Tropical vegetation evidence for rapid sea level changes associated with Heinrich Events

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Tropical vegetation evidence for rapid sea level changes associated with Heinrich Events

Catalina González[1,2], Lydie M. Dupont[1]

[1]MARUM - Centre for Marine Environmental Sciences, University of Bremen, Leobener Strasse, D-28359 Germany

[2]Geosciences Department, University of Bremen, Klagenfurter Strasse, D-28359 Bremen, Germany

E-mail: catalina@uni-bremen.de; dupont@uni-bremen.de

Abstract. A Cariaco Basin pollen record shows the development of tropical salt marshes during marine isotope stage 3. Rapid and abrupt expansions of salt marsh vegetation in tropical South America are associated with north Atlantic Heinrich Events stadials (HE-stadials). Intervals of salt marsh expansion have an internal structure, which consists of a recurrent alternation of species that starts with pollen increments of Chenopodiaceae, that are followed by increments of grasses, and subsequently by increments of Cyperaceae. This pattern suggests a successional process that is determined by the close relationship between sea-level and plant community dynamics. The salt tolerant Chenopodiaceae, indicate hypersaline intertidal environments, which were most likely promoted by extremely dry atmospheric conditions. Rapid sea-level rise characterizes the onset of HE-stadials, causing the continued recruitment of pioneer species, which are the only ones tolerating rapid rates of disturbance. Once sea-level rise decelerates, marsh plants are able to trap and stabilize sediments, favouring the establishment of more competitive species. These results add to the scarce knowledge on the dynamics of tropical salt marsh ecosystems, and provide independent paleoclimatic evidence on sea-level changes following Antarctic climate variability.

1. Introduction

The timing of sea level changes during marine isotope stage 3 (MIS 3; 60-25 ka) is a key issue in understanding the role of ice sheets in millennial-scale climate variability. The available reconstructions of sea level changes during this interval greatly rely on oxygen isotope records from deep-sea cores (since coral-based data are sparse and chronologies less precise), and consistently show four cycles of similar amplitude of sea level change in the order of 20-30 m [1, and references therein]. However, there is little agreement on the exact timing of these changes or on the relative roles of the Southern and Northern Hemisphere ice sheets in global sea level scenarios.

The ecological response of sensitive terrestrial ecosystems can provide independent information that complements the almost exclusively marine body of evidence of millennial sea level change. For this purpose, intertidal tropical ecosystems can be particularly useful, since they are very sensitive to environmental gradients in the sea-continent interface. In tidal salt marsh plant communities, species composition varies with elevation, usually in a banded pattern parallel to the shore. Its variation often reflects environmental gradients that result from the interaction between tidal regime, local

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topography, freshwater input, and biota. It has been proposed that the zonation is a spatial expression of successional changes over time and has potential to be reconstructed for the past by pollen analysis. If patterns of pollen deposition follow zonation and succession patterns, these can be reconstructed back in time by establishing a time-depth relationship with the fossil evidence, this then enables past sea level to be reconstructed. In this study, we present a palynological reconstruction from marine core MD03-2622, Cariaco Basin, in northernmost South America, that evidences the dynamics of intertidal plant communities during intervals associated with Heinrich Event stadials (HE-stadials), linking them to the well-constrained North Atlantic millennial- to sub-millennial climatic variability.

The Cariaco Basin is located on the northern shelf of Venezuela and is particularly sensitive to the seasonal shifts of the Intertropical Convergence Zone (ITCZ), which deeply influence the hydrology and oceanographic features of the basin. During MIS 3, the Cariaco Basin record displays a clear North Atlantic climatic variability, shifting from dry conditions during cold stadials to wet conditions and increased river runoff during warm interstadials. This hydrological pattern is reflected by variations in the input of terrestrial materials and has been explained by the latitudinal migration of the ITCZ [2, 3, 4]. The chronology used in this study was established by linking similar features of sediment reflectance profile of Cariaco site MD03-2622 with that of the nearby ODP Site 1002D, which has an extremely high-resolution age model for the past 60 ka based on more than 350 AMS ^{14}C data on planktic foraminifera [5, 6] (correlation coefficient between both chronologies is 0.74). Bigger uncertainties in the chronology arise before 40 ka, because of the differences between Hulu Cave chronology (used to tie Cariaco Basin chronology) and Greenland chronologies. Thus, the age model during the high resolution interval of this study is highly reliable.

2. Tropical salt marsh response to millennial climate and sea level changes

During glacial periods, when sea level was 80-120 m lower than today, a broad shallow shelf –the Unare platform- became exposed south of the Cariaco Basin. Periods of extremely dry atmospheric conditions might, therefore, have resulted in hypersaline coastal environments. These extreme conditions could have been tolerated only by a limited number of plant species. Chenopodiaceae, Poaceae and Cyperaceae belong to the most common representatives of salt tolerant plants in tropical and subtropical wetlands [7] (figure 1).

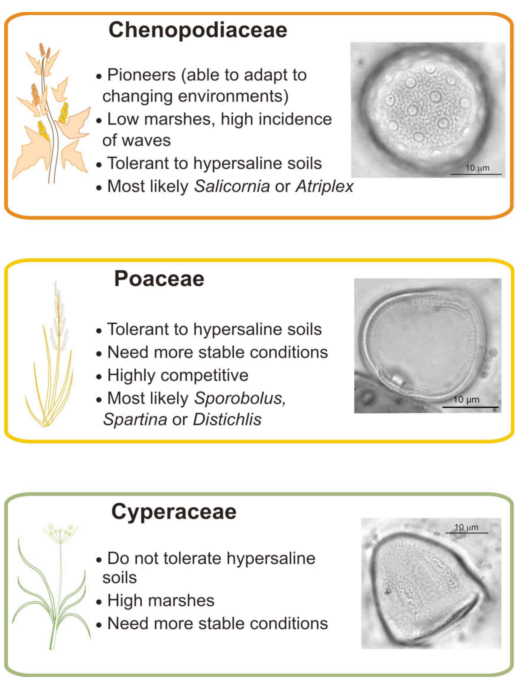

Figure 1. Ecological preferences of three salt marsh taxa.

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2.1. The pollen record

Five high-amplitude vegetation shifts were recorded in the pollen record during MIS 3 (60-25 ka), indicating rapid oscillations of environmental conditions in northernmost South America. Recurrent salt-tolerant vegetation expansions were shown to correlate with HE stadials 3-6. Within single HE-stadials, a recurrent and directional succession of pollen taxa was observed in the following order: abrupt increases in saltbush (Chenopodiaceae) followed by a dominance of grasses (Poaceae), which in turn were replaced by sedges (Cyperaceae) (figure 2 and 3). Once interstadial conditions returned, mangroves and other arboreal species replace the herbaceous taxa.

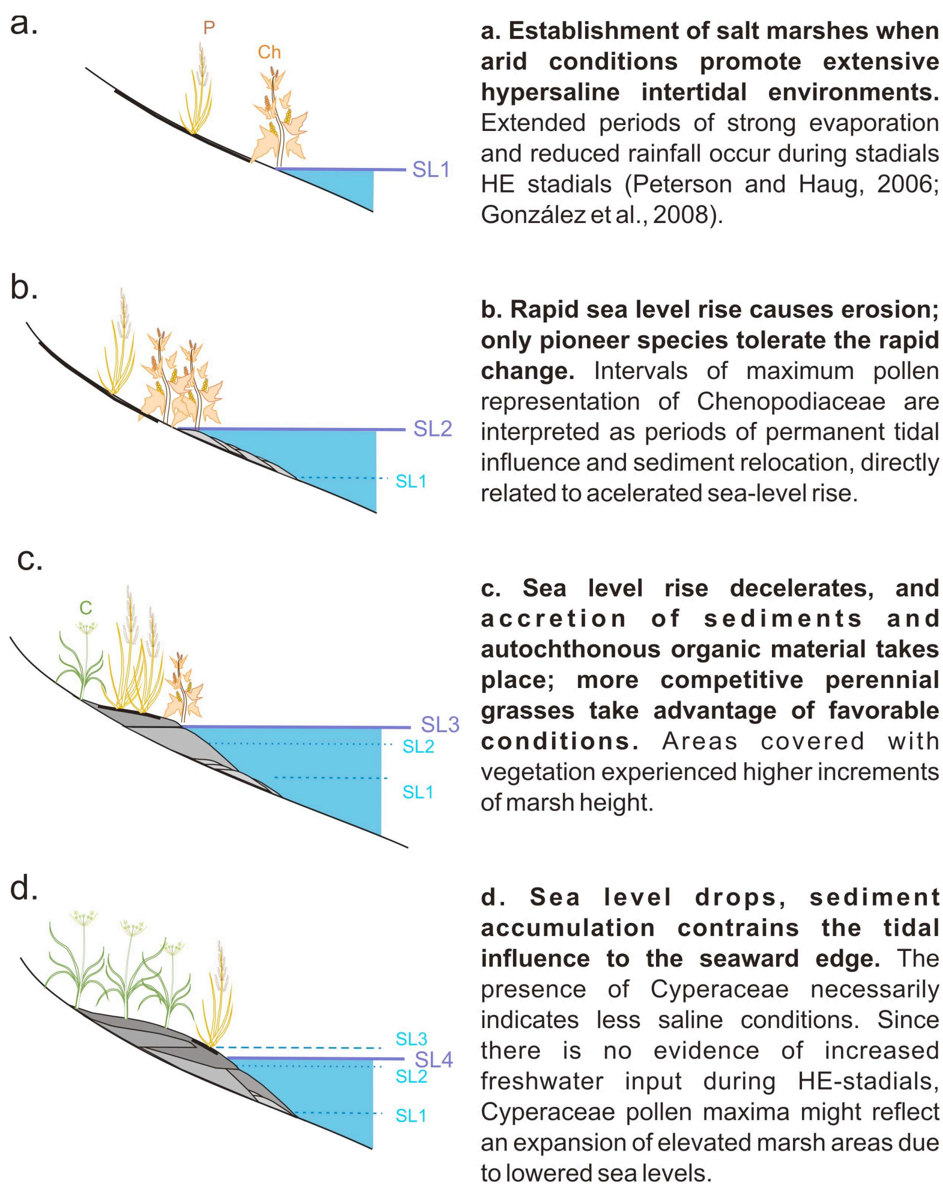

Figure 2. Schematic representation of salt marsh community dynamics in a changing sea level environment according to the Cariaco Basin pollen record [11]. Thicker black lines indicate areas of soil hypersalinity. SL 1 to SL4 denote different sea levels reconstructed from the pollen record and correspond with phases indicated in figure 3.

Even if Chenopodiaceae, Poaceae and Cyperaceae can occur in diverse environments, several lines of evidence suggest that the succession indicated in the MD03-2622 pollen record during HE-stadials represents the expansion of salt-marshes on coastal environments, and thus can be used as sea-level indicator. The morphology of the pollen grains, the current distribution of the genera in the neighboring area of Cariaco Basin, and perhaps most convincing, the coincidence of the mangrove tree *Rhizophora* (only occurs intertidally) all suggest a gradational pattern indicative of intertidal habitats.

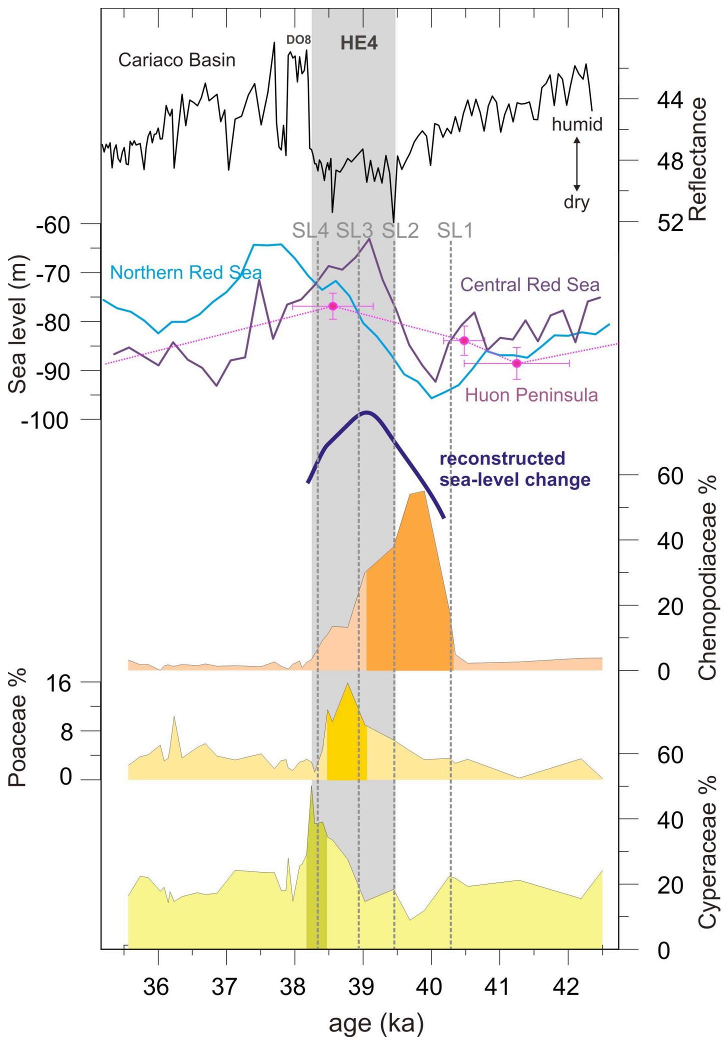

Figure 3. Comparison of the high-resolution palynological record from core MD03-2622 (Cariaco Basin) with sea level reconstructions from Red Sea marine sediment cores and Huon Peninsula (Papua New Guinea) fossil corals during HE-stadial 4 (González and Dupont, 2009). Top to bottom: Reflectance data from core MD03-2622 [18]. Sea level data; dark blue line - central Red Sea [1, 14], light blue line - northern Red Sea (Arz et al., 2007), and dotted pink line - Huon Peninsula [10]. Reconstructed direction of sea-level changes based on pollen reconstruction. Pollen relative abundance of Chenopodiaceae, Poaceae, and Cyperaceae [11] indicating the directional alternation of salt marsh species. Dotted gray lines SL1 to SL4 denote different sea levels reconstructed from the Cariaco Basin pollen record, which correspond to phases explained in figure 2.

In this sequence, salt marshes started to develop under extremely arid stadial conditions [3, 4] when intertidal habitats became hypersaline due to extended periods of strong evaporation and reduced rainfall. The salt marshes were most likely restricted to narrow intertidal areas because under strongly seasonal conditions they are usually fringed on the landward side by extensive bare salt pans (figure 2a, b; [7]). Early colonizing species of salt marshes, like the annual *Atriplex* and *Salicornia* (Chenopodiaceae), first colonize bare zones of lower and middle marsh areas, with a high incidence of waves and prolonged inundation regimes [8]. Thus, intervals of maximum pollen representation of Chenopodiaceae are interpreted as periods of direct tidal influence and sediment relocation. Frequent tidal flooding under accelerated sea level rise would result in flooding of the marsh surface, transforming it into a new seafloor, with the later landward accretion of new, low marsh sediments (figure 2b).

By comparing our high-resolution pollen data with sea level reconstructions from the Red Sea [1, 9 and references therein] and the independently dated fossil corals from the Huon Peninsula [10] for the period between 40.5-38 ka, we found that the phase dominated by Chenopodiaceae corresponds closely with an interval of accelerated sea level rise (figure 3). This confirms that only early successional plants, with high colonizing abilities (e.g., rapid growth, annuals or short-lived perennials) were capable of surviving the stressful high rates of change (figure 2a). Moreover, the erosion of low marsh sediments would wash out and transport the pollen produced in situ (figure 2b).

As soon as sea level rise decelerated (ca. 1 ka after the Chenopodiaceae peak), some vegetation was able to establish permanently. In low marsh areas, sediment accretion greatly depends on vegetation cover, which limits erosion, and enhances sediment and organic matter trapping. Thus, areas covered with vegetation experienced higher marsh heights. The build-up of middle and high marsh environments favoured the expansion of more competitive perennial grasses (Poaceae), thus replacing Chenopodiaceae pioneer species (figure 2c, d and 3). In contrast, the presence of Cyperaceae indicates less saline conditions, since sedges do not tolerate salinity excess. Thus, since there is no evidence of increased freshwater input during HE-stadials, Cyperaceae pollen maxima might reflect an expansion of elevated marsh areas (figure 2c, d).

Once interstadial conditions resumed and the average position of the ITCZ shifted northwards, the increased availability of freshwater might have alleviated salinity stress on soils, allowing a more complex plant community to develop on the shelf, and pushing the upper borders of the salt marsh seawards. Simultaneous increases in mangrove pollen [11] confirm that coastal environments became less saline and increasingly suitable for the establishment of forests during stadial-interstadial transitions. In addition to freshening, decelerated sea level rise (or sea level fall) would be required to allow the establishment of mangroves, since mangroves do not survive if sea level rise occurs too rapidly [12,13].

2.2. An alternative view of Chenopodiaceae?

Most of our interpretation of Cariaco pollen record in terms of sea-level change is based on the assumption that Chenopodiaceae peaks are indicating rapid sea-level rise episodes. However, due to the affinity of these plants for hypersaline soils, one could intuitively argue that, on the contrary, Chenopodiaceae indicate periods of decreasing sea-level and the corresponding expansion of suitable areas for colonization. In this respect, we should highlight first, that during dry periods, tropical salt marshes only occupy narrow intertidal areas in direct contact with seawater that are usually fringed on their landward side by extensive hypersaline vegetation-bare flats. As a result, with decreasing sea-levels, absolute size of bare areas would increase, but the integrated areas that are inundated by tides in fact decrease (for a bathymetry like that of Cariaco Basin where the perimeter of isobaths become smaller with increasing depth). Following the same reasoning, we estimated an increment of ~2200 km^2 of intertidal areas by the effect of rising sea-level from -90 to -60 m below sea-level (figure 4), that at a rate of 3 cm/yr [1] would imply an approximate gain of 2.3 km^2 of intertidal marsh surface area every year during ca. 1000 years.

Conversely, the counterargument that high percentages of Chenopodiaceae pollen are indicating lowering instead of rising sea levels might provide an alternative, valid explanation. By following the opposite logic, we would require an explanation to reconcile the succession of plant species with the expected sequence from sea-level changes. Under this alternative view, Chenopodiaceae would expand due to the rapid expansion of suitable areas. The lower the sea-level, the larger the suitable areas, and the more Chenopodiaceae plants that can grow. It is important to note that succession is not a symmetrical process, and what occurs on one direction does not necessarily occur in the opposite. When sea-level drops, secondary species like Poaceae and Cyperaceae can compete for resources with pioneers especially on higher marsh areas, where conditions are more stable (i.e. less erosion, accumulation of substrate, eventually less salinity). With a permanent drop in sea-level occurring along several hundreds of years, there is no reason for pioneers to dominate the pollen record and persist over secondary species, as it is the case in the Cariaco Basin record. Therefore, based on this reasoning, we conclude that the rapid change of sea-level indicated by the direction of the succession of species, supports rising and not lowering sea-levels, as one might possibly argue.

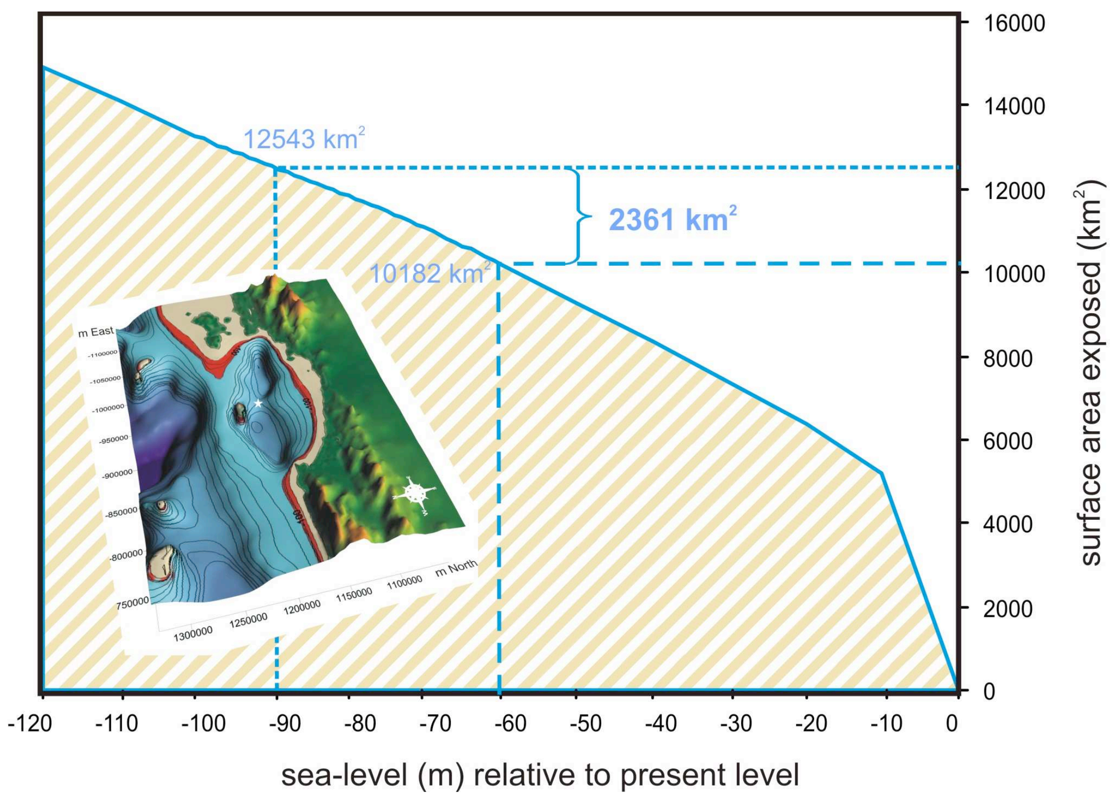

Figure 4. Estimated surface area (km^2) exposed in the Cariaco Basin at different sea-levels. The blue dotted lines indicate the increment of surface area by the effect of rising sea-levels from -90 to -60 m. On the lower corner, the bathymetric map of Cariaco Basin and adjacent areas. The red-shaded area denotes the increment of marsh surface area by 30 m of sea-level rise (from -90 to -60 m.b.s.l.).

3. Comparison and climatic implications

The Cariaco Basin pollen record also shows a similar relation between salt-marsh expansion and sea level rise during HEs 3, 5, 5a and 6, in spite of dating uncertainties and poorer resolution of the vegetation data [11]. In all five cycles, maximum values of Chenopodiaceae pollen coincide with the onset of HE stadials in the North Atlantic, and with warming phases in Antarctica. According to our palynological evidence, sea level started to rise before the ice sheet collapse that caused Heinrich layers in the North Atlantic, being in agreement with both Red Sea sea level reconstructions during the HE 4 (figure 3; [1, 9] and with fossil coral data from the Huon Peninsula [10]. However, a subsequent decelerated rise or fall of sea level is needed to reconcile with the expansion of Poaceae. In this case, our data supports the timing of central Red Sea reconstruction [1, 14, 15], the independently dated corals from the Huon Peninsula, and models, which suggest that melting in Antarctica might have accounted for a rise in sea level of about 20 m [15,16,17].

4. Conclusions

The palynological analysis in marine core MD03-2622 from northernmost South America, allowed the reconstruction of interstadial vegetation dynamics during MIS 3, suggesting rapid and repeated sea level changes. Five intervals of expanded salt marsh vegetation corresponded to the onset of HEs of the northern high latitudes and indicate periods of accelerated sea level rise in the tropical Atlantic. The close relationship between sea level rise and community dynamics is consistent with a resource-based mechanism of succession, where soil development and salinity gradients are the main factors determining plant succession patterns of coastal marshes. In this context, the Cariaco Basin palynological record is especially informative on the timing of sea level changes during MIS 3 and their connection with HEs, supporting the idea that sea level fluctuations followed Antarctica climate variability.

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References

[1] Siddall, M., Rohling E.J., Thompson, W.G. and Waelbroeck, C., 2008: Marine isotope stage 3 sea level fluctuations: Data synthesis and new outlook, *Reviews of Geophysics*, 46: RG4003, doi: 10.1029/2007RG00226.

[2] Peterson, L.C., Haug, G.H., Hughen, K.A. and Röhl, U., 2000: Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial, *Science*, 290: 1947-1951.

[3] Peterson, L. and Haug, G., 2006: Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela), *Palaeogeography Palaeoclimatology Palaeoecology*, 234: 97-113.

[4] González, C., Dupont, L.M., Behling, H. and Wefer, G., 2008: Neotropical vegetation response to rapid climate changes during the last glacial: palynological evidence from the Cariaco Basin, *Quaternary Research*, 69: 217-230.

[5] Hughen, K., Lehman, S., Southon, J., Overpeck, J., Marchal, O., Herring, C. and Turnbull, J., 2004: 14C activity and global carbon cycle changes over the past 50,000 years, *Science*, 303: 202-207.

[6] Hughen, K., Southon, J., Lehman, S., Bertrand, C. and Turnbull, J., 2006: Marine-derived 14C calibration and activity record for the past 50,000 years updated from the Cariaco Basin, *Quaternary Science Reviews*, 25: 3216–3227.

[7] Adam, P., 2002: Saltmarshes in a time of change, *Environmental Conservation*, 29: 39-61.

[8] Ranwell, D.S., 1972: *Ecology of salt marshes and sand dunes*, Chapman and Hall, 258 p.

[9] Arz, H.W., Lamy, F., Ganopolski, A., Nowaczyk, N. and Pätzold, J., 2007: Dominant Northern Hemisphere climate control over millennial-scale glacial sea-level variability, *Quaternary Science Reviews*, 26: 312–321.

[10] Thompson, W.G. and Goldstein, S.L., 2006: A radiometric calibration of the SPECMAP timescale, *Quaternary Science Reviews*, 25: 3207-3215.

[11] González, C. and Dupont, L.M., 2009: Tropical salt marsh succession as sea-level indicator during Heinrich events, *Quaternary Science Reviews*, 28: 939-946.

[12] Ellison, J.C., 1993: Mangrove retreat with rising sea-level, Bermuda, *Estuarine, Coastal and Shelf Science*, 37: 75-87.

[13] Woodroffe, C.D., 1999: Response of mangrove shorelines to sea-level change, *Tropics*, 8: 159-177.

[14] Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, Ch., Melschner, D., Schmelzer, I. and Smeed, D.A., 2003: Sea-level fluctuations during the last glacial cycle, *Nature*, 423: 853-858.

[15] Rohling, E.J. et al., 2008: New constraints on the timing of sea level fluctuations during early to middle marine isotope stage 3, *Paleoceanography*, 23: doi:10.1029/2008PA001617.

[16] Rohling, E.J., Marsh, R., Wells, N.C., Siddall, M. and Edwards, N., 2004: Similar melt-water contributions to glacial sea-level variability from Antarctic and northern ice sheets, *Nature*, 430: 1016-1021.

[17] Flückiger, J., Knutti, R. and Watts, J.W.C., 2006: Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events, *Paleoceanography*, 21: PA2014, doi: 10.1029/2005PA001204.

[18] Laj, C., 2004: *Cruise Report: MD 132 –P.I.C.A.S.S.O. Images XI, Fortaleza-Baltimore-Brest, Mai Juin 2003*, Institut Polaire Francais Paul Emile Victor, 53p.