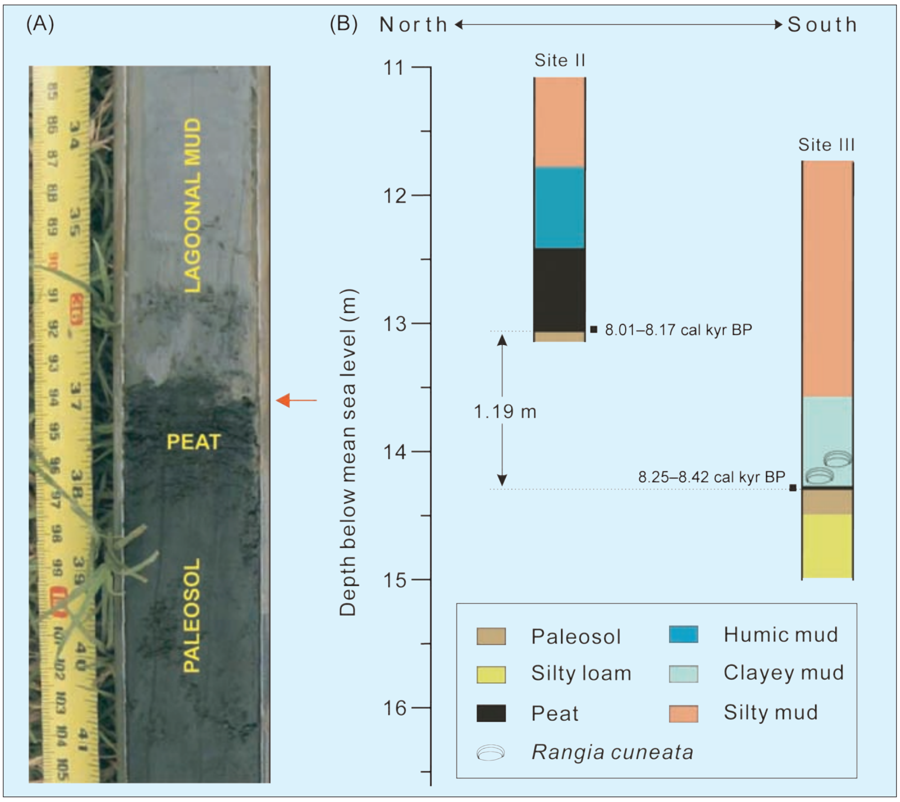

*Figure 2: **A**) A sedimentary sequence including a paleosol (fossil soil) that caps the Pleistocene substrate, basal peat and lagoonal mud from the Mississippi Delta. Note the sharp contact (arrow) between the ~2 cm thick peat layer and the overlying lagoonal mud, which represents an abrupt sea level rise at ca. 8.2 cal ka BP. **B**) Stratigraphic signature of the abrupt sea level rise at ca. 8.2 cal ka BP at Bayou Sale, Mississippi Delta (Törnqvist et al., 2004). The occurrence of* Rangia cuneata*, a brackish water clam characteristic of estuarine and lagoonal environments, is also shown.*

Barber et al., 1999). This rapid sea level rise serves as an example of how the amount and source of meltwater can be inferred from sea level records by the fingerprinting method; a technique that capitalizes on the distinct spatial pattern of the global sea surface due to the gravitational attraction of large ice and/or water masses (Mitrovica et al., 2001; Clark et al., 2002; Kendall et al., 2008). However, more detailed records are required to refine the estimate of the water volume impounded in these glacial lakes. To this end, our ongoing high-resolution sea level work in the Mississippi Delta aims to refine the timing and amplitude of the rapid sea level rise corresponding to the "8.2 ka event" by detailed stratigraphic studies. With regard to the "7.6 ka event", its extent still remains a matter of debate. Some records suggest a ca. 3 m rapid rise that occurred at about 7.5 cal ka BP or slightly later (e.g., Siddall et al., 2003; Liu et al., 2004; Bird et al., 2007), while others indicate a smooth rise of sea level during this time window (e.g., Van de Plassche, 1982; Törnqvist et al., 2006). The causes of such spatial contrasts are at present unknown but may in part be related to the location of the associated meltwater sources and their sea level fingerprints. We therefore conclude that our understanding of rapid sea level rise during the early Holocene is still in its infancy. Many more high-resolution sea level records for this critical time interval are needed. Combined with "fingerprint modeling", they could serve to refine the timing, amplitude and origin of such abrupt events.

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Coastal vegetation evidence for sea level changes associated with Heinrich Events

Catalina González and Lydie M. Dupont
MARUM - Centre for Marine Environmental Sciences, Geosciences Department, University of Bremen, Germany; catalina@uni-bremen.de

A Cariaco Basin pollen record shows the development of tropical salt marshes during marine isotope stage 3 and suggests that millennial sea level changes during the periods encompassing Heinrich Events followed Antarctic climate variability.

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 (Siddall et al., 2008 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 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. Here, we present new palynological evidence from the marine core MD03-2622 collected from the Cariaco Basin that reconstructs the history of intertidal plant communities during intervals associated with Heinrich Events (HEs), linking them to the well-constrained North Atlantic signal of millennial- to sub-millennial-variability.

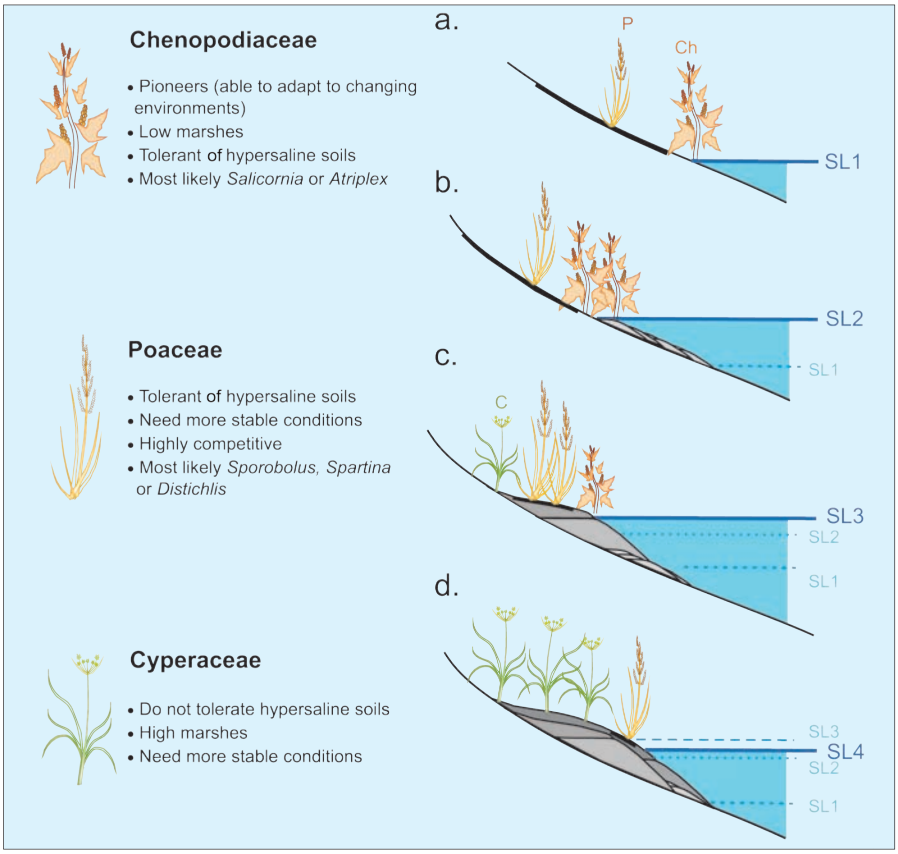

Figure 1: Left - main ecological preferences of 3 salt marsh taxa. Right - schematic representation of salt marsh community dynamics in a changing sea level environment according to the Cariaco Basin pollen record (González and Dupont, 2009). Thicker black lines indicate areas of soil hypersalinity. SL 1 to SL4 denote different sea levels reconstructed from the pollen record and correspond with phases indicated in Fig. 2. ***a****) Establishment of salt marshes when arid conditions promote extensive hypersaline environments;* ***b****) rapid sea level rise causes erosion; only pioneer species tolerate the change;* ***c****) sea level rise decelerates, and accretion of sediments and autochthonous organic material takes place; more competitive species take advantage of favorable conditions;* ***d****) sea level drops, sediment accumulation constrains the tidal influence to the seaward edge.*

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 (Peterson et al., 2000; Peterson and Haug, 2006; González et al., 2008). 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 (Hughen et al., 2004; 2006).

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 became exposed south of the Cariaco Basin. Periods of extremely dry atmospheric conditions might, therefore, have resulted in hypersaline coastal environments (Medina et al., 1989). 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 (Adam, 2002) (Fig. 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 (i.e., the development of salt marshes) were shown to correlate with HEs 3-6. Within single HE intervals, 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 sedge (Cyperaceae) (Fig. 2). Once interstadial conditions returned, salt marshes were replaced by mangroves and other arboreal species.

In this sequence, salt marshes started to develop under extremely arid stadial conditions (Peterson and Haug, 2006; González et al., 2008) 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 (Fig. 1a, b; Adam, 2002). 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 (Ranwell, 1972). 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 (Fig. 1b).

By comparing our high-resolution pollen data with sea level reconstructions from the Red Sea (Arz et al., 2007; Siddall et al., 2008 and references therein) and the independently dated fossil corals from the Huon Peninsula (Thompson and Goldstein, 2006) 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 (Fig. 2). 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 (Fig. 1a). Moreover, the erosion of low marsh sediments would wash out and transport the pollen produced in situ (Fig. 1b).

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 favored the expansion of more competitive perennial grasses (Poaceae), thus replacing Chenopodiaceae pioneer species (Figs. 1c, d and 2). 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 HEs, Cyperaceae pollen maxima might reflect an expansion of elevated marsh areas (Fig. 1c, 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 (González and Dupont, 2009) 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 (Ellison, 1993; Woodroffe, 1999).

Comparison

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 (González and Dupont, 2009). 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 (Fig. 2; Siddall et al., 2008; Arz et al., 2007) and with fossil coral data from the Huon Peninsula (Thompson and Goldstein, 2006). 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 (Siddall et al., 2003; 2008; Rohling et al., 2008), 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 (Rohling et al., 2004; 2008; Flückiger et al., 2006).

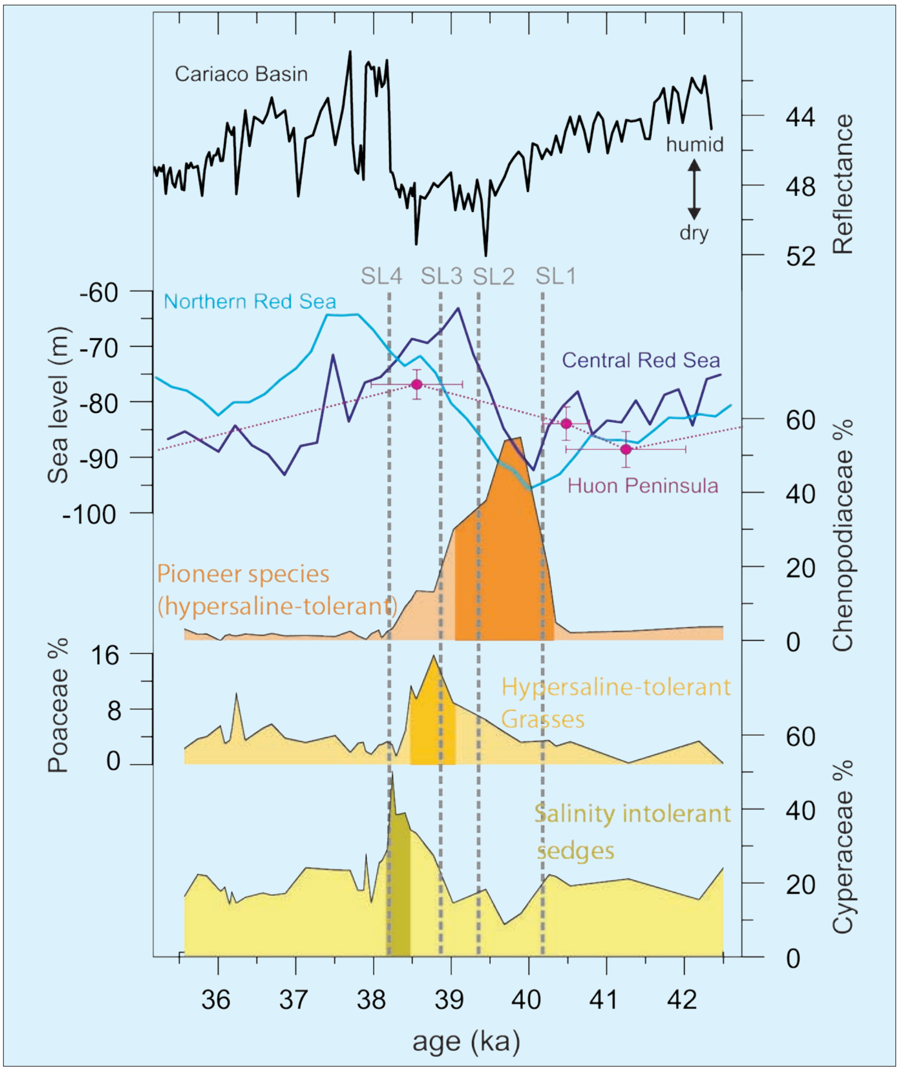

*Figure 2: Comparison of the high-resolution palynological record from core MD03-2622 (Cariaco Basin) with sea level reconstructions from Red Sea marine sediment cores and Huon Peninsula (Papua New Guinea) fossil corals during HE 4 (González and Dupont, 2009). Top to bottom: Reflectance data from core MD03-2622 (Laj, 2004). Sea level data; **dark blue** line - central Red Sea (Siddall et al., 2003; 2008), **light blue** line - northern Red Sea (Arz et al., 2007), and dotted **pink** line - Huon Peninsula (Thompson and Goldstein, 2006). Pollen % of Chenopodiaceae, Poaceae, and Cyperaceae indicating the directional alternation of salt marsh species during HE4. Dotted **gray** lines SL1 to SL4 denote different sea levels reconstructed from the Cariaco Basin pollen record, which correspond to phases explained in Figure 1.*

Conclusions

Through the palynological reconstruction of intertidal vegetation in core MD03-2622 we provided indirect evidence of rapid sea level change during MIS 3. Five intervals of expanded salt marsh vegetation corresponded to the onset of HEs of the northern high latitudes and suggest 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 the vegetation dynamics 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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