL) database for the Caribbean region (5°N to 25°N and 55°W to 90°W) that consists of 499 sea-level index points and 238 limiting dates. The database was compiled from multiple sea-level indicators (mangrove peat, microbial mats, beach rock and acroporid and massive corals). We subdivided the database into 20 regions to investigate the influence of tectonics and glacial isostatic adjustment on RSL. We account for the local-scale processes of sediment compaction and tidal range change using the stratigraphic position (overburden thickness) of index points and paleotidal modeling, respectively. We use a spatio-temporal empirical hierarchical model to estimate RSL position and its rates of change in the Caribbean over 1-ka time slices. Because of meltwater input, the rates of RSL change were highest during the early Holocene, with a maximum of 10.9 ± 0.6 m/ka in Suriname and Guyana and minimum of 7.4 ± 0.7 m/ka in south Florida from 12 to 8 ka. Following complete deglaciation of the Laurentide Ice Sheet (LIS) by ~7 ka, mid-to late-Holocene rates slowed to < 2.4 ± 0.4 m/ka. The hierarchical model constrains the spatial extent of the mid-Holocene highstand. RSL did not exceed the present height during the Holocene, except on the northern coast of South America, where in Suriname and Guyana, RSL attained a height higher than present by 6.6 ka (82% probability). The highstand reached a maximum elevation of +1.0 ± 1.1 m between 5.3 and 5.2 ka. Regions with a highstand were located furthest away from the former LIS, where the effects from ocean syphoning and hydro-isostasy outweigh the influence of subsidence from forebulge collapse.

1. Introduction

Changes in relative sea level (RSL, the height of the ocean surface relative to the land surface or ocean floor) in the Caribbean during the Holocene are driven by eustatic, glacial isostatic adjustment (GIA), tectonic and local factors that act over a variety of spatial and temporal scales (Peltier, 1998; Milne et al., 2009).

Eustatic sea-level (ESL) change (i.e., sea-level equivalent or ocean volume change) in the Holocene is dominated by Northern Hemisphere deglaciation (Lambeck et al., 2014), with varying rates of RSL rise suggested from GIA modeling. At the start of the Holocene ~11.7 ka, ESL was ~60 m below present and rose at rate of ~15 m/ka from ~11.4 to 8.2 ka (Lambeck et al., 2014). The rate of ESL

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rise decreased from ~8 to 7 ka, consistent with the final phase of Laurentide Ice Sheet (LIS) deglaciation at ~7 ka, followed by a progressive decrease in the rate of rise from 7 ka to present (Peltier, 2004; Lambeck et al., 2014; Peltier et al., 2015; Bradley et al., 2016).

As the rate of ESL rise decreased in the Holocene, processes associated with GIA dominated the temporal and spatial pattern of RSL change (Milne et al., 2005; Milne and Peros, 2013). The magnitude of subsidence associated with the collapsing LIS forebulge diminishes with distance from the regions of peak forebulge collapse near the former LIS margin; therefore, in the Caribbean, located >2000 km away from the LIS margin, the magnitude of this signal lessens and signals from ocean syphoning, hydro-isostatic loading and perturbations to Earth's rotation vector become dominant and may create a higher than present RSL, i.e., a mid-Holocene highstand (Peltier et al., 1978; Pirazzoli, 1991; Mitrovica and Peltier, 1991; Peltier, 1998; Milne and Mitrovica, 1998; Mitrovica and Milne, 2002; Milne et al., 2005). However, the spatial extent of forebulge subsidence and emergence of mid-Holocene highstands on Caribbean continental margins is not well documented, in part because of its active tectonic setting.

The complex tectonic setting of the Caribbean region also influences RSL. The Caribbean plate interacts with the North American, South American, Nazca and Cocos plates, each characterized by a diversity of tectonic regimes (Benz et al., 2010). Inclined zones of deep earthquakes (Wadati-Benioff zones), deep ocean trenches, and volcanic arcs indicate subduction of oceanic lithosphere along the Central American and Atlantic Ocean margins of the Caribbean plate (Dixon et al., 1998; DeMets et al., 2000; Benz et al., 2010). Shallow seismicity and focal mechanisms of major shocks in Guatemala, northern Venezuela and the Cayman Ridge/Trench indicate transform fault and pull-apart basin tectonics (Weber et al., 2001; Benz et al., 2010). Furthermore, lateral variations in mantle viscoelastic structure from a high-viscosity slab associated with subduction of the South American Plate beneath the Caribbean Plate have been shown to suppress local GIA deformation and decrease RSL rise predicted during deglaciation (Austermann et al., 2013). The combined effect of tectonic processes on regional Holocene RSL histories in the Caribbean, however, is unknown.

Local factors, such as changes in tidal range and sediment consolidation, affect RSL records. Temporal variations in tides occur on a global scale because of glaciation-driven changes in the availability of dissipation sites of tidal energy (e.g., Uehara et al., 2006; Griffiths and Peltier, 2008, 2009; Hill et al., 2011). These changes influence RSL reconstructions because no sea-level indicators form precisely at mean sea level (Horton et al., 2013). Sediment consolidation due to compaction of pre-Holocene strata (e.g., Horton and Shennan, 2009) and the accumulation of overlying Holocene material and land drainage (e.g., Kaye and Barghoorn, 1964; Törnqvist et al., 2008) also cause RSL reconstructions to deviate from true values.

Here, we compile a Caribbean sea-level database to provide a framework for developing our understanding of the primary mechanisms of RSL change during the Holocene. The database consists of 737 sea-level index points and limiting dates that span the period from 12 ka to present (Fig. 1). We define the indicative meanings and ages of multiple sea-level indicators including mangrove peat, microbial mats, beach rock, and corals. We account for local effects by using the stratigraphic position (overburden thickness) of index points to adjust samples for sediment compaction where appropriate (Shennan et al., 2000b; Törnqvist et al., 2008; Horton and Shennan, 2009) and provide an additional error for changes in tidal range over the Holocene using a paleotidal model (Hill et al., 2011; Hall et al., 2013; Horton et al., 2013). We consider the influence of GIA and tectonics on local RSL histories and employ a spatio-temporal statistical model to examine patterns and rates of RSL change (and their associated uncertainty) and constrain the magnitude and spatial extent of the mid-Holocene highstand in the Caribbean.

2. Methodology to reconstruct relative sea level

The standardized methodology developed by the International Geological Correlation Projects (IGCP) 61, 200, 495 and 588 (e.g., Preuss, 1979; van de Plassche, 1982; Gehrels and Long, 2007; Hijma et al., 2015) was followed to determine RSL, age, and associated errors of sea-level index points. To calculate past RSL, each sample's indicative meaning (Shennan, 1986; van de Plassche, 1986; Horton et al., 2000) must be known. The sample ages within the database were measured using ^{14}C and U–Th dating. The ^{14}C data were calibrated to years before present (where present is 1950 AD) using the most recent IntCal13 and Marine13 calibration curves (Reimer, 2013).

2.1. Indicative meaning of sea-level indicators

The indicative meaning is defined as the relationship of an indicator to sea level (van de Plassche, 1986) and has two components: the reference water level, which defines the relationship of the indicator to a contemporaneous tide level (e.g., mean higher high water [MHHW]) and the indicative range, which is the elevational range occupied by the sea-level indicator (Fig. 2). When litho-, bio-, or chemostratigraphic data indicate deposition in terrestrial or marine environments, these data provide an upper or lower limit on the position of RSL respectively and are classified as limiting dates (Shennan and Horton, 2002).

2.1.1. Mangrove and sedimentary indicators

Mangrove peats comprise most ($n = 313$) of the index points in the database. The vertical distribution and characteristics of mangrove species (e.g., *Rhizophora mangle, Avicennia germinans* and *Laguncularia racemosa*) are related to the frequency and duration of tidal inundation (Tomlinson, 1986; Smith, 1992; Mendelssohn and McKee, 2000). In the Caribbean, growth of peat-forming mangroves is constrained to the upper half of the intertidal zone (e.g., Davis, 1940; Thom, 1967; Twilley et al., 1996; Dawes, 1998; Davis and Fitzgerald, 2003; Lara and Cohen, 2006). Therefore, we define the indicative meaning of mangrove peat to be mean tide level (MTL) to highest astronomical tide (HAT) (Table 1). We use microfossils (e.g., Ramcharan and McAndrews, 2006; Jessen et al., 2008), δ^{13}C values (e.g., Klosowska, 2003; McKee et al., 2007) and plant macrofossils (e.g., Wooller et al., 2003; Monacci et al., 2009) to support the accumulation of peat in a mangrove environment.

Microbial mats from hypersaline lagoons comprise a small ($n = 5$) portion of index points in the database (Knowles, 2008). Microbial mats are predominantly formed from cyanobacteria living on bedding surfaces that aggrade vertically by cellular growth and by binding detrital particles (Gerdes and Krumbein, 1994; Gerdes, 2010). Following Livsey and Simms (2013), who surveyed the elevation of modern microbial mats from the Gulf of Mexico, we assign an indicative meaning of mean lower low water (MLLW) to MHHW.

A small number of index points ($n = 5$) were obtained from organic muds and peats from floodplain facies of the Orinoco Delta (Warne et al., 2002). Studies in the Mississippi River and Rhine-Meuse deltas suggest deposition between mean sea level (MSL) and mean high water (MHW) (van Dijk et al., 1991; van de Plassche, 1995; Cohen, 2003; Törnqvist et al., 2004). We take a conservative approach and assign these samples an indicative meaning of MTL to HAT.

Terrestrial limiting dates ($n = 35$) were derived from: (1) peat