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High-and low-latitude forcing of the East African climate since the LGM: Inferred from the elemental composition of marine sediments off Tanzania

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ABSTRACT

We present X-Ray Fluorescence (XRF) Scanner measurements from a 6 m long sediment core (GeoB12624-1) on the upper slope of Tanzania to reconstruct the climatic evolution in East Africa since the Last Glacial Maximum (LGM). Log-ratios of Fe/Ca and Ti/Ca are indicative for sediment discharge of the Rufiji River, which is controlled by climatic conditions in the Rufiji catchment area. The most significant changes in major elemental composition occurred at 15.1 and 7.4 ka highlighted by the regime shift index values. The data set records distinct precipitation peaks during the early Holocene. This corresponds a maximum in the Northern Hemisphere (NH) summer insolation and results in a transition from the arid LGM to the humid early Holocene. Our geochemical record also indicates that this climatic transition was interrupted by two severe droughts that occurred during NH cold intervals: the Heinrich stadial 1 (HS1) and the Younger Dryas (YD). Through a comparison with other nearby paleoclimatic records, we suggest that arid climatic conditions only occurred in East Africa north of 8–10°S, whereas in southern East Africa around 15–20°S increased humidity during the HS1 and YD prevailed. We thus conclude that these two drought events were caused by a southward migration of the Intertropical Convergence Zone (ITCZ) which was fostered by the NH cooling during the HS1 and YD. Hence, our new geochemical record clearly documents that the East African climate not only responded to low-latitude insolation forcing on sub-orbital time scales, but also, was strongly influenced by high-latitude cooling during the HS1 and YD periods.

1. Introduction

Since the Last Glacial Maximum (LGM), climatic conditions in tropical Africa have been widely related to precessional summer low-latitude insolation (Kutzbach and Street-Perrott, 1985; Gasse et al., 2008; Shanahan et al., 2015); or seasonal contrasts between Northern Hemisphere (NH) and Southern Hemisphere (SH) insolation (Verschuren et al., 2009; Berke et al., 2012; Collins et al., 2017). The humid conditions in North Africa during the early and mid-Holocene, termed by deMenocal et al. (2000) as the African Humid Period (AHP), are generally considered to have been triggered by an increase in low-latitude NH summer insolation which strengthened the African monsoon. In East Africa, at the same time, humid conditions are suggested to have been caused by increased rainfall occurred during the NH summer season, which reduced rainfall variety between different seasons (Barker et al., 2011; Tierney et al., 2011a). However, when the NH was relatively cold, e.g., the Heinrich stadial 1 (HS1; ~18–14.6 ka) and the Younger Dryas (YD; ~12.8–11.5 ka; Barker et al., 2009), forcing from high-latitudes might have controlled the humid and arid phases in tropical Africa, which modulates the seasonal movement of the Intertropical Convergence Zone (ITCZ) (Tierney and deMenocal, 2013; Otto-Bliesner et al., 2014; Castañeda et al., 2016; Bastian et al., 2017). According to marine records, the ITCZ shifted southward during these cold periods, which caused humid conditions in southern East Africa (Schefuß et al., 2011; Mohtadi et al., 2014; van der Lubbe et al., 2014), and drought throughout equatorial and

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northern East Africa (Tierney and deMenocal, 2013; Castañeda et al., 2016). Such southward migration of the ITCZ have been related to slowdown of the Atlantic Meridional Overturning Circulation (AMOC) during HS1 and the YD stadial (Ritz et al., 2013; Mohtadi et al., 2016).

These changes are also manifested in various lake records (Johnson et al., 2002; Brown et al., 2007; Garcin et al., 2007, 2009; Chevalier and Chase, 2015). High lake levels during the HS1 from Lakes Malawi and Chilwa (Filippi and Talbot, 2005; Thomas et al., 2009) indicate that during the HS1 the ITCZ moved southward and caused wet conditions in southern East Africa. Increased northerly winds over the Lake Malawi lake during the YD (Johnson et al., 2002; Castañeda et al., 2007, 2009; Talbot et al., 2007); however, Lake Masoko, located close to Lake Malawi, experienced wet conditions at the same time (Garcin et al., 2006a, 2007). Such spatial and temporal heterogeneity in lake records has limited the comprehensive understanding of the East African evolving climate since the LGM. In spite of controlling factors such as the migration of the ITCZ, other factors including distance to the sea, local wind regimes, and land topography could also be involved, creating different lake climate records. In contrast, marine sediments deposited off the African continent have provided complete and well-dated paleoclimatic records (deMenocal, 2014).

High-resolution of geochemical scanner profiles have improved time resolution of sampling (Bard, 2013), which allowed us to obtain continuous sediment sequences with high temporal resolution marine records. To date, unlike the well study on the western north tropical Africa (Shanahan et al., 2015), only few studies on marine sediments off East Africa, demonstrating inland climatic conditions since the LGM, have been carried out. These include sedimentological and geochemical archives representing Nile hydrology from the eastern Mediterranean Sea (Box et al., 2011; Revel et al., 2014; Castañeda et al., 2016), biomarker based precipitation variability in marine sediments off northern and southern East Africa (Schefuß et al., 2011; Tierney and deMenocal, 2013), and geochemical (Foraminiferal Ba/Ca) and sedimentological (grain size) proxy data off the Zambezi River mouth, in the Mozambique Channel (Just et al., 2014; van der Lubbe et al., 2014; Weldeab et al., 2014a).

Our key objective is therefore to present a continuous, high-resolution climatic record from a marine sediment gravity core off the Rufiji River mouth, Tanzania, to establish the timing and pace of climatic change in southern East Africa and its driving force since the LGM. Through comparisons with other marine and terrestrial paleoclimatic records, and the latest SST data from the tropical Indian Ocean, we will illustrate what the predominant forcing mechanisms on the regional climatic change are in different intervals such as the HS1, the YD, and the AHP. These new data will help model and foresee extreme variations in the water cycle with either episodes of drought or periods of extreme flooding in Africa in the future (Defrance et al., 2017).

2. Regional setting

2.1. Climatic and oceanographic setting

East Africa receives seasonal rainfall as a result of the passage of the ITCZ twice a year (Fig. 1a): a short one in the NH autumn (short rains; September to November) and a longer one in the NH spring (long rains; March to May; Nicholson, 2000). In addition, rainfall during the short rains is also modulated by SSTs of the Western Indian Ocean (WIO), which brings heavier rainfall when the SST of the seawater adjacent to the East African mainland is warmer (Ummenhofer et al., 2009) or higher SST gradients occur between the WIO and eastern tropical Indian Ocean (Saji et al., 1999; Webster et al., 1999; Bahaga et al., 2015). The present climatic system of tropical East Africa is complicated because moisture transfer from the Atlantic, as well as, the Indian Ocean plays a role (Tierney et al., 2011a). The convergence of these different moisture sources marks the Congo Air Boundary (CAB). Previous studies suggest that the El Niño-Southern Oscillation (ENSO) also impact the East African rainfall, which could cause abundant rainfall during the short-rains season during warm ENSO events (Nicholson and Kim, 1997).

The WIO is mainly influenced by the East African Coastal Current (EACC), a branch of the South Equatorial Current (SEC; Fig. 1b). The SEC splits into the north-flowing EACC and the south-flowing Mozambique Current (MC) at the coast of East Africa near 11°S after passing the northern part of Madagascar (Beal et al., 2013). During the southeast (SE) monsoon, the EACC can has a higher velocities of 2 m/s; which reduce to lower than 0.2 m/s during the northeast (NE) monsoon (Newell, 1957). Combined with the south-flowing Somali Current (SC), the EACC leaves eastward off the mainland around ~3°S during the NE monsoon, which forms the east-flowing Equatorial Countercurrent (ECC, Fig. 1b) (Kohn and Zonneveld, 2010). This seasonal reversal in the wind patterns causes upwelling (Fig. 1b), which occurs off the Kenyan and Somalian coasts (McClanahan, 1988; Birch et al., 2013). In contrast, to south of 4°S, surface waters (such as our core location) are represented by low nutrient contents and low surface and benthic productivity (Birch et al., 2013).

2.2. The Rufiji River

The Rufiji River, the largest river in Tanzania draining the rift mountains, drains a basin of 177 000 km^2 (Shaghude, 2005). Most of the plateau and mountain sections of the basin are covered by gneissic and schistose metamorphic rocks, whereas southeastern section of the basin are underlain by arenaceous stratified rocks mainly of Karroo age (Temple and Sundborg, 1972, Fig. 2a). Because of the narrow continental shelf and channel system off Tanzania (Fig. 2b–c), the Rufiji River is the main terrigenous sediment source to our research location (Liu et al., 2016a), with a sediment yield of ~95 t/km^2/yr (Milliman and Syvitski, 1992). Due to deposition of sediment discharged by the Rufiji River, the Rufiji delta protrudes 15 km into the Mafia channel, covering an area of ~1200 km^2 (Shaghude, 2005). The Rufiji delta, composed of by fluvial sand, silt and clay (Shaghude, 2005; Punwong et al., 2013), contains the largest estuarine mangrove forest in East Africa, with a total area of ~500 km^2 (Duvail and Hamerlynck, 2007).

Together with other rivers (e.g., the Zambezi and Limpopo Rivers; Fig. 1a), in this region, large amounts of terrigenous sediments are discharged into the WIO (Shaghude, 2007), which would impede the growth of carbonate-producing biota (e.g., corals; Arthurton, 2003). Mangroves beds, however could filter freshwater derived from theses inland rivers and promote the growth of coral reefs offshore (Shaghude, 2005; Romahn et al., 2015).

3. Materials and methods

3.1. Marine sediment cores

Marine sediment core GeoB12624-1 (8°14.05′S; 39°45.16′E) was retrieved from the upper continental slope off Tanzania (Fig. 2b–c) at the water depth of 655 m, during a R/V *METEOR* cruise (M75/2) in February 2008 (Savoye et al., 2013). The 600 cm long core sediments are composed by dark olive-gray fine-grained muddy deposits. They derive from the discharged sediments of the Rufiji River and flow into the WIO at the southwest of the Mafia Island (Liu et al., 2016a). The age model of core GeoB12624-1 was based on