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Two phases of the Holocene East African Humid Period: Inferred from a high-resolution geochemical record off Tanzania

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ABSTRACT

During the Holocene, the most notably climatic change across the African continent is the African Humid Period (AHP), however the pace and primary forcing for this pluvial condition is still ambiguous, particularly in East Africa. We present a high-resolution marine sediment record off Tanzania to provide insights into the climatic conditions of inland East Africa during the Holocene. Major element ratios (i.e., log-ratios of Fe/Ca and Ti/Ca), derived from X-Ray Fluorescence scanning, have been employed to document variations in humidity in East Africa. Our results show that the AHP is represented by two humid phases: an intense humid period from the beginning of the Holocene to 8 ka (AHP I); and a moderate humid period spanning from 8 to 5.5 ka (AHP II). On the basis of our geochemical record and regime detection, the termination of the AHP initiated at 5.5 ka and ceased around 3.5 ka. Combined with other paleoclimatic records around East Africa, we suggest that the humid conditions in this region responded to Northern Hemisphere (NH) summer insolation. The AHP I and II might have been related to an eastward shift of the Congo Air Boundary and warmer conditions in the western Indian Ocean, which resulted in additional moisture being delivered from the Atlantic and Indian Oceans during the NH summer and autumn, respectively. We further note a drought event throughout East Africa north of 10°S around 8.2 ka, which may have been related to the southward migration of the Intertropical Convergence Zone in response to the NH cooling event.

1. Introduction

Various well documented records have demonstrated that northern Africa experienced a more pluvial early–mid Holocene (12–5.5 ka; e.g., Gasse, 2000; Tierney et al., 2011; Junginger and Trauth, 2013; Blanchet et al., 2015; Shanahan et al., 2015). This relative humid period, termed the African Humid Period (AHP; deMenocal et al., 2000), extends from North Africa to as far south as 10°S in East Africa (Gasse, 2000; Castañeda et al., 2007; Burrough and Thomas, 2013). Existing hydrological reconstructions however exhibit significant heterogeneity in both the timing and abruptness of the AHP termination, and in the pace of humid–arid transitional interval, which is still the subject of intense debate (Chevalier and Chase, 2015; Castañeda et al., 2016). Records from the northwestern African margin sediments show a synchronous abrupt termination of the AHP around 5.5 ka (deMenocal et al., 2000; Kuhlmann et al., 2004; McGee et al., 2013). In contrast, in the eastern Sahara, pollen and sedimentological records from Lakes Yoa and Chad document a gradual end in the humid condition (Kröpelin et al., 2008; Amaral et al., 2013; Claussen et al., 2013; Francus et al., 2013). In Eastern Mediterranean sediments, the end of the AHP is expressed by a progressive hydrological shift in the Nile River based on geochemical and sedimentological proxy data (Hamann et al., 2008; Revel et al., 2010; Blanchet et al., 2013; Ehrmann et al., 2013; Flaux et al., 2013; Weldeab et al., 2014b). Furthermore, isotope hydrological indicators from marine sediments off the central western Africa coast suggest a gradual termination of the AHP (Schefuß et al., 2005; Weldeab et al., 2007). It seems that the abrupt transition is limited in the Western Sahara, where its precipitation is controlled by the Western African monsoon with vegetation feedback (Hély et al., 2009). Recent research, however, shows that the abrupt termination of the APH extends to East Africa (Garcin et al., 2012; Tierney and deMenocal, 2013; Forman et al., 2014; Morrissey and Scholz, 2014; Castañeda et al., 2016). Based on the δD_{wax} data from Lakes Challa and Tanganyika and the Gulf of Aden, Tierney and deMenocal (2013) hypothesize that the rapid termination of the AHP in East Africa reflects convection feedbacks associ-

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ated with Indian Ocean sea-surface temperature (SST). In contrast, Berke et al. (2012) found that δD_{wax} derived from Lake Victoria show a gradual termination of the AHP, indicating a predominantly insolation forcing. These different findings could be caused by changes in the source of moisture rather the amount effect associated with local precipitation as proposed by Leduc et al. (2013). Indeed, recent studies have demonstrated that delepted δD_{wax} during the early Holocene may indicate an increase in moisture derived from the Atlantic Ocean, which is more isotopically depleted than Indian Ocean sourced moisture (Costa et al., 2014; Castañeda et al., 2016).

Under the influence of the Atlantic and Indian Oceans, the climate system in East Africa is complex (Nicholson and Kim, 1997). The available data concerning the humid–arid transition in East Africa mainly depend on the lacustrine sediments and vary significantly from site to site. For instance, shoreline reconstruction documents a rapid drop in lake level for Lake Turkana (Garcin et al., 2012; Forman et al., 2014; Morrissey and Scholz, 2014), whereas a gradual humid–arid transition is recorded in the Lake Chew Bahir and Lake Suguta, located to the north and south of the Lake Turkana (Foerster et al., 2012; Junginger and Trauth, 2013). In contrast to these terrestrial archives, marine sediments accumulating along the African continent margins provide complete and well-dated climate sequence (deMenocal, 2014). However, to date, few sediment cores are available off East Africa comparing with regions off West Africa, which has led a limited understanding of the Holocene climatic changes in East Africa. Therefore, high-resolution marine climatic profiles (e.g., geochemical scanning data) are imperative to allow us to study the AHP (Bard, 2013). Here, we present a high-resolution marine sediment core, obtained off Tanzania, western Indian Ocean (WIO), to reveal the pace and magnitude of environmental changes during the AHP in East Africa. This work will make contributions to critical debates, such as, the role of insolation in forcing East African climatic change, the relative importance of the Atlantic and Indian Ocean SSTs in controlling the rainfall in East Africa, and the linkage between high and low latitude climate systems during the AHP.

2. Regional setting

2.1. Present climate system

Modern East Africa experiences a semiannual rainfall cycle (Nicholson, 2000), which is driven by the migration of the Intertropical Convergence Zone (ITCZ) back and forth across the equator (Fig. 1). There are two distinct rainy seasons in March–May (MAM; the long rains), and October–December (OND; the short rains) between the transition of monsoon. The East African long-rains season is characterized by heavy rainfall in April and May that is driven by the northward migration of the ITCZ, whereas the heavy rainfall experienced during the short-rains season is a result of the migration of the ITCZ to the south (Black et al., 2003). In addition, the area is influenced by the Congo Air Boundary (CAB), separating the air masses containing moisture derived from the Atlantic and Indian Ocean. Long rains over the northeastern Tanzania are associated with advection of moisture from both the Indian Ocean and Atlantic Oceans (Kijazi and Reason, 2012). As the southward migration of the ITCZ is more rapid than the northward migration, the period of heavy rainfall is shorter during the short-rains season (Clark et al., 2003). Rainfall during the short rains is related to Indian Ocean SST anomalies, attributed to the Indian Ocean Dipole (IOD) and/or El Niño/Southern Oscillation (ENSO; Nicholson, 2000). Observations and simulations indicate that wet (dry) short rains seasons tend to correspond to colder (warmer)-than-usual SSTs in the tropical eastern Indian Ocean and

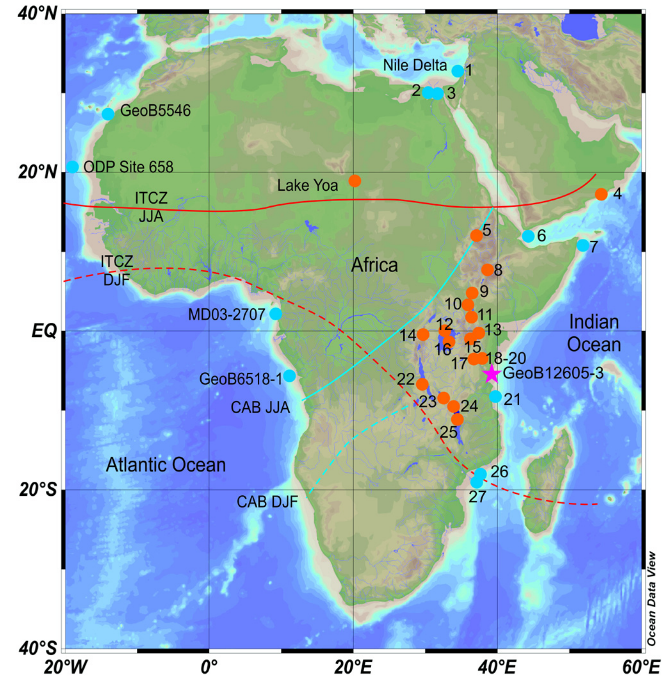

Fig. 1. Present climatic system of Africa. Locations of the Inter-tropical Convergence Zone (ITCZ; solid line) and the Congo Air Boundary (CAB; dashed line) for Northern Hemisphere summer (JJA: June, July, and August) and winter (DJF: December, January, and February) season, modified from Willis et al. (2013). Locations of the research sites and paleoclimatic records mentioned in the text are presented. Solid orange circles represent terrestrial records, while blue ones represent marine record. Core GeoB12605-3 is indicated by pink star. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

warmer (colder)-than-usual SSTs in the WIO (Hastenrath, 2007; Brown et al., 2009; Bahaga et al., 2015). Such shifts in zonal circulation can be caused by anomalously warm SSTs in the western Indian Ocean (Ummenhofer et al., 2009), positive IOD events (Saji et al., 1999), and the ENSO (Nicholson and Kim, 1997).

2.2. Oceanography

The current system in the target region is mainly influenced by the north-flowing East African Coastal Current (EACC), which is controlled by a strong seasonal monsoon (Beal et al., 2013; Manyilizu et al., 2016). The EACC and the southward flowing Mozambique Current (MC) originate from the South Equatorial Current (SEC), which passes the northern part of Madagascar and continues westward to the coast of Africa near 11°S (Fig. 2). During the southeast monsoon (Fig. 2a), cold, nutrient-rich waters are upwelled to the surface (McClanahan, 1988), however, upwelling is limited to northern region of the WIO. In contrast, surface waters south of 4°S are stratified all year-round, characterized by relatively low surface and benthic productivity, associated with low a nutrient content (Birch et al., 2013). During the northeast monsoon the EACC moves away from the coast near 3°S and combines with the southward flowing Somali Current (SC) to form the Equatorial Countercurrent (ECC, Fig. 2b, Kohn and Zonneveld, 2010).

The East African coast is drained by several major rivers (e.g., Pangani, Rufiji, and Ruvuma Rivers in Fig. 2a) and numerous minor rivers (Shaghude, 2007). Specific to our research locations, the major sediment discharge comes from the Pangani River (Liu et al., 2016). Headwaters of the Pangani River are located in the volcanic region of Mt. Kilimanjaro and Mt. Meru, which is covered with olivine and alkaline basalts, phonolites, trachytes, nephelinites and pyroclastics (Schluter, 2008).