

Northern Hemisphere Controls on Tropical Southeast African Climate During the Past 60,000 Years

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The processes that control climate in the tropics are poorly understood. Here, we apply compound-specific hydrogen isotopes (δD) and the TEX₈₆ temperature proxy to sediment cores from Lake Tanganyika to independently reconstruct precipitation and temperature variations during the past 60,000 years. Tanganyika temperatures follow northern hemisphere insolation, and indicate that warming in tropical Southeast Africa during the last glacial termination began to rise ~3000 years before atmospheric carbon dioxide concentrations. δD data show that this region experienced abrupt changes in hydrology coeval with orbital and millennial-scale events recorded in northern hemisphere monsoonal climate records. This implies that precipitation in tropical Southeast Africa is more strongly controlled by changes in Indian Ocean sea-surface temperatures and the winter Indian monsoon than migration of the Inter-Tropical Convergence Zone.

The mechanisms that cause fluctuations of rainfall and temperature in the tropics – home to a large portion of the world's population and a region of central importance to the global hydrologic cycle – are poorly understood. One process often invoked to explain past changes in tropical precipitation and temperature is a shift in the mean-annual position of the Inter-Tropical Convergence Zone (ITCZ), which migrates meridionally in response to seasonally- and orbitally-driven changes in interhemispheric heat distribution (1, 2). However, loci of tropical precipitation and convergence within the ITCZ itself respond to changes in sea-surface temperatures (SSTs) and coupled ocean-atmosphere zonal modes, such as the El Niño-Southern Oscillation and the Indian Ocean Dipole (IOD) (3, 4), as well as the strength of the monsoons that bring moisture into the continents (5). The importance of these zonal forces acting on tropical rainfall, vis-à-vis changes in ITCZ position, is incompletely understood, in part because long, high-resolution paleoclimatic reconstructions that constrain tropical rainfall and temperature are rare.

Tropical Africa is a site of deep tropical convection and contains a population that is economically vulnerable to climatic change. The African Great Lakes, situated in the East African Rift Valley, are exquisite archives of climate change in tropical East Africa. Reconstructions of lake level fluctuations establish that East Africa was generally dry during the Last Glacial Maximum (LGM), humid during the early Holocene, and dry during the late Holocene (6). Furthermore, high-resolution records from these lakes based upon indicators such as fossil pollen, geochemistry and lithology, show that East African environmental changes are linked to global climate processes on millennial timescales (7-11). Yet available records from East Africa rarely extend beyond the LGM, and do not independently constrain rainfall and temperature. This has confounded the interpretation of humid and arid intervals in this region; the Younger Dryas, for example, is variously thought to be wet and dry in tropical Southeast Africa (8, 11).

To better understand the controls on East African temperature and hydrology, we applied the TEX₈₆ ('TetraEther index of 86 carbon atoms') paleotemperature proxy together with hydrogen isotopic analyses of terrestrial leaf waxes to sediment cores from Lake Tanganyika, at an average time-step of 300 years (Fig. 1). TEX₈₆ is based on the relative degree of cyclization of aquatic archaeal glycerol dialkyl glycerol tetraether (GDGT) isoprenoidal lipids, is linearly correlated with temperature (12), and can be applied to reconstruct the temperature of some large lakes, including Lake Tanganyika (13, 14) (SOM text 2).

Terrestrial plants are the dominant source of long-chain (C₂₆-C₃₀) monocarboxylic fatty acids in lacustrine sediments, and their deuterium/hydrogen (D/H) ratio is an excellent indicator of terrestrial hydrologic conditions (15, 16). We analyzed the δD of the C₂₈ *n*-acid (hereafter $\delta D_{\text{leaf wax}}$, expressed in ‰ vs. VSMOW), the most abundant fatty acid in our cores. Since the isotopic fractionation that occurs during leaf wax synthesis appears consistent across different plant types (due to the interactive effects of vegetation type and

relative humidity), $\delta D_{\text{leaf wax}}$ reflects changes in the δD of precipitation (15). The primary control on δD of tropical East African precipitation is the “amount effect” (17), although moisture source and history may play a secondary role. Thus, enriched δD values indicate reduced precipitation, and more depleted values represent wet periods.

Our TEX_{86} and $\delta D_{\text{leaf wax}}$ reconstructions show that temperature and hydrology in the Tanganyika basin were extremely variable throughout the past 60,000 years (Fig. 2). Holocene lake surface temperature (LST) fluctuated between $\sim 27\text{--}29^\circ\text{C}$, whereas temperatures during the LGM were $\sim 4^\circ\text{C}$ cooler. The magnitude and timing of this temperature shift is similar to that of nearby Lake Malawi (14), indicating that our TEX_{86} record captures regional temperature change in tropical Southeast Africa during deglaciation.

$\delta D_{\text{leaf wax}}$ spans a range of $\sim 50\text{‰}$, and records numerous abrupt shifts between arid and humid conditions throughout the past 60,000 yr BP. During Marine Isotope Stage (MIS) 3, rapid excursions toward enriched $\delta D_{\text{leaf wax}}$ values indicate millennial-scale pulses of aridity, the most pronounced of which is centered at $37,255 \text{ yr BP} \pm 917 \text{ yr BP}$. This event is coincident with Heinrich Event 4 (H4), which occurred at 38,000 yr BP and is the largest of the six Heinrich events during MIS 3 in the North Atlantic (18). It is possible that arid events at 47,500 and 57,000 yr BP in our record are associated with Heinrich Events 5–6 (Fig. 3), though our age control is not sufficient to constrain their timing. A positive, 15‰ shift in $\delta D_{\text{leaf wax}}$ at $\sim 16,700 \text{ yr BP}$ indicates that the most arid conditions of the past 60,000 yr BP occurred during Heinrich Event 1 (H1), yet we do not observe changes in $\delta D_{\text{leaf wax}}$ during Heinrich Events 2 and 3 (H2, H3). The dramatic expression of H4 and H1 in our record and the lack of H2 and H3 suggest a variable sensitivity of climate in the Tanganyika basin to North Atlantic climate processes, possibly due to the different magnitude of the Heinrich events themselves and their ability to propagate into the southern tropics.

Climate in the Tanganyika basin switched from arid conditions during the LGM and H1 to humid conditions in the early Holocene in two rapid steps. A 260 yr-long, 17‰ decrease in $\delta D_{\text{leaf wax}}$ occurs at 15,100 yr BP, coincident with the onset of the Bølling (19), followed by a 270 yr-long, 23‰ decrease at 11,600 yr BP, the end of the Younger Dryas (19) (Fig. 3). The early Holocene was the wettest period in our record, as indicated by $\delta D_{\text{leaf wax}}$ values that are depleted by 30‰ relative to late Holocene values. The transition toward a more arid late Holocene at about 4,700 yr BP was also abrupt, occurring within 300 years. Such rapid changes from humid to arid conditions are a persistent feature of our $\delta D_{\text{leaf wax}}$ record, suggesting that rainfall in this region responds in a nonlinear fashion to changing climatic parameters.

Interestingly, Tanganyika LST did not cool during the millennial-scale arid intervals recorded by $\delta D_{\text{leaf wax}}$ (Fig. 3). However, precipitation and temperature do co-vary on orbital timescales (Fig. 2). Shifts between warm/wet and cool/dry conditions follow northern hemisphere summer insolation, as opposed to austral summer or annual insolation at 6° S , indicating that the heat and moisture budget of this part of Africa is dynamically linked to the northern hemisphere.

In particular, Tanganyika LST at the end of the LGM follows rising northern hemisphere summer insolation, a potential trigger for deglaciation (20). Temperatures rise at $20,000 \pm 380 \text{ yr BP}$, just as they do in a TEX_{86} LST record from Lake Malawi (14) (Fig 3). This timing is consistent with rising temperatures at ca. 20,000 yr BP in Antarctica, yet leads the deglacial CO_2 rise recorded in Antarctic ice cores (21) by about 3,000 yr, a difference that is outside the chronological errors of the ice core and the LST records. Increasing greenhouse gas concentrations are therefore not responsible for the initial transmission of warming from the high latitudes to the Southeast African tropics. Yet a rapid, presumably atmospheric communication mechanism must exist for this region to “feel” northern hemisphere insolation. Aside from CO_2 , changes in the hydrologic cycle are suspect – but our $\delta D_{\text{leaf wax}}$ record indicates that precipitation did not increase until 15,100 yr BP. Thus, the mechanism linking deglacial temperature changes between high and low latitudes remains elusive.

Our $\delta D_{\text{leaf wax}}$ data is remarkably similar to isotopic records of the Asian monsoon from Hulu and Dongge Caves in China (22, 23), with arid events during the Younger Dryas, H1, and H4–H6, a wet early Holocene, and a dry late Holocene, though the timing of their respective transitions to a more arid late Holocene is different (Fig. 3). This in-phase behaviour is surprising, as northern and southern hemisphere rainfall records should be out of phase if ITCZ position were the dominant control on rainfall variability in the Tanganyika basin. During the early Holocene “African Humid Period”, for example, the ITCZ was situated farther north over Africa (24), and the region around Lake Tanganyika should have become more arid as the ITCZ spent less time in the southern tropics. Likewise, we observe that the Younger Dryas was arid in the Tanganyika basin, though a southward shift of the ITCZ would predict humid conditions (2, 9). Proxy evidence from Lake Malawi also indicates that the Younger Dryas and Heinrich events 1–5 were dry (10, 11), implying that precipitation patterns over much of tropical Southeast Africa did not respond predictably to ITCZ migration. This behavior is distinctly different from the rainfall history of southern tropical South America, which is clearly anti-phased with the northern hemisphere (25).

If ITCZ position alone cannot explain rainfall variability in tropical Southeast Africa, factors controlling the advection of

moisture to the ITCZ, as well as the strength of convergence itself, must be implicated. Indeed, sea surface temperatures, which control latent heat flux into the atmosphere, ocean-basin SST gradients, which influence large-scale atmospheric circulation patterns, and the strength of the winds that advect humidity into the continents are all important to tropical African precipitation (26, 27). These factors could effect changes in precipitation in the Lake Tanganyika basin via several different mechanisms. Wet conditions could arise from an increase in Atlantic Ocean moisture flux via the Congo Basin, as proposed by Schefuß *et al.* (27) to explain humid conditions during the early Holocene in central Africa. However, moisture flux into the Congo Basin is low at ca. 11,000 yr BP and does not reach a maximum until ca. 8,000 yr BP (27), significantly different from the timing of changes in $\delta D_{\text{leaf wax}}$ that we observe in Lake Tanganyika.

Alternatively, we argue that changes in moisture flux into Africa from the Indian Ocean basin control East African precipitation variability. Modern precipitation in Southeast Africa is highly seasonal, occurring from October – April, and most of this moisture is derived from the Indian Ocean (28). Thus we expect precipitation to vary in concert with Indian Ocean SSTs (which govern the generation of moisture), as well as the strength of the winter Indian monsoon circulation (which affects the transport of moisture). Though the winter and summer monsoons are commonly thought to work in opposition to one another (29), global climate modelling experiments show that on orbital timescales increases in northern hemisphere precession result in amplified seasonality that should intensify both the summer and winter monsoons (30, 31). A more vigorous winter Indian monsoon, then, could explain the humid conditions that prevailed in the Tanganyika basin during the Early Holocene as well as during precession maxima in MIS 3.

Winter monsoon strength does not, however, satisfactorily explain the arid episodes we observe during the Younger Dryas, H1 and H4. Zr/Ti data from Lake Malawi indicate strong northerly winds in Southeast Africa during these events (10), implying vigorous winter monsoon circulation and a southward migration of the ITCZ. Yet these events are distinctly arid in both the Tanganyika and Malawi basins. We therefore surmise that cold SSTs during millennial-scale stadials reduced latent heat flux from the western Indian Ocean, minimizing the amount of moisture transported into East Africa by the winter monsoon. Data from the Pakistan margin that indicate cooler SSTs during millennial-scale stadials in MIS 3 support this hypothesis (32).

Thus the mechanisms controlling precipitation in tropical Southeast Africa evidently vary over different timescales, though they are not necessarily mutually exclusive; Indian Ocean SSTs may also play a role in influencing orbital-scale

changes in East African rainfall. During the Early Holocene, enhanced cooling in the eastern Indian Ocean is thought to have modified Walker circulation over the basin, producing longer and more frequent positive Indian Ocean Dipole events (30). The positive IOD phase is associated with warmer SSTs in the western Indian Ocean, an intensification of convergence, and an increase in East African rainfall (4). This mechanism, alongside an increase in the Indian seasonal monsoons, could account for the humid conditions that characterize tropical East Africa during this time.

The fact that both temperature and precipitation in the Tanganyika basin show many characteristics of northern hemisphere climatic variability demonstrates that the northern hemisphere has a significant influence on climate in tropical Southeast Africa. An early warming during the last deglaciation highlights the importance of atmospheric teleconnections linking the high and low latitudes, though the mechanisms behind this relationship remain unknown. Although ITCZ migration strongly influences East African climate by modifying seasonal wind strength (9, 10) it is apparently not the dominant control on precipitation variability in tropical Southeast Africa; rather, oceanic and atmospheric factors controlling moisture generation and advection heavily influence rainfall variability in this region. Particularly, the highly non-linear character of our $\delta D_{\text{leaf wax}}$ record implies that precipitation regimes in East Africa are liable to change abruptly in response to climatic forcing. This behavior has implications for modelling the response of East African hydrology to anthropogenic climate change.

References and Notes

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Supporting Online Material

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Materials and Methods

SOM Text

Figs. S1 to S6

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References

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Fig. 1. Map of East Africa and Lake Tanganyika. Two Kullenberg piston cores collected from the Kalya Horst (S 6°42', E 29°50') in 2004 (NP04-KH04-3A-1K and NP04-KH04-4A-1K) were selected to compile a continuous sedimentary record for the past 60,000 years. The Tanganyika basin and watershed span 2–10°S, covering much of the Southeast African tropics. See SOM text 1 for regional climatology.

Fig. 2. $\delta D_{\text{leaf wax}}$ and TEX_{86} lake surface temperature (LST) from Lake Tanganyika. $\delta D_{\text{leaf wax}}$ and TEX_{86} data from core NP04-KH04-3A-1K are plotted in blue and red, and data from and NP04-KH04-4A-1K are plotted in purple and orange. The TEX_{86} data show a 0.5° offset between the two cores – this is likely due to core NP04-KH04-4A-1K's more proximal location to the eastern shore of the lake, where seasonal coastal upwelling occurs today (SOM text 2). $\delta D_{\text{leaf wax}}$ data line up well between cores, reflecting the regional character of the proxy. Chronology is constrained by 33 ^{14}C AMS dates, which are plotted for NP04-KH04-3A-1K and NP04-KH04-4A-1K as black and orange triangles, respectively (SOM Materials and Methods). June-July-August (JJA) insolation for 30°N (solid line) emphasizes the northern hemisphere influence evident in the temperature and precipitation data. December-January-February (DJF) insolation for local (6°S) (dotted line) is shown for contrast.

Fig. 3. Comparison of Lake Tanganyika TEX_{86} and $dD_{\text{leaf wax}}$ with other records of paleoclimate. Records are plotted as follows: (A) Hulu and Dongge cave $\delta^{18}\text{O}$ (21, 22). (B) Lake Tanganyika $\delta D_{\text{leaf wax}}$. (C) Deglacial CO_2 record from the Epica Dome C ice core (20). (D) Lake Malawi TEX_{86} lake surface temperature (13). (E) Lake Tanganyika TEX_{86} LST, with the NP04-KH04-4A-1K values corrected for the 0.5°C offset described in Fig. 2. Gray bars indicate the Younger Dryas (YD) and Heinrich Events 1-6 (H1-H6) as recorded in Hulu Cave and Lake Tanganyika. The onset of warming in East Africa is marked with a dotted line.





