Palaeogeography, Palaeoclimatology, Palaeoecology 423 (2015) 80–90

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Northeast African temperature variability since the Late Pleistocene

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ARTICLE INFO

Article history:
Received 12 August 2014
Received in revised form 15 January 2015
Accepted 1 February 2015
Available online 8 February 2015

Keywords:
Tropical paleoclimate
East Africa
GDGT
Paleotemperature
Holocene
Lake Tana

ABSTRACT

The development and application of lacustrine paleotemperature proxies based on microbial membrane lipid structures, including the TEX_{86} and branched glycerol dialkyl glycerol tetraether (brGDGT) paleothermometers, have greatly advanced our understanding of the late-glacial and postglacial temperature history of Africa. However, the currently available records are from equatorial and southern hemisphere sites, limiting our understanding of the spatial patterns of temperature change. Here we use the brGDGT paleotemperature proxy to reconstruct Late Pleistocene and Holocene temperatures from Lake Tana, Ethiopia (12°N, 37°E). Following the termination of Heinrich Stadial 1 at ~15 ka, Lake Tana experienced a 3.7 °C oscillation over 1.2 ky. Temperatures then increased abruptly by nearly 7 °C between 13.8 and 13.0 ka, followed by a slow warming trend that peaked during the mid Holocene. Temperatures subsequently cooled from ~6 ka to ~0.4 ka. These data indicate that temperature at Lake Tana was sensitive to climate changes caused by variations in the Atlantic Meridional Overturning Circulation during the Late Pleistocene, as well as to regional hydroclimatic changes and reorganizations of the monsoons. Our record suggests that late-glacial temperature changes in northeast Africa were linked to high-latitude northern hemispheric climate processes, but that subsequent post-glacial temperature variations were strongly influenced by tropical hydrology.

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1. Introduction

Quantitative paleoclimate reconstructions are crucial for testing global climate models and for understanding the drivers of past and future climate change (Schmittner et al., 2011; Shakun et al., 2012). Despite the importance of tropical temperatures in driving atmospheric convection, continental temperature reconstructions from the tropics are very limited. This is largely due to difficulties in reconstructing tropical continental temperatures using conventional proxies, such as tree rings (e.g., Gebrekirstos et al., 2009), pollen (e.g., Coetzee, 1967), and stable isotopes (e.g., Thompson et al., 2002). In recent years, the development of glycerol dialkyl glycerol tetraether (GDGT) paleothermometry has greatly enhanced our ability to reconstruct terrestrial tropical temperatures and the thermal history of Africa in particular. The TEX_{86} proxy (TetraEther indeX of tetraethers with 86 carbon atoms; Schouten et al., 2002), based on the relative abundances of isoprenoidal GDGTs produced by mesophilic archaea, has been used to reconstruct past temperature in Lakes Malawi (Powers et al., 2005; Woltering et al., 2011), Tanganyika (Tierney et al., 2008), Turkana (Berke et al., 2012b), Victoria (Berke et al., 2012a), and Albert (Berke et al., 2014). However, TEX_{86} is only applicable in some large lakes (Powers et al., 2010), limiting its ability as a widespread terrestrial paleotemperature proxy.

Branched GDGTs (brGDGTs) are produced by heterotrophic acidobacteria (Weijers et al., 2006, 2010; Sinninghe Damsté et al., 2011, 2014) and their relative abundances are also temperature dependent (Weijers et al., 2007a). BrGDGTs are much more abundant than isoprenoidal GDGTs in sediments from smaller lakes (e.g., Tierney and Russell, 2009; Powers et al., 2010; Loomis et al., 2014a), and they have been used to reconstruct paleotemperatures using lake sediments at temperate (Fawcett et al., 2011; Niemann et al., 2012), subtropical (Woltering et al., 2014), and tropical (Loomis et al., 2012) latitudes. GDGT-based temperature records from equatorial East Africa have begun to illuminate the region's thermal history and generally exhibit coherent trends and amplitudes of change on orbital timescales. For instance, these records suggest that, compared to pre-industrial period, temperatures were 3–5 °C cooler at the last glacial maximum (LGM; Powers et al., 2005; Tierney et al., 2008; Loomis et al., 2012) and between 1 and 3°C warmer during the mid-Holocene, ca. 7–5 ka (Powers et al., 2005; Tierney et al., 2008; Berke et al., 2012b; Loomis et al., 2012), similar to findings from TEX_{86} reconstructions from the region's large lakes.

Thus far, all of the published paleotemperature records from eastern Africa are from equatorial regions or the southern hemisphere, hindering our understanding of inter-hemispheric temperature variability on longer timescales. In order to better understand the climatic controls on northeastern African temperature variability and cross-equatorial spatial gradients from the late Pleistocene through the Holocene, we have reconstructed paleotemperatures from Lake Tana, Ethiopia, using the brGDGT paleotemperature proxy.

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http://dx.doi.org/10.1016/j.palaeo.2015.02.005
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2. Materials and methods

2.1. Site information

Lake Tana (12.0°N, 37.3°E; 1830 m elevation; Fig. 1) is a large (3156 km^2) but shallow (maximum depth = 14 m, mean depth = 9 m) freshwater lake located on the basaltic plateau of northeastern Ethiopia. It is a slightly alkaline (pH = 8), oligo-mesotrophic lake (Wood and Talling, 1988) with four major inflows that contribute >95% of the riverine input, and one outflow, the Blue Nile (Lamb et al., 2007).

Mean annual air temperature at Lake Tana is 18.8 °C, and total annual precipitation is 1450 mm (Kebede et al., 2006). Atmospheric temperature seasonality at Lake Tana is relatively weak, with monthly temperatures ranging from 16.3 °C in December to 21.3 °C in May (Kebede et al., 2006). Precipitation seasonality, however, is extreme at Lake Tana due to its position near the northern limit of the annual migration of the Inter-tropical Convergence Zone (ITCZ), with monthly average rainfall ranging from 2 mm in February to 430 mm in July (Kebede et al., 2006). Wind direction also varies seasonally, with southerly flow during boreal summer and northeasterly flow during boreal winter due to the east African and Indian monsoons (Wondie et al., 2007).

Mean surface water temperature at Lake Tana is 22.9 ± 0.7 °C, and water temperature does not correlate with increased runoff or primary productivity (Wondie et al., 2007). The large surface area of the lake relative to its depth, combined with diurnal atmospheric temperature variations and wind strength, inhibits the development of a thermocline in the lake, resulting in minimal seasonal stratification (Wood and Talling, 1988; Wondie et al., 2007). Given the local climate and surface water temperature measurements, hydrodynamic modeling predicts that bottom water temperatures at the deepest point (14 m) are ~1 °C colder than surface water temperatures (Dargahi and Setegn, 2011).

2.2. Core collection, sedimentology, and chronology

In October 2003, a 10.3 m sediment core (03TL3) was recovered from 13.8 m water depth near the center of the lake using a Livingstone piston corer. This core has four distinct lithological units (Lamb et al., 2007). Unit 1 (1030–1000 cm) is a dark gray silt with an organic matter content of 9–22%, and is overlain by Unit 2 (1000–955 cm), a dark brown herbaceous peat with an organic matter content of 30–70%. Unit 3 (955–937) has sharp upper and lower contacts, is comprised of slightly calcareous silt and organics, and diatom evidence suggests that it was likely deposited in waters with higher conductivity (3500 μS/cm) (Lamb et al., 2007).

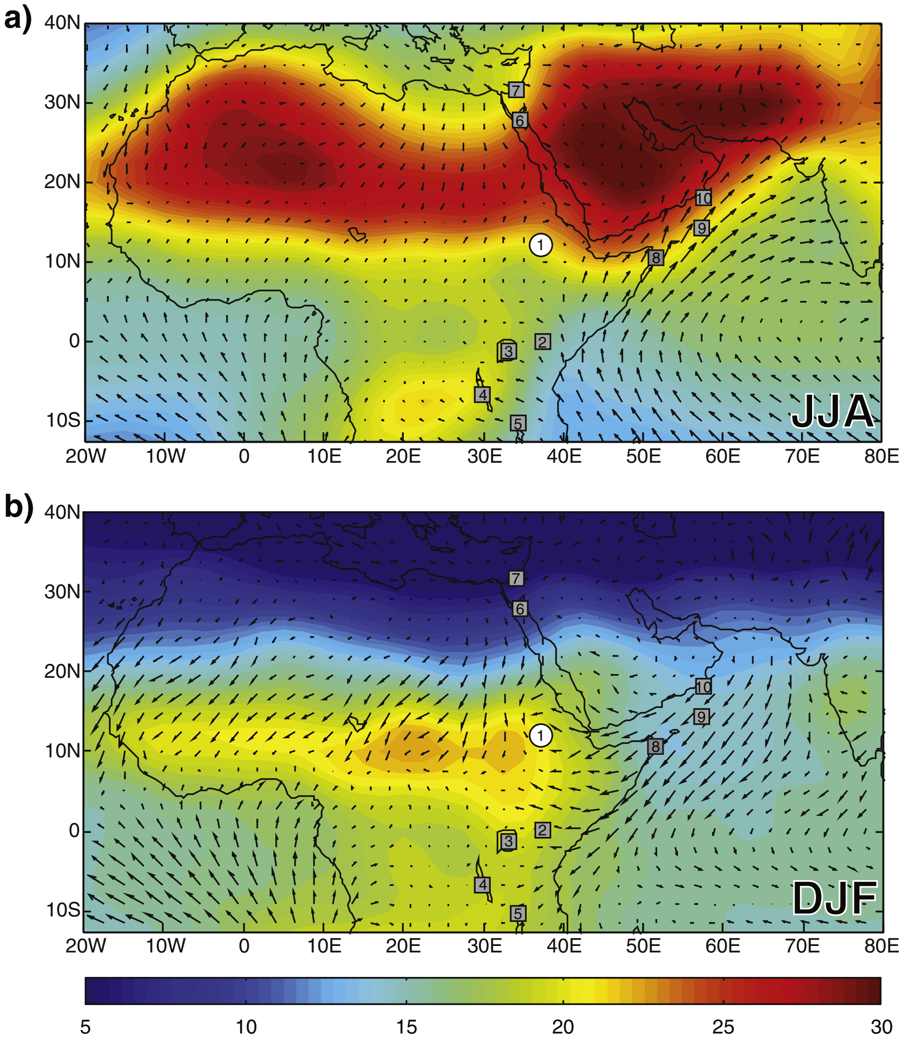

Fig. 1. Map of average surface winds and air temperatures at 850 mb. a) June, July, and August (JJA), b) December, January, and February (DJF). White dot (1) marks the location of Lake Tana core 03TL3 (this study, Marshall et al., 2011, and Costa et al., 2014), and gray boxes mark the locations of other paleoclimate records mentioned in the text. 2: Sacred Lake, (Loomis et al., 2012); 3: Lake Victoria (Berke et al., 2012a); 4: Lake Tanganyika (Tierney et al., 2008); 5: Lake Malawi (Powers et al., 2005); 6: Red Sea, GeoB 5844-2 (Arz et al., 2003); 7: Eastern Mediterranean, GeoB 7702-3 (Castañeda et al., 2010); 8: Arabian Sea, 905P (Zonneveld et al., 1997); 9: Arabian Sea, 74KL (Huguet et al., 2006); 10: Arabian Sea, ODP 723A (Naidu and Malmgren, 1996, 2005).

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