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Contrasting responses of two Caribbean mangroves to sea-level rise in the Guajira Peninsula (Colombian Caribbean)

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ABSTRACT

Local geomorphology plays an important role in the response of mangrove communities to both sea-level rise and precipitation changes, mostly because it exerts an important control of the erosion–progradation balance. Here we present contrasting changes in the palynological records of two sediment cores retrieved from locations occupied by mangroves in the northeastern Caribbean coast of Colombia: Calancala and Navío Quebrado. Sediments were treated with standard procedures used in palynologycal analysis, and dated with AMS ^{14}C and ^{210}Pb. Age-depth models of both cores were constructed by linear interpolation between dated samples. The main modern differences between the studied sites are fresh water availability and sediment supply throughout the year. While Calancala, located at the Ranchería River Delta, has direct fresh water influence throughout the year, coastal lagoon Navío Quebrado is only sporadically influenced by fresh water sources. According to our findings, two main factors contributed to mangrove establishment in the Colombian Caribbean: i) high and accelerated sea-level rise around 6000 cal yr BP originating coastal lagoons that favored mangrove establishment, and ii) marine still stand and high precipitation around 3000 cal yr BP leading to a second wave of mangrove expansion. A drought between about 2850 and 2450 cal yr BP and the strengthening of easterly trade winds caused a change from *Rhizophora*-dominated to *Avicennia*-dominated stands. Increased precipitation after 2500 cal yr BP and subsequent increase of fluvial sediment input promoted recovery of *Rhizophora*-dominated mangroves. Sea-level rise during the last 150 yr has caused landward mangrove expansions in deltas and progradation of coastal environments. However, the general pattern shows a net loss of mangrove vegetation as the result of coastal erosion.

1. Introduction

Mangroves are ecosystems distributed along tropical and subtropical coasts worldwide (Giri et al., 2011). They are typically composed of plants physiologically and morphologically adapted to living in the intertidal zone, which is periodically inundated by brackish water. Mangrove communities develop in a diverse range of sedimentary environments, ranging from highly depositional alluvial habitats to oceanic islands with little or no permanent contribution of allochtonous sediments. Their establishment and growth are determined by many factors, the most important being high air temperatures, tidal and fresh water flooding, salinity, geomorphological setting, soil type, nutrient and light availability, and carbon dioxide (CO_2) concentrations (Krauss et al., 2008). Vegetation structure and composition of mangroves result from the differential response of both mangrove and associated species to the environmental setting, although regional and local flora diversity as well as disturbance regimes may also play important roles (Lugo and Snedaker, 1974; Urrego et al., 2009a).

Given their ubiquity mediated by particular environmental conditions, mangroves are sensitive to environmental changes. Modern relationships between mangrove species and the environment are assumed to have operated similarly during the Quaternary, making possible the inference of past coastal environments through the analysis of fossil vegetation (Hooghiemstra et al., 2006; Ellison, 2008). Of special interest is the reconstruction of changes in sea-level and/or coastal progradation or erosion (Hooghiemstra et al., 2006; Ellison, 2008) at various time scales. In fact, because of the specialized distribution of particular mangrove species along environmental gradients, they can be used as proxies for specific ecological conditions at local scales (Tomlinson, 1995; Urrego et al., 2009a). In palynological reconstructions from the Caribbean, mangrove forests are typically represented by four true tree mangrove species which are usually found in the

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following order of relative importance: *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa* and *Conocarpus erectus* (Urrego et al., 2010). However, other non-arboreal species are also important colonizers at the beginning of the forest succession and/or indicators of degraded mangroves. Such is the case of *Batis maritima*, *Sesuvium portulacastrum* and the "mangrove fern" *Acrostichum aureum* (Tomlinson, 1995). Although associated species are usually poorly represented, they are important proxies for specific ecological features and successional stages.

High percentages of *Rhizophora* pollen in sediment samples usually indicate either the proximity of pure mangrove stands (Muller, 1959; Behling et al., 2001), or high flooding levels and shorter distances to the sea (Urrego et al., 2010). Conversely, low *Rhizophora* proportions indicate tidal or fluvial transport of pollen grains, and/or mangroves located at foothills close to the transition to hinterland or highly disturbed mangrove forests (Urrego et al., 2009a, 2010). Contrastingly, *Avicennia* pollen, though usually underrepresented in pollen records, typically reflects saline environments (Urrego et al., 2010), hurricane-disturbed mangroves or severe droughts and plagues (González et al., 2010). High percentages of *Laguncularia* and *Acrostichum* indicate disturbed open canopies and early successional stages following mangrove disturbance (Medina et al., 1990; Tomlinson, 1995). Also, the presence of herbaceous and salt marsh pollen species in the Caribbean usually indicate salinity gradients (González and Dupont, 2009a), early successional stages after disturbance (González et al., 2010), or marine transgressive events (González and Dupont, 2009a; Urrego et al., 2009b). A special feature in coastal plains is the sequence of Amaranthaceae (formerly Chenopodiaceae, *sensu* Stevens, 2001) – Poaceae – Cyperaceae, which indicates salt marsh expansion and sediment relocation under direct tidal influence usually followed by mangrove forest development (González and Dupont, 2009b).

Mangrove pollen records have provided indirect reconstructions of sea-level and/or coastal progradation–erosion balance (Hooghiemstra et al., 2006; Ellison, 2008), and today most of our knowledge on Holocene sea-level variability in the Caribbean derives from past vegetation reconstructions on coastal environments (e.g. Rull et al., 1999; Ramcharan, 2004). However, in some instances, the importance of factors such as physiographic settings and precipitation has overwhelmed sea-level change signals (Eslami-Andargoli et al., 2009), calling for a careful interpretation of mangrove pollen records. When comparing the existing evidence on mangrove dynamics in the Caribbean, the lack of synchronicity among mangrove establishment and sea-level changes during the Holocene is noteworthy, highlighting the importance of including local processes in the interpretation. Based on two new sedimentary records from the Colombian Caribbean, we reconstruct mangrove dynamics in the study area from the mid-Holocene to present. Also, we address two basic questions: i) what was the relationship between mangrove dynamics and sea-level changes? and ii) were the changes in mangrove communities from the Colombian Caribbean the result of regional (Caribbean-wide) scale processes?

2. Study area

Calancala (11° 34′30″ N, 72° 52′36″W) and Navío Quebrado (11° 24′ 39″ N, 73°06′00″ W) are both located 1 m asl, in the Colombian Caribbean coast, which is a 1760-km-long coast line that extends from the Gulf of Urabá to the Gulf of Venezuela, the northernmost part of South America. Warm climates predominate in the area with a marked precipitation gradient that goes from wet to arid conditions in the southwestern Caribbean and the Guajira Peninsula, respectively (Fig. 1). Mean annual temperature in La Guajira area is 27 °C with annual extremes of 15 and 38 °C (Sánchez-Páez et al., 1997). As in most of northern South America, the Intertropical Convergence Zone (ITCZ) modulates the bimodal distribution of precipitation and consequently the fluvial sediment supply to the study locations. Mean annual precipitation is 550 mm (HIMAT, 1994), with dry periods between December and April, and July and August. The Caribbean Low Level Jet blows parallel to the Guajira coast, inducing coastal upwelling (Andrade and Barton, 2005) and diverting rainfall from the sea.

With a 4296-km^2 basin, the Ranchería River flows northwestward down the Sierra Nevada de Santa Marta (ca. 3000 m asl) and reaches the coastal plain near the city of Riohacha, where the Calancala study site is located. Downslope (between 100 and 250 m asl), the Ranchería River valley has a predominant southwestern-northeastern orientation. The study site is dominated by alluvial sediments that are underlain by Neogene folded sediments with some local input of aeolian sediments. The valley is enclosed by foothills and a mountainous landscape. The coastal sedimentary plain is slightly undulated and is mainly fed by alluvial sediments from the Cesar and Ranchería rivers, and additional influence of marine and aeolian sediments. An estuary is formed by the river mouth during the rainy season and remains closed during the rest of the year (IGAC, 2009). The second study site, Navío Quebrado lagoon, is located 22 km south of Riohacha and is isolated from the Caribbean Sea by sand spits. It was formed by the abrasive action of waves, and refilled by alluvial sediments. Several intermittent creeks that form deltas during the rainy season feed the lagoon (Fig. 1). High coastal erosion is driven by wave action and east-northeasterly winds that hit the coast (Raasveldt and Tomic, 1958).

Mangrove forests in the region are under severe stress, mainly exerted by low precipitation, non-permanent input of freshwater, and increased high sediment input when trade winds intensify. Additionally, forest regeneration is threatened by human occupation through cattle feeding upon mangrove propagules (Lema et al., 2003), timber exploitation (Guerrero et al., 2005), extraction of products for subsistence of fishermen, and pollution from urban sewage and solid waste. While *R. mangle* proliferates on the edge of the channels and the river mouths, mangrove communities found along the coasts are dominated by *A. germinans*, with scattered *L. racemosa* trees (IGAC, 2009). In open areas the fern *A. aureum* is commonly found. Some *C. erectus* shrubs appear at the outer boundaries of the forest, with abundant patches of *B. maritima* and *S. portulacastrum* (Vásquez, 2000). In the seasonally flooded zone that surrounds the mangrove forests, *Eleocharis acutangula* (Cyperaceae) and *Leptochloa* cf. *uninervia* (Poaceae) are abundant. Sandy beaches are dominated by *Hibiscus tiliaceus, Hippomea mancinella* and the spiny shrub *Caesalpinia coriaria* (Sánchez-Páez et al., 1997) nevertheless many native species are not present today mostly because of human disturbance.

3. Methods

Two sediment cores were raised in the Guajira region (Fig. 1) using a Dachnovsky corer. A 375-cm-long core was retrieved from Calancala, a branch of the Ranchería River delta located near the city of Riohacha. A second 400-cm-long core was recovered from Navío Quebrado coastal lagoon, 22 km south east from Riohacha city. Sediment samples of 1 cc were taken every 5 cm and treated with standard procedures to recover palynomorphs that were subsequently analyzed using transmitted-light microscopy (Erdtman, 1960; Faegri and Iversen, 1989). We aimed at a pollen sum of 250 including all trees, herbaceous taxa from salt marshes, and the mangrove fern *A. aureum* (all other spores were counted but excluded from the pollen sum). Although it is unusual to include fern spores in the pollen sum, we did so in this case because *Acrostichum* is an important component of mangrove ecosystems and its occurrence and abundance are highly indicative of environmental conditions, ecological processes, and successional stages. Oxidizing conditions are common under extremely dry environments such as the site where our study was conducted, causing poor pollen preservation. Thus, pollen sums of some samples were lower than 200 grains and should be cautiously interpreted. In fact, pollen sums of only between 100 and 150 grains were reached for 19% and 5% of samples of Navio Quebrado and Calancala, respectively (Figs. 2 and 3). Pollen sums for 21% of samples of Navio