Quaternary Science Reviews 83 (2014) 58–67

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Isotopic reconstruction of the African Humid Period and Congo Air Boundary migration at Lake Tana, Ethiopia

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ARTICLE INFO

Article history:
Received 7 June 2013
Received in revised form
9 October 2013
Accepted 28 October 2013
Available online 22 November 2013

Keywords:
Tropical paleoclimate
East Africa
Compound specific hydrogen isotopes
African Humid Period
Holocene paleoclimate
Air mass trajectories
Congo Air Boundary

ABSTRACT

The African Humid Period of the early to mid-Holocene (12,000–5000 years ago) had dramatic ecological and societal consequences, including the expansion of vegetation and civilization into the "green Sahara." While the humid period itself is well documented throughout northern and equatorial Africa, mechanisms behind observed regional variability in the timing and magnitude of the humid period remain disputed. This paper presents a new hydrogen isotope record from leaf waxes (δD_{wax}) in a 15,000-year sediment core from Lake Tana, Ethiopia (12°N, 37°E) to provide insight into the timing, duration, and intensity of the African Humid Period over northeastern Africa. δD_{wax} at Lake Tana ranges between −80‰ and −170‰, with an abrupt transition from D-enriched to D-depleted waxes between 13,000–11,500 years before present (13–11.5 ka). A similarly abrupt transition from D-depleted to D-enriched waxes occurs ca 8.5–8 ka and is followed by generally D-enriched waxes throughout the late Holocene. Trends in δD_{wax} covary with changes in Northern Hemisphere summer insolation and reflect increased precipitation at Lake Tana during the AHP; however, the transition from D-depleted to D-enriched waxes occurs earlier at Lake Tana (ca 8 ka, vs 5 ka) than in many other regional records, and the amplitude of D-depletion during the AHP is larger at Lake Tana as well. We attribute this early enrichment to a reduction of moisture derived from westerly sources (the Congo Basin and Atlantic Ocean) which we suggest are D-depleted relative to moisture sourced from the east (Indian Ocean) and the north (Red Sea and Mediterranean Sea). Our new record highlights the importance of both the northward migration of the tropical rain belt as well as east-west migration of the Congo Air Boundary to precipitation source and amount during the African Humid Period.

1. Introduction

The climate of Intertropical Africa is governed by changes in the strength and position of the tropical rain belt, related to the Inter-Tropical Convergence Zone (ITCZ). The tropical rain belt migrates at seasonal to orbital time-scales in response to variations in the interhemispheric temperature gradient (Broccoli et al., 2006). Eleven thousand years before present (11 ka), when Northern Hemisphere summer insolation was at a maximum, the mean position of the tropical rain belt shifted to the north, generating increased rainfall across much of Northern Africa (Gasse, 2000). Increased precipitation and the northward expansion of vegetation zones during the African Humid Period (AHP, ca 12–5 ka) allowed ancient civilizations in North Africa to thrive, and the subsequent return to arid-semiarid climate has been invoked to explain major societal shifts, including the collapse of the Egyptian Old Kingdom (Brooks et al., 2005; Kuper and Kröpelin, 2006). The early Holocene shift to humid conditions was particularly extreme in North Africa (deMenocal et al., 2000; Gasse, 2000; Chalie and Gasse, 2002; Garcin et al., 2012), but it has also been observed in the tropical Americas (Haug et al., 2001), Asia (Wang et al., 2001; Dykoski et al., 2005), and the Middle East (Fleitmann et al., 2007).

While there is strong evidence for an orbitally-forced African Humid Period, the spatial and temporal patterns of AHP onset, intensity, and termination are highly debated. The transition into and out of the AHP has been alternately described as synchronous and abrupt (deMenocal et al., 2000; Adkins et al., 2006; Shanahan et al., 2006; Tierney et al., 2008) and asynchronous and gradual (Jung et al., 2004; Kröpelin et al., 2008; Chase et al., 2009; Niedermeyer

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http://dx.doi.org/10.1016/j.quascirev.2013.10.031

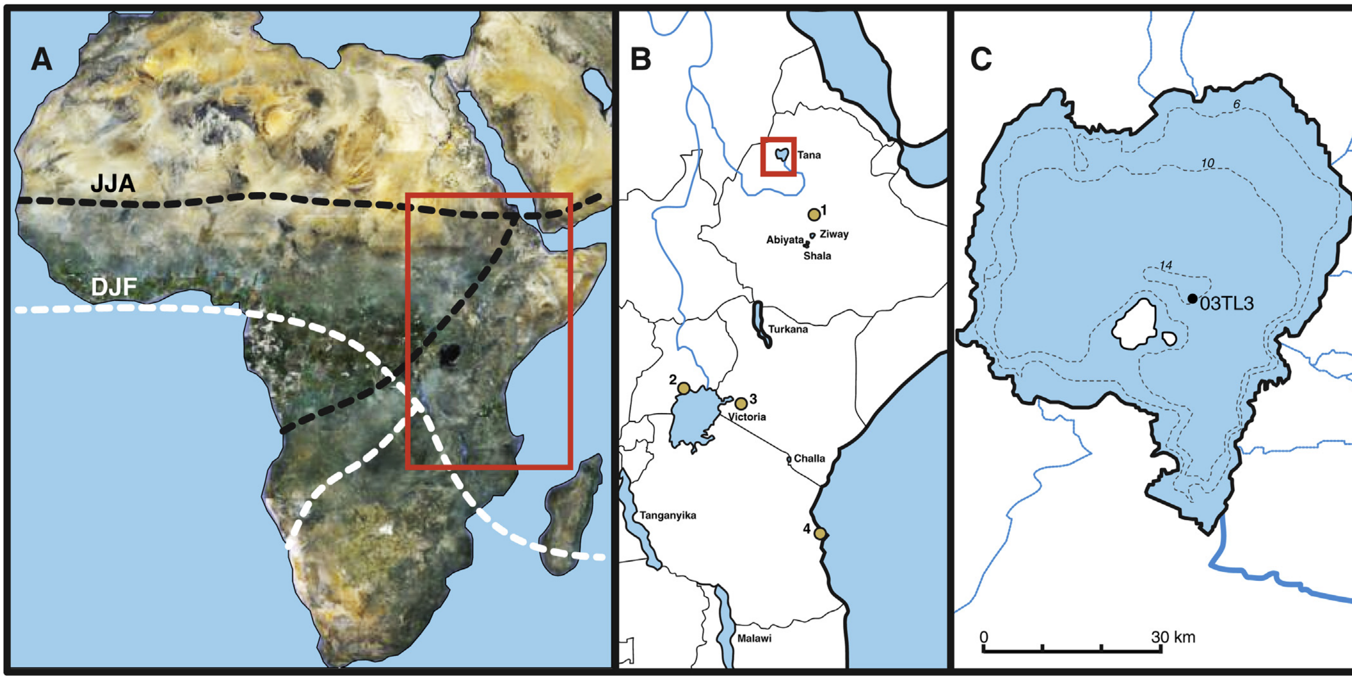

Fig. 1. A) Map of Africa illustrating the northern (JJA, black dashed lines) and southern (DJF, white dashed lines) limits of the tropical rain belt and the Congo Air Boundary (Nicholson, 1993; Tierney et al., 2011a). The red box denotes the East African lakes region. B) Magnification of the East African lakes region. Lake Tana sources the Blue Nile, which joins with White Nile, sourced from Lake Victoria, to form the Nile proper. The red box denotes Lake Tana. Numbered yellow circles indicate Global Network of Isotopes in Precipitation (GNIP) stations: 1. Addis Ababa, Ethiopia 2. Entebbe, Uganda 3. Kericho, Kenya 4. Dar es Salaam, Tanzania. C) Map of Lake Tana, showing the lake bathymetry and the location of core 03TL3. Dotted blue lines indicate river inflow, solid blue line indicates outflow, i.e., the Blue Nile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2010; Marshall et al., 2011). Results from climate models are similarly inconclusive, suggesting, for example, an abrupt transition in West Africa and a gradual one in East Africa (Hély et al., 2009) or an abrupt vegetation collapse followed by gradual precipitation decline (Liu et al., 2007). Abrupt and synchronous changes in North African rainfall have often been attributed to positive feedbacks between vegetation and precipitation (Claussen et al., 1999; deMenocal et al., 2000). However, AHP responses have also been attributed to changes in Indian Ocean sea surface temperatures, feedbacks between the monsoons and coastal upwelling intensity, and migration not only of the tropical rain belt, but also the Congo Air Boundary (CAB), the convergence zone over Central Africa that separates Atlantic and Indian Ocean air masses (Liu et al., 2003; Adkins, 2006; Tierney et al., 2008). Understanding the rate and synchroneity of the onset and termination of the AHP is important to identifying the underlying atmospheric circulation patterns and feedbacks that respond to and amplify orbitally-forced changes in the tropical rain belt, with potential significance for climate changes in the future.

Existing proxy reconstructions exhibit significant differences in the timing of the onset and, more particularly, the termination of the AHP over northern and eastern Africa. While these differences could indicate real gradients in the early to mid-Holocene hydroclimate of tropical Africa, they could also arise from the use of very different proxies (e.g., dust flux, lake salinity, vegetation), which have different inherent sensitivities, threshold effects, and possible lags when used to reconstruct surface moisture balance. The emergence of compound-specific hydrogen isotope (δD) records of African hydroclimate could help mitigate these inter-proxy inconsistencies (Tierney et al., 2008, 2011b; Konecky et al., 2011; Schefuss et al., 2011; Berke et al., 2012). This is because δD primarily records large-scale atmospheric processes such as precipitation, circulation, and convection. This paper presents a new compound-specific hydrogen isotope record from Lake Tana, Ethiopia to provide insight into how the migration of the tropical rain belt and the CAB impacts on the timing, duration, and intensity of the AHP over northeastern Africa.

2. Site information, materials, and methods

Lake Tana (12°N, 37.25°E, 1830 m elevation) is Ethiopia's largest lake, containing 50% of the country's freshwater resources (Fig. 1) (Lamb et al., 2007; Vijverberg et al., 2009). Four permanent rivers supply 95% of the lake's inflow. Hydrologic balance is maintained mainly through evaporation (64% of water loss) and outflow via the Blue Nile (Vijverberg et al., 2009). The lake is surrounded by dry montane forest as well as permanent and seasonal wetlands that are predominantly populated by *Cyperus papyrus*, *Typha latifolia*, *Phragmites karka*, *Persicaria senegalensis*, *Vossia* spp., *Scirpus* spp., and *Nymphaea lotus* (Vijverberg et al., 2009). The average annual precipitation at Lake Tana is 1410 mm (Lamb et al., 2007). Precipitation occurs almost entirely during the May–October rainy season (Vijverberg et al., 2009), when the tropical rain belt is at its northern limit and the CAB is at its eastern limit (Nicholson, 2000).

The modern isotopic composition of Ethiopian precipitation is anomalously enriched relative to other East African locations: the mean annual hydrogen isotope composition of rainfall (δD_{precip}) at Addis Ababa is 1.8‰, compared to −11.2‰ at Entebbe, Uganda, −16.3‰ at Kericho, Kenya, and −13.3‰ at Dar es Salaam, Tanzania (Rozanski et al., 1993; Levin et al., 2009). Previous work has debated the causes of this isotopically enriched precipitation, and in particular the relative influence of moisture sources derived from the Indian Ocean versus the Congo Basin and Atlantic Ocean. Some authors have attributed the D-enrichment of precipitation to the incursion of D-enriched vapor derived from the Atlantic Ocean and recycled over the central African rainforests during June–August