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A mid-Holocene thermal maximum at the end of the African Humid Period

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ABSTRACT

The termination of the African Humid Period (AHP) about 5 thousand years ago (ka) was the most dramatic climate shift in northern and equatorial Africa since the end of the Pleistocene. Based on TEX_{86} paleotemperature data from Lake Turkana, Kenya, we show that a temperature shift of 2–4 °C occurred over the two millennia spanning the end of the AHP, with the warmest conditions occurring at ~5 ka. We note a similar shift, though of a smaller magnitude, in other East African temperature records from Lakes Malawi and Tanganyika, as well as Mt. Kilimanjaro. Additionally, we document the temperature history for the last 220 years from Lake Turkana that indicates the thermal anomaly at 5 ka was warmer than the present day Lake Turkana temperatures and on par with modern temperatures of Lakes Tanganyika and Malawi. We suggest that the thermal response at the end of the AHP may be linked to local insolation during September–November, when local air temperature rises to an annual maximum over Lakes Malawi and Tanganyika and a secondary maximum over Lake Turkana and Mt. Kilimanjaro. September–November insolation peaked at ~5 ka and likely caused air and water temperatures in the region to rise to maxima at that time.

1. Introduction

The precise timing, pace and extent of the African Humid Period (AHP) are the focus of continued investigation, particularly the rate at which much of northern and equatorial Africa changed from a wet, verdant landscape, with a lake-filled "green Sahara" and high lake levels as far south as Lake Rukwa (~8 °S latitude) to expansive desert, diminished lake levels, and the replacement of mesic with drought-tolerant plants. The AHP lasted from ~14.5 to 5 ka, and is attributed to a non-linear response to Northern Hemisphere summer insolation forcing that first strengthened, then weakened the African Monsoon system, amplified by atmosphere-vegetation feedbacks (Kutzbach and Street-Perrott, 1985; Claussen and Gayler, 1997; Liu et al., 2007; Tierney et al., 2011). The environmental response at the end of the AHP, with its abrupt, seemingly geographically extensive character, has been likened to other dramatic wide-spread environmental events, such as the Younger Dryas (deMenocal et al., 2000). However, the climate signal of the AHP appears somewhat spatially and temporally variable across Africa, so the term "African Humid Period," applies neither to the entire continent, nor is its duration fixed within the part of the continent where it does apply. Consequently, understanding the environmental shift at the end of the AHP has been confounded by responses captured in paleorecords, with evidence for both an abrupt shift towards aridity, completed over decades to centuries, and for a more gradual response over several millennia (Niedermeyer et al., 2010; Vincens et al., 2010). While the AHP is reported to have terminated abruptly at 5.5 ka based on changes in dust concentration in ocean sediment core records off northwest Africa (deMenocal et al., 2000), the actual shift to more arid conditions appears to have been latitudinally time transgressive across much of northern Africa (Kuper and Kropelin, 2006).

The thermal evolution during the termination of the AHP is not well documented, partly because of a lack of suitable temperature proxy records. Recently, however, a number of African lake temperature records have been produced through the application of the TEX_{86} temperature proxy. TEX_{86} is based on the degree of cyclization of membrane lipids from aquatic Thaumarchaeota, previously referred to as Crenarchaeota (Brochier-Armanet et al., 2008), specifically isoprenoid glycerol dialkyl glycerol tetraethers (GDGTs), which are well preserved in marine and lacustrine sediments (Schouten et al., 2002; Kim et al., 2010; Powers et al., 2010). The distribution of these compounds correlates with surface water temperature in the oceans and some lakes, and thereby provides the opportunity to reconstruct past temperature (Schouten et al., 2002; Kim et al., 2010; Powers et al., 2010). In many lakes, TEX_{86} may not be a reliable proxy for past temperature, particularly in small lakes where substantial amounts of

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soil-derived isoprenoid tetraether compounds confound the signal derived from aquatic Thaumarchaeota (Blaga et al., 2009; Powers et al., 2010). This terrestrial influence is quantified by the so-called BIT (Branched and Isoprenoid Tetraether) index, a ratio of predominantly soil-derived branched GDGTs to isoprenoid GDGTs produced by aquatic Thaumarchaeota. The BIT index ranges from 0 (predominantly aquatic) to 1 (predominantly terrestrial) (Hopmans et al., 2004). TEX_{86} is not considered to be a reliable recorder of past temperature in lake sediment when BIT values exceed ~0.4 (Blaga et al., 2009). Additionally, the relative distribution of GDGTs can be biased by the presence of methanogenic Euryarchaeota, which generate some of the same membrane lipids as Thaumarchaeota but lack the appropriate temperature relationship (Schouten et al., 2007b). GDGT-0 is a commonly found membrane lipid of Archaea, while crenarchaeol is thought to provide more specific evidence of Thaumarchaeota (Sinninghe Damsté et al., 2002; Pitcher et al., 2011). Thus, a ratio of GDGT-0 to crenarchaeol can be used to assess the influence of methanogenesis, and should be low (<2) for sediments with low methanogenic input (Schouten et al., 2002; Blaga et al., 2009). The TEX_{86} proxy has been applied to several African lake systems, such as Malawi and Tanganyika, and shown to record known climate events such as glacial–interglacial cycles (Powers et al., 2005; Tierney et al., 2008; Woltering et al., 2011) and the Younger Dryas (Powers et al., 2005).

We generated a lake temperature record from Lake Turkana using this TEX_{86} paleothermometer, which shows, in combination with other records, that much of tropical East Africa experienced a significant shift in temperature over the two millennia centered on 5 ka, which undoubtedly added to the stress imposed on the fauna and flora from hydrological changes associated with the end of the AHP.

2. Regional setting and modern climatology

Lake Turkana (3°35′N, 36°7′E) lies in a broad depression at 360 m above sea level between the Ethiopian Rift to the northeast and the Kenyan Rift to the south and is the largest lake in the eastern arm of the Rift Valley, with a length of about 250 km and an average width of 30 km (Fig. 1). The Turkana basin is hot and arid, and subject to extended periods of intense diurnal winds. The amplitude of seasonal variability in air temperature and rainfall, while present at Lake Turkana, is subdued compared to the other great lakes of East Africa. Surface water temperatures in Lake Turkana typically range from about 26 °C to 30 °C throughout the year, while bottom water temperatures exhibit only minor seasonal fluctuations between 24.5 °C and 26.5 °C (Ferguson and Harbott, 1982) (Fig. 2). The lake exhibits weak thermal stratification during the spring months, in contrast to more uniform temperature structure due to wind mixing at other times of the year (Ferguson and Harbott, 1982). Daily mean maximum and minimum air temperatures recorded on the western shore of the lake in 1973–1975 were 32.5 °C and 26.0 °C, respectively, and were slightly cooler in the summer months than in the winter, due to the cooling influence of occasional rains and clouds with passage of the African rain belt, associated with the Intertropical Convergence Zone (ITCZ) (Ferguson and Harbott, 1982). Modern Lake Turkana typically exhibits temperatures 1–3 °C warmer in the north basin than in the south due to upwelling in the south basin produced by the predominantly southerly winds (Fig. 2). Mean annual rainfall in the Turkana Depression is about 200 mm yr^{-1} (Nicholson et al., 1988), while the annual evaporation rate is about 2300 mm yr^{-1} (Ferguson and Harbott, 1982). The closed-basin lake receives 80–90% of its fresh water from the Omo River, which drains the Ethiopian Highlands to the north (Fig. 1), where annual rainfall is in the range of 800–1200 mm yr^{-1} (Ferguson and Harbott, 1982). Lake Turkana has a salinity of about 25, dominated by Na^{+}, HCO_3^{-}, and Cl^{-} ions, and a pH averaging 9.1 (Cerling, 1979; Ferguson and Harbott, 1982). A unique aspect of Lake Turkana among the great lakes of the Rift Valley is that its bottom waters are continuously oxygenated due to its average depth of just 35 m and frequent exposure to intense wind.

3. Materials and methods

3.1. Sample collection

We generated a high-resolution (<90 year time step) temperature record spanning the termination of the AHP in East Africa

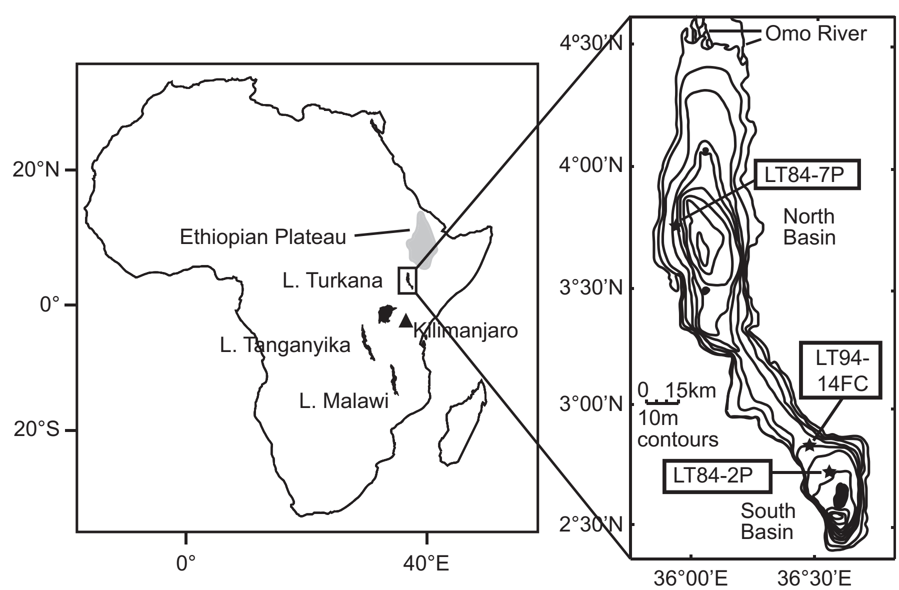

Fig. 1. Map of Africa with Lakes Turkana, Malawi, Tanganyika, and Mt. Kilimanjaro (triangle), and Ethiopian Plateau (shaded), with inset map of Lake Turkana bathymetry and core locations. Bathymetric contours are at 10 m intervals. Two piston cores were chosen for this study, recovered in 57 m of water from the south basin, (LT84-2P) and from 40 m depth in the north basin, (LT84-7P). A freeze core was also used, taken in 38 m of water in the south basin (LT94-14FC).