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Hydro-climate changes over southwestern Arabia and the Horn of Africa during the last glacial–interglacial transition: A pollen record from the Gulf of Aden

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ABSTRACT

We studied a marine sedimentary section deposited at a high sedimentation rate in the Gulf of Aden (core MD92-1002) to document environmental and hydrological changes since the end of the last glacial period and better understand the onset and decay of the Holocene Humid Period (HHP). Pollen analysis reveals that the period from the LGM to 13.5 ka was hyper arid with sparse vegetation cover characterized by xerophitic taxa from the Saharo-Sindian phyto-geographical region. Humidity increased since 14.9 ka to reach a maximum between ~9 and 7.5 ka, as revealed by peak abundances of the tropical mangrove *Rhizophora* and high values of a pollen-based humidity index. The HHP ended up gradually, starting to decline as soon as 7.5 ka and collapsing definitively at 4 ka. This decline is characterized by the appearance of Mediterranean taxa and the return of arid conditions, comparable to that of today. Comparison of our pollen record with three speleothem records from the Arabian Peninsula makes it possible to reconstruct a northward and westward shift of the Inter-Tropical Convergence Zone at the onset of the HHP.

1. Introduction

The tropical deserts of Northern Africa and the Arabian Peninsula constitute one of the driest environments on Earth. These areas have experienced high amplitude climatic variations during the late Quaternary with one of the most spectacular arid-humid shift during the early Holocene leading to the development of freshwater lakes over Arabia and the Horn of Africa (Gasse, 1977; Gasse and Fontes, 1989; Lézine et al., 2011, 2014 and reference therein). It is now well understood since e.g., COHMAP (1988) that this large-scale climate change resulted from the orbitally-induced increase in summer solar radiation, which was responsible for increased thermal contrast between land and sea and thus produced strong summer monsoon rainfalls over regions that are arid today and resulted in significant changes in atmospheric dynamics and wind patterns (e.g. Kutzbach and Street-Perrot, 1985; Prell and Kutzbach, 1987; Clemens and Prell, 1990; Liu et al., 2003; Barker et al., 2004; Marzin and Braconnot, 2009; Bassinot et al., 2011; Lézine et al., 2011). Although orbitally-driven summer insolation variations took place gradually, several paleoclimatic records have provided evidence of abrupt changes at the onset or termination of the Holocene Humid Period (HHP, 15–5 ka BP), which could be resulting either (i) from the remote influence of centennial-scale, high-latitude instabilities on tropical climate dynamics, in particular through latitudinal shifts of the Inter-Tropical Convergence Zone (ITCZ; e.g. Peterson et al., 2000; Haug et al., 2001), or (ii) from internal climate feedbacks and/or climate-biosphere feedbacks (Renssen et al., 2006; Castañeda et al., 2009). Reconstructing the precise spatio-temporal evolution leading to and from the HHP is mandatory to fully understand the mechanisms at play. Yet, there are significant discrepancies between paleoclimate reconstructions of humidity/aridity changes across tropical Africa and the Arabian area since the last glacial period, and the timing and structure of the Holocene humid period onset and termination are still debated (e.g., deMenocal et al., 2000; Kröpelin et al., 2008).

Tierney and deMenocal (2013), for instance, claimed that the onset and termination were both abrupt and generally synchronous all over East Africa from Lake Tanganyika to the South (6°S—15.76 ka) to the Gulf of Aden to the North (12°N—14.68 ka), illustrating the strong teleconnection that exists between equatorial/subequatorial and high latitudes of the northern hemisphere as already noted by Gasse et al. (2008). However, in the Chew Bahir basin (southern Ethiopia), sedimentological changes derived from high-resolution XRF-core scanning show that the HHP started earlier, at 19 ka, and was characterized by

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two abrupt, step-like increases in humidity that were coeval with (i) the onset of B/A and (ii) the termination of the YD, respectively (Foerster et al., 2012). But the end of the HHP, on the other hand, was rather progressive (Foerster et al., 2012), suggesting a climatic transition that was gradual, confirming what has been deduced from lacustrine sediments in the Sahara desert (Kröpelin et al., 2008).

Lézine et al. (2014) stressed out regional differences in the dynamics of HHP onset and termination based on a comprehensive dataset of nearly 2147 well-dated hydrological records (lacustrine, palustrine, spring and fluvial, arid). They showed that the Arabian Peninsula and the Horn of Africa have experienced a significantly shorter humid period compared to northern Africa even though the optimum of the Holocene humidity was contemporaneous. Lézine et al. (2014) also concluded that the onset and termination of the HHP were progressive in western Africa, but more abrupt in eastern Africa (Sudan, Egypt), and possibly also over the Horn of Africa and Arabia, although the low amount of well-dated hydrological data in these two regions made it more difficult to conclude.

In order to provide additional pieces of evidence to help deciphering properly the set of events that lead to the onset and termination of the Holocene humid period, we studied pollen assemblages from marine core MD92-1002 recovered in the Gulf of Aden to reconstruct main environmental and climate changes, which occurred at the junction between the Horn of Africa and Southwestern Arabia. The exceptionally high sedimentation rates, which characterize this record (~45 cm/ka), enable us to cope in details with the structure and timing of the last deglaciation. Comparison with earlier studies from marine cores (Core P178-15P-Tierney and deMenocal, 2013, and core KL74-Sirocko et al., 1993) and continental archives from both lacustrine deposits (Lézine et al., 2014) and speleothems (Neff et al., 2001; Fleitmann et al., 2007; Shakun et al., 2007; Van Rampelbergh et al., 2013) make it possible to examine the relative influence of southern (African) or northern (Arabian) origin and reconstruct the spatial and temporal changes of summer monsoon, with a special emphasis on the Holocene humid period and environmental changes across the last deglaciation.

2. Modern environmental setting

2.1. Regional climatology

The hydrology over the Southern Arabian Peninsula and the Horn of Africa is modulated by the seasonal migration of the ITCZ. During the boreal summer (June–September), the South Asian landmass is warmer than the Indian Ocean; a low-pressure gradient develops resulting in SW–NE winds blowing over the Arabian Sea and transferring humid air masses to the surrounding continents as part of the general northward shift of the ITCZ. This air flux reaches the Horn of Africa and follows the Southern Arabian coasts where precipitations occur. During the boreal winter (November–February), the continents cool down more strongly than the adjacent ocean. Pressure gradients reverse, which in turn causes a reversal of atmospheric wind circulation over the Arabian Sea with major wind blowing NE–SW direction, in association with the shift of the ITCZ to the South. As a result, arid conditions settle over the Arabian Peninsula while, the Mediterranean depressions penetrate southward through the Red Sea and the Persian Gulf (Fig. 1).

Because ITCZ does not extend far north over the Arabian Peninsula during the summer season, monsoonal precipitations remain largely confined to restricted areas along the southwestern part of the peninsula and the regional climate is dry with high annual temperature (26–36 °C) and low rainfall (less than 100/year).

2.2. The Gulf of Aden

The Gulf of Aden is located in the Arabian Sea between Yemen, on the southern coast of the Arabian Peninsula, and Somalia in the Horn of Africa (Fig. 2). It is connected to the Red Sea through the Bab-el-Mandeb strait (~ 20 miles wide and ~140 m deep; Sheppard, 2000). Because of the arid surrounding environments, the terrigeneous material that feeds marine sedimentation is mainly eolian, windborne dust particles originating from Northern Africa and/or the Arabian Peninsula (Sirocko et al., 1993, 2000; Leuschner and Sirocko, 2000; Stein et al., 2007). The Gulf of Adenis bathed by bottom waters with low oxygen content, which result from the strong export productivity in the Arabian Sea and its insufficient ventilation (van Weering et al., 1997). The low oxygen content of bottom water results in the good preservation organic carbon, and the overall high abundance of pyrite in sediments (Bouilloux et al., 2013a, 2013b).

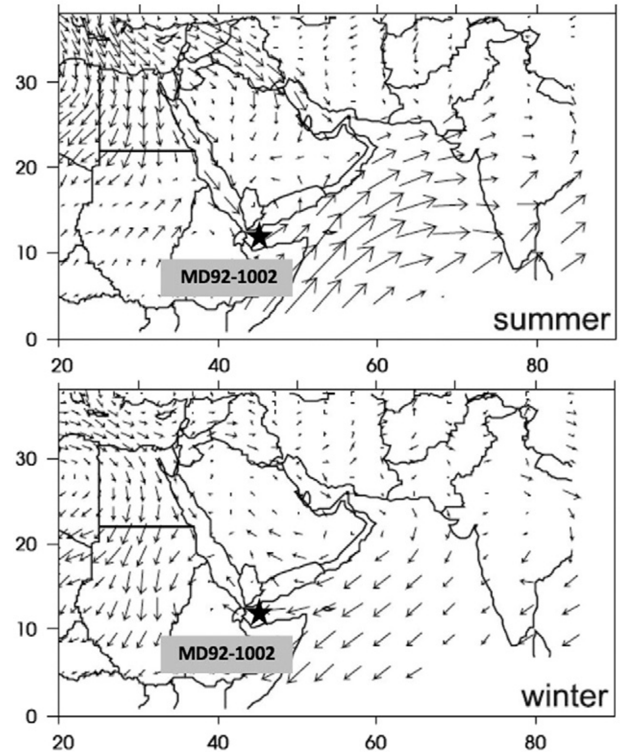

Fig. 1. Surface wind trajectories (1000 hP) during the summer (JJA) and winter (DJF; (ECMWF analyses 1990–1997). Location of core MD92-1002.

2.3. Vegetation

The regional vegetation belongs to four distinct phytogeographical domains (Fig. 2; Ghazanfar and Fisher, 1998; Wood, 1997; Zohary, 1973; White, 1983). The Saharo-Sindian domain in the Arabian deserts is characterized by scarce, herbaceouspopulations mainly composed of *Artemisia monosperma*, *Cornulaca arabica*, *Calligonum comosum*, *Cyperus conglomeratus*, *Tribulus arabicus*, *Plantago ciliate* and *Dipterygium glaucum*. The Irano-Turanian domain to the North of the Arabian Peninsula at the edge of the Mediterranean region and to the Northeast, is characterized by *Artemisia herba-alba* associated with *Centaurea sp.*, *Ephedra sp.* and various Asteraceae. The Somalia-Masai domain to the South-West of the Arabian Peninsula and the Horn of Africa is composed of semi-arid grasslands and deciduous woodland and scrubs with *Acacia sp.*, *Commiphora* sp. associated with various Euphorbiaceae, *Cadaba longifolia* and *Dodonea viscosa*.

The Afromontane domain, between 1000 and 3000 m above sea level in the Ethiopian plateaus to the South and the high mountains of Yemen and Oman to the North and Northeast, is composed of evergreen forests. This domain is extremely reduced in the Arabian highlands with only *Olea europea* and *Juniperus procera* among the most characteristic species. In East Africa, the Afromontane vegetation is more diverse,