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# Abrupt or Gradual? Change Point Analysis of the Late Pleistocene-Holocene Chew Bahir Record from Southern Ethiopia

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# ABSTRACT

We have used a change point analysis on a Late Pleistocene-Holocene lake-sediment record from the Chew Bahir basin in the southern Ethiopian Rift to determine the amplitude and duration of past climate transitions, and then assessed their possible influence on the development of early modern human cultures. The most dramatic changes occurred over 240 years (from ~15,700 to 15,460) during the onset of the African Humid Period (AHP), and over 990 years (from ~4,875 to 3,885 a BP) during its protracted termination. The AHP was interrupted by a distinct dry period coinciding with the high-latitude Younger Dryas (YD) stadial, which had an abrupt onset (less than ~100 years) at ~13,260 a BP and lasted until ~11,730 a BP. Wet-dry-wet transitions prior to the AHP may reflect the high-latitude Dansgaard-Oeschger cycles, as indicated by cross-correlation of the K record with the NorthGRIP ice core record between ~45–20 ka BP. These findings provide a valuable contribution to the debate regarding the amplitude and duration of past climate transitions and their possible influence on the development of early modern human cultures.



**Keywords:** Late Pleistocene; Holocene; Change point analysis; Principal component analysis; Paleoclimatology; Southern Ethiopian Rift; African Humid Period; Younger Dryas; Dansgaard-Oeschger cylces

# INTRODUCTION

Determining the nature and pace of changes in the environment of early modern humans is crucial to understanding the factors that influenced technological, behavioural and cognitive innovation: different modes of climate variability would have caused different modes of climatic stress and environmental boundaries (Hildebrand and Grillo, 2012; Vogelsang and Keding, 2013; Foerster et al., 2015, 2016). The timing and synchronicity of the dry-wet-dry oscillations that have significantly modulated the climate across eastern Africa are of particular interest, with important implications for human adaptation and survival in (e.g. highland) refugia (Ambrose et al., 1998; Hildebrand et al., 2010; Foerster et al., 2015) and for human dispersal, both within Africa and beyond (Carto et al., 2009; Castañeda et al., 2009).

Testing hypotheses concerning the relationship between climate and human cultural change is complicated by the complex interplays between climate, environment, and human behaviour, and relies largely on archaeological datasets and modelling (e.g., Widlok et al., 2012). The reconstruction of the climatic component on which we have focused can be compromised by uncertainties in the interpretation of climate proxies, the dating of climate archives, and the validation of modelling results. For example, while consensus prevails on the causes and nature of the African Humid Period (~14,800–5,500 a BP; deMenocal et al., 2000), the precise timing of this interval and the relative abruptness of its onset and termination in different regions remain a matter of debate (e.g., Kröpelin et al., 2008a, b; Brovkin and Claussen, 2008; Junginger and Trauth, 2013; Tierney and deMenocal, 2013; Shanahan et al., 2015; Tierney et al., 2017). Furthermore, evaluating the response of the tropical and subtropical African climate to North Atlantic cold events such as the Heinrich Events and the Younger Dryas stadial has proved controversial, with a general acceptance that the Younger Dryas had a drying effect on the African climate but with different interpretations of its timing (Roberts et al., 1993; Garcin et al., 2007; Tierney and deMenocal, 2013; Berke et al., 2014). The impacts of the Dansgaard-Oeschger (D-O) cycles and the Heinrich events of the northern hemisphere high latitudes on East African moisture availability are also subject to debate (e.g. Brown et al., 2007; Lamb et al., 2007; Garcin, 2008; Tierney and deMenocal, 2013).

In this paper we present the results of a change point analysis on high-resolution environmental records from the Chew Bahir, which we used to determine the abruptness of climatic transitions. We then discuss the possible impact of such transitions on human cultural evolution. The Chew Bahir is a 30 x 70 km saline mudflat within a tectonically bounded basin, located in a transition zone between the Main Ethiopian Rift and the Omo-Turkana basin (Fig. 1). In the Omo-Turkana basin the fossils of one of the oldest (~196 ka, McDougall et al., 2005) known anatomically modern humans have been found, although recent discoveries in Jebel Irhoud, Morocco, suggest that our species actually appears much earlier (~315 ka, Richter et al., 2017; Hublin et al., 2017). The south-western Ethiopian Highlands, which are within the 32,400 km$^2$ Chew Bahir catchment, may have been a refugium for groups of *H. sapiens* during times of climatic stress (Ambrose et al., 1998; Brandt and Hildebrand, 2005) as well as a possible hotspot of cultural innovation (Brandt et al., 2012). The several km thick deposits of the Chew Bahir basin therefore present a promissing archive of past environmental changes, containing clues to their possible influence on human expansion and cultural innovation (Campisano et al., 2017).

Our environmental record is based on a comprehensive multi-proxy analysis of six sediment cores up to 18.8 m long, collected along an approximately 20 km long NW-SE transect across the western half of the basin (Fig. 1). Three of these cores (CB-01, CB-03 and CB-05), which were collected in a pilot study for the Hominin Sites and Paleolakes Drilling Project (HSPDP; HSPDP-CHB deep coring site in Fig.1) (Cohen et al., 2016; Campisano et al., 2017) and the Collaborative Research Center CRC-806, have been described in previous publications (Foerster et al., 2012, 2015; Trauth et al., 2015). By incorporating new data from CB-02, CB-04 and CB-06 we can make a definitive contribution to the discussion on the timing of the onset and termination of the AHP, the YD, and earlier dry-wet-dry cycles, as well as the rates of change involved. As in our previous publications, we use potassium concentrations (standardized counts of XRF scans) as a proxy for aridity in the Chew Bahir (Foerster et al., 2012, 2015; Trauth et al., 2015). The potassium record spans the last 45,280 years, including the last two orbitally-driven dry-wet-dry climate alternations in north-east Africa. A dynamic time warping algorithm was used to compare and correlate proxy time series from the six sediment cores, and a principal component analysis to unmix the records and help us to separate regional from local influences. Since this continuous high-resolution record from the 32,400 km$^2$ large Chew Bahir catchment can be considered to be representative of the whole of the southern Ethiopian Plateau region, it is a promissing dataset against which to test hypotheses concerning human responses to climatic changes in north-east Africa over the last ~45 ka.

# REGIONAL SETTING

Chew Bahir (4.1–6.3°N, 36.5–38.1°E; WGS 84; Fig. 1) is a closed basin, separated from the Turkana Basin to the west by the Hammar Range. It therefore forms a terminal sink for weathering products from its 32,400 $km^2$ catchment. The perennial Weyto and Segen rivers drain from the north/north-west and north-east, respectively, to feed the playa lake. Large alluvial fans reach into the Chew Bahir basin from the flanks of the southern Ethiopian Rift and are activated during arid intervals, when the vegetation cover is sparse (Foerster et al., 2012). The Hammar Range to the west and the highlands to the north and north-east consist of Late Proterozoic granitic and mafic gneisses with minor occurrences of meta-sedimentary rocks, whereas the eastern part of the catchment is dominated by Miocene basaltic lava flows with subordinate rhyolite-trachyte and felsic tuff intercalations. Oligocene basalt flows with subordinate rhyolites, trachytes, tuffs and ignimbrites cover the Precambrian basement units in the distal north-eastern, northern, and north-western parts of the catchment (Moore and Davidson, 1978; Davidson, 1983; Fig. 1).

The present-day climate in east and northeast Africa is influenced by a number of major air streams and convergence zones, with their effects superimposed on regional influences associated with topography, large lakes, and the oceans (Nicholson, 2017). According to the classic explanation of the seasonal cycle rainfall in the Chew Bahir catchment is associated with the passage of the ITCZ, resulting in a strongly bimodal annual cycle. The two resulting rainy seasons follow the latitudinal position of the overhead sun with a time lag of about 4-6 weeks; the "long rains" occur between March and May and the "short rains" between October and November. Short-term (annual to decadal) fluctuations in the intensity of precipitation relate to E-W adjustments in the zonal Walker circulation associated with the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), possibly as a direct response to sea-surface temperature (SST) variations in the Indian and Atlantic Oceans, which are in turn affected by the ENSO and the IOD. Changes in the relative strength of these Pacific and Indian Ocean anomalies may also explain the continuous decline of the intensity of the long rains in recent decades (Nicholson, 2017).

# MATERIALS AND METHODS

The Late Pleistocene-Holocene dry-wet-dry oscillations in the Chew Bahir basin have been reconstructed from the six sediment cores (CB01–06) collected along a ~20 km long NW–SE transect across part of the basin (Foerster et al., 2012, 2015) (Table 1, Figs. 1 and 2). The CB01 and CB02 cores were retrieved from the distal margins of an alluvial fan on the western edge of the basin, an area that is predominantly influenced by the fans from the Hammar Range and the Weyto River, while the CB04 to CB06 cores were collected from towards the center of the basin, in an area predominantly controlled by fluvio-lacustrine processes and the Segen River. The sediments in the CB03 core, which was from an intermediate location along the transect, were of mixed alluvial, lacustrine and fluvial origins with the latter relating to the Weyto and Segen rivers.

The climate proxy record from the Chew Bahir basin discussed herein is based on the abundance of potassium (K) in the sediment, as determined by micro X-ray fluorescence (µXRF); potassium has previously been shown to be a reliable proxy for aridity in the Chew Bahir cores (Foerster et al., 2012, 2014; Trauth et al., 2015). We used dynamic time warping (DTW) to automatically align the K records from cores CB02 to CB06 with the K record from core CB01 (Figs. 2 and 3). Dynamic time warping, included in MATLAB function as the `dtw` function (Mathworks, 2017a), stretches two time series onto a common set of points in time such that the sum of the Euclidean distances between corresponding points is as small as possible (Sakoe and Chiba, 1978; Paliwal et al., 1982). The core depths of the aligned cores CB01 to CB06 were converted into ages using the age model of Trauth et al. (2015) (Fig. 3)

We used a principal component analysis (PCA), included in the MATLAB function `pca` (Mathworks, 2017b), to unmix (or separate) the mixed regional and local environmental signals in cores CB01 to CB06 (Pearson, 1901; Hotelling, 1931) (Fig. 4). More than 94% of the total variance of the data set is contained in the first principal component (PC1), which we interpret to represent the regional climate signal. However, complete unmixing of the regional and site-specific signal components (including noise) was not possible since the K values from the CB01 to CB06 cores are not perfectly Gaussian distributed (Fig. 4). The temporal resolution of the climate proxy record in CB01 has a mean of approximately 16 years, ranging from ~4 years up to almost 2,000 years between about 41 and 42 ka BP. The K record after DTW alignment and PCA-based unmixing was interpolated to an evenly spaced time axis running from 0 to 45,350 a BP at 15 year intervals, which is close to the mean interval in the original data (~16 years).

In order to test the synchronicity of the African Humid Period across tropical and subtropical Africa and the relative abruptness of its onset and termination, we applied a change point search algorithm from Killick et al. (2012) to the standardized K record, i.e. the mean K values were subtracted from the individual K values and then divided by the standard deviation. The algorithm, which has recently been included in MATLAB as the `findchangepts` function (MathWorks, 2017a), detects change points by minimizing a cost function over all possible numbers and locations of change points. The `findchangepts` function yields the number of significant changes in the mean, the standard deviation, and the trend of a time series (not exceeding a maximum number of permissible changes defined by the user) that minimize the sum of the residual error and an internal fixed penalty for each change.

In order to test the Chew Bahir record for any influence from the pre-AHP centennial to millennial climate oscillations of D-O cycles and Heinrich events we calculated the correlation coefficient between the K record and the NorthGRIP (also known as NGRIP) $\delta^{18}O$ ice core record (North Greenland Ice Core Project members, 2004). We then also calculated the correlation coefficient within a sliding window of a given length covering the two records. We used Pearson's linear product-moment correlation coefficient and, since this coefficient is very sensitive to disturbances, we also used the Spearman and Kendall correlation coefficients, all implemented in the MATLAB function `corr` (MathWorks, 2017b).

# RESULTS

The micro X-ray fluorescence (µXRF) scans provided data on the elemental content of six cores CB01 to CB06 (for 26 to 47 elements, depending on the setting of the core scanner) (Figs. 2 to 4). Of all the elements analyzed we only made statistical analyses of the K records, as these have been shown to reflect past climate variability on millennial to centennial time scales (Foerster et al., 2012, 2015; Trauth et al., 2015) (Figs. 2 to 4). After DTW alignment and PCA-based unmixing the application of the change point search algorithm to the data means yielded about 15 significant transitions during the last ~45 ka (Fig. 5a). Increasing the maximum number of changes permitted in `findchangepts` yielded additional transitions bounding narrow minima (i.e. short wet episodes, based on interpretation of the K record) to the series of change points. Reducing the maximum number of changes to 10, however, resulted in the gradual increase in K concentrations at the end of the AHP being defined by just a single change point (at 4,860 a BP). Adjusting the maximum number of change points to an intermediate value placed the termination of the AHP between ~4,875 to 3,885 a BP, as suggested by two significant change points, one at the beginning of this climate transition and one at the end. The transition from wet to dry at the end of the AHP therefore appears to have lasted ~990 years in the Chew Bahir basin.

A second set of important transitions is the one defining the episode of higher K concentrations that coincides with the Younger Dryas stade. According to our analysis the onset of this ~1,500 year long dry episode in the Chew Bahir basin was at 13,260 a BP and it lasted until 11,730 a BP. Prior to the YD there was a transition from dry to wet evident in the CB01–CB04 and CB06 cores, but not in the central core (CB05). This very abrupt transition is dated at 15,640 a BP, most likely marking the onset of the AHP in the Chew Bahir basin. Earlier transitions from an even drier to a wetter climate (as indicated by changes from high to low K concentrations) occur at 19,860 and 20,520 a BP. In the older parts (i.e. prior to ~20 ka BP) of the cores, there are numerous rapid shifts from dry (high K) to wet (low K) and back within less than a thousand years; the pattern of these rapid transitions resembles the D-O cycles of high latitudes, as discussed below.

Many of these transitions in the mean K concentration are also associated with changes in the variability of K concentrations, as indicated by the change point search in the standard deviation (Fig. 5b). For instance, the change point algorithm finds a step-wise decrease in variability at 4,875 a BP, and again at 3,870 a BP, most likely caused by an episode of relative instability that is characterized by a relative wet climate between

~7.15 and ~5 ka BP interrupted by at least fourteen distinct dry events, each lasting between ~20 and 80 years (Figs. 2 to 4); this episode is followed by a relatively dry and stable climate after ~5 ka BP (Fig. 3a in Trauth et al., 2015). The Younger Dryas dry period is also bounded by two transitions in the standard deviation (from wet to dry and then back again), at 13,260 and 11,730 a BP, which are the same dates as the transitions in the mean. The onset of the AHP, as defined by a change in the mean K concentration at 15,640 a BP, is also associated with a change point in the standard deviation at about the same date. Similarly, the older step-wise dry-wet transitions in the mean K concentration are associated with changes in the standard deviation at more or less the same times.

The change point search algorithm also allows us to analyse changes in the trend of the K concentration (Fig. 5c). It is interesting to note that the termination of the AHP took much longer if one considers the trend, extending from 5,835 to 3,840 a BP and therefore including a longer period of the episode of instability detected from the mean K concentrations, which lasted from ~7.15 to 3.8 ka BP. The trend analysis suggests that the wet-dry-wet episode corresponding to the Younger Dryas started at 13,260 a BP and ended at 11,730 a BP, which is very close to the dates obtained from analysis of the mean K concentrations. According to the change point in the trend the onset of the African Humid Period was at 15,640 a BP, which is exactly the same as the date obtained from the mean and standard deviation analyses. The search for change points in the trend of the older part of the K record reveals numerous sawtooth-type intervals, terminated by significant change points, with the earlier ones defining short periods with lower K concentrations (i.e. wetter conditions).

Correlating the entire K record from CB01 with the $\delta^{18}O$ record from the NorthGRIP ice core (North Greenland Ice Core Project members, 2004) yields a Pearson correlation coefficient of –0.61, which is similar to the Spearman correlation coefficient (–0.60) but differs from the Kendall correlation coefficient (–0.42), i.e. high negative $\delta^{18}O$ values correlate with high positive K values (Fig. 6). These results suggest a weak but consistently negative correlation, i.e., cold climates in the high northern latitudes correlate with (but do not necessarily cause) dry climates in the Chew Bahir basin. Piecewise cross correlation using the Spearman coefficient with a window size of 100 data points (corresponding to 100 x 15 a = 1,500 a) reveals that this negative correlation is not stationary. In fact periods of negative and positive correlation alternate with each other, interrupted at times by periods with no correlation. It is interesting to note that episodes with a correlation below –0.5 occur prior to ~25 ka BP, briefly at about 20 ka BP, and between 15 and 10 ka BP, i.e. at the same times as D-O cycles and the YD stadial in Greenland, whereas the correlation is positive or absent (values of 0–0.5) during relatively wet climatic episodes. Qualitatively similar results were obtained from correlation analyses using Pearson's and Kendall's correlation coefficients instead of the Spearman's coefficient.

# DISCUSSION AND CONCLUSIONS

*Climatic transitions in the Chew Bahir record*

The potassium record from the Chew Bahir basin provides one of the most complete and detailed records of eastern African climatic variations, covering two full precessional cycles (the last ~45 ka) (Figs. 5 and 6). The six cores (CB01–06) generally recorded the same climate signals but with different intensities (Figs. 2 to 4). The CB01–03 cores were collected at increasing distances from the Hammar Range, which is the main sediment source, while the CB04–06 cores were collected towards the centre of the basin. The centre of the Chew Bahir basin is influenced to some extent by the Segen River, whereas the more western sites are increasingly influenced by runoff from the Hammar Range via the extensive alluvial fans, and episodically by the Weyto River. As a result there are significant differences in the type of sediment, the rate of sedimentation and, most importantly, in the potassium concentrations in the sediments as well as the variability of these potassium concentrations. These differences can be used to separate influences that are specific to particular coring locations from regional influences with features that are clearly common to all areas. The AHP and the dry period during the YD stadial can, for example, be identified in all of the investigated cores and the dry-wet-dry alternations during the D-O events in most of them, while some of the less distinct dry-wet transitions during glacial times can only be observed in the CB01, CB04 and CB06 cores, and to a lesser extent also in CB03.

The high-resolution K record from the Chew Bahir basin is a promissing dataset for testing currently debated hypotheses on the abruptness of the onset of the AHP and the gradual character of its termination (e.g., deMenocal et al., 2000; Kröpelin et al., 2008a, b; Brovkin and Claussen, 2008; Junginger and Trauth, 2013; Tierney and deMenocal, 2013; Costa, et al., 2014; Shanahan et al., 2015). The onset and termination of the AHP, and also of the YD, are represented by the most dramatic changes in most environmental records from northern and equatorial Africa, for example in the terrestrial dust records from off the West African coast that are used as a proxy for aridity (deMenocal et al., 2000), in the $\delta^{15}N$ data from the Gulf of Oman (18°N) used as a proxy for denitrification and productivity (Altabet et al., 2002), and in the δD leaf wax data from Lake Tanganyika used as a record of precipitation (Tierney et al., 2008); they are also represented by the most dramatic changes in the K record from lake sediments in the Chew Bahir basin (Figs. 5 and 6).

There is a general consensus that the AHP was a result of increased insolation, higher sea-surface temperatures in the Indian Ocean, and increased atmospheric greenhouse gas concentrations (e.g., Kutzbach and Street-Perrott, 1985; Gasse, 2000; Otto-Bliesner et al., 2014). The results of our statistical analysis leave no doubt that the AHP, as recorded in the sediments of the Chew Bahir basin in southern Ethiopia, started abruptly at ~15,640 a BP. Given that our age model is sufficiently accurate, this transition would have taken less than 250 years (Figs. 5 and 6). In contrast, the termination of the AHP was rather gradual, as recorded by an 990 year transition in the mean K concentration (between 4,875 to 3,885 a BP), or an even longer transition (~1,995 years) in the trend of the K concentration (between 5,835 to 3,840 a BP). Both estimates for the duration of the wet-dry transition at the end of the AHP suggest that the climate changed more rapidly than the orbitally-induced reduction in insolation, which in turn suggests a nonlinear response of the Chew Bahir climate to the resultant forcing (Claussen et al., 1999) (Figs. 5 and 6). The mid-point of the termination of the AHP at ~4,860 a BP, as determined by our change point analysis with a small number of possible transitions, is in agreement with the findings of Kuper and Kröpelin (2006) and Shanahan et al. (2015), suggesting a time-transgressive termination of the AHP during the course of the gradual southward migration of the tropical rain belt over approximately the last 7 ka. Holocene speleothem records from the south-eastern Ethiopian highlands, with annual to decadal resolutions, also show a gradual decrease in rainfall between ~6.5 and 4.5 ka BP (Asrat et al., 2007; Baker et al., 2010).

One of the remarkable features of the K record from the Chew Bahir basin is the significant wet-dry-wet oscillation between 13,260 and 11,730 a BP (Foerster et al., 2012) (Figs. 5 and 6) in which the transition into and out of the dry episode is synchronous (within the errors of the age model) with the high northern latitude Younger Dryas stade (12,900–11,700 a BP; Alley, 2000), suggesting a strong climate teleconnection between high and low latitudes over millennial time scales. This teleconnection is also expressed in the $TEX_{86}$ temperature and dD leaf wax record from Lake Albert (Berke et al., 2014), which show dramatic variations in temperature and moisture within the YD chronozone. The transition from wet to dry at the onset of the dry episode in the Chew Bahir record occurred within ~45 years (i.e. three data points of the K record), whereas the dry-to-wet transition lasted ~250 years (i.e. 17 data points of the K record). The abruptness and magnitude of change from wet to dry and back again within decades or centuries enables us to discern the impact of this dramatic global (or hemispheric) climate change on the region.

The rapid fluctuations between ~46 and 20 ka BP are reminiscent of the high-latitude D-O cycles, whose expression in the tropics is also a matter of intense discussion (e.g. Brown et al., 2007; Garcin, 2008; Brown et al., 2008; Tierney and deMenocal, 2013). Our analysis clearly demonstrates that D-O type patterns are evident in the Chew Bahir record, as indicated by a high negative correlation between the K concentrations and the $\delta^{18}O$ record from the NorthGRIP ice core (North Greenland Ice Core Project members, 2004). It is interesting to note that a similar negative correlation also exists between ~15–10 ka BP, including the dry episode during the YD stadial, whereas there is either a positive correlation or no correlation (correlation coefficient values of 0–0.5) during those episodes with wetter climates.

### *Implications of different climatic transitions for humans*

Understanding how the east and northeast African climate switched from dry to wet and back to dry is essential for deciphering the effect that environmental instability may have had on human behaviour (e.g., Bradtmöller et al., 2012; Widlok et al., 2012; Foerster et al., 2015). The K record in Chew Bahir lake sediments provides detailed information on how the environment responded to the gradual changes in insolation that occurred in a nonlinear, saddle-node bifurcation type of transition at the end of the AHP (Trauth et al., 2015). This high-resolution (~15 a) record provides an important basis for discussions on the nature of, and reasons for, the human cultural transition in this region from fishing to herding (Ambrose, 1998; Marshall and Hildebrand, 2002; Scheinfeldt et al., 2010). The record clearly shows that the climate evolved from rather stable wet conditions prior to ~7.15 ka BP towards rather stable dry conditions after ~3.8 ka BP.

Most of the intermediate interval between 7.15 and 3.8 ka BP is characterized by rather wet conditions but these are interrupted by at least 14 dry events that recurred every 160±40 years and lasted between 20 and 80 years (Figs. 5 and 6), which may have had a major influence on the livelihoods and life decisions of the human population. The final transition to predominantly dry conditions, and hence the actual termination of the AHP in the Chew Bahir basin, occurred over a relatively long time period of about 990 years. The impact that this prolonged transition from wet to dry conditions had on the livelihood of humans compared to that of a series of precursor droughts that occurred prior to the termination of the AHP is a matter of considerable interest for future investigation. In contrast, the transition from wet to dry within ~45 years (at ~13,260 a BP, within the errors of the age model) at the onset of the dry episode coinciding with the YD stadial must have certainly affected humans living in the area. Our record suggests that this change in climate was likely to have had a much more dramatic effect on human behaviour than the drought events that occurred just before the end of the AHP.

It would be interesting to examine the archaeological evidence in order to determine if there was any corresponding change in the behaviour of humans with respect to food gathering, population size, or migration. The end of this dry episode at ~11,730 a BP would have resulted in a return to more favourable conditions for humans. This transition from dry to wet conditions occurred over about 250 years which is considerably longer than a human lifespan and probably did not result in any catastrophic flooding of previously dry lakes (such as the Chew Bahir); it may therefore not have forced any change in human habitats. Analysis of archaeological data from the Chew Bahir region related to these rapid climate changes caused by the high latitude YD teleconnection will improve our understanding of the influence that such changes had on human behaviour. Similarly, archaeological data for time periods characterized by D-O triggered dry-wet-dry fluctuations are likely to provide additional insights into early human behaviour during periods of rapid climate change.

Human-environment interactions are difficult to understand and even more difficult to reconstruct from paleorecords. The inter-relationship is complex and although causality is often inferred purely on the basis of time correlation between climatic change and human reaction (evolution, migration, adaption), it may not be as simple a cause-and-effect relationship as often portrayed by natural scientists (Widlok et al., 2012; Bradtmöller, 2012). High-resolution paleoclimate records such as that of Chew Bahir help us to critically evaluate established hypotheses and to design alternatives, thus leading to a better understanding of human-environment interactions.

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Figure 1 | (A) Geologic map of the Chew Bahir basin, showing the three generalized rock types: Cenozoic rift sediments, Cenozoic rift volcanics, and Proterozoic basement. Compilation based on Omo River Project Map (Davidson, 1983), Geology of the Sabarei Area (Key, 1987), Geology of the Yabello Area (Hailemeskel and Fekadu, 2004), and Geology of the Agere Maryam Area (Hassen et al., 1997). (B) Topographic map of the Chew Bahir basin, showing the outline of the catchment, the drainage network, the location of the short cores in the pilot study (2009, 2010), and the 2014 HSPDP-CHB drill site.

Figure 2 | Variation in the K concentration of the CB01–06 cores (in standardized counts per second, cps) plotted against the core depth (in cm). For comparison with CB01, which was measured using a molybdenum tube, all records were standardized (mean=0, standard deviation=1). Please note reverse scale of potassium axis.

Figure 3 | Variation in the K content (in standardized counts per second, cps) of the Chew Bahir plotted against age (in ka BP). We used dynamic time warping (DTW) to automatically align the K records from cores CB02 to CB06 with that from core CB01. The core depths of the aligned cores were converted into ages using the age model of Trauth et al. (2015). Please note reverse scale of potassium axis. We have offset the individual time series by 2 standardized cps in each case to allow an overlap-free display of the K records.

Figure 4 | Results of a principal component analysis to unmix (or separate) the regional environmental signal from the local signal in cores CB01 to CB06. More than 94% of the total variance of the data set is contained in the first principal component (PC1), which we interpret to represent the regional climate signal. We have offset the individual time series by 2 standardized cps in each case to allow an overlap-free display of the K records.

Figure 5 | Results of change point analyses on the K record after DTW alignment and PCA-based unmixing: (a) change points in the mean; (b) change points in the standard deviation; (c) change points in the trend.

The change point algorithm yields about 15 significant transitions in the mean, standard deviation and trend, the most marked of which occur at the onset of, and during, the termination of the African Humid Period (AHP), interrupted by the Younger Dryas (YD) dry episode. Note reversed scale of potassium axis.

Figure 6 | Comparing the K record after DTW alignment and PCA-based unmixing with the $\delta^{18}O$ data from the NorthGRIP ice core (North Greenland Ice Core Project members, 2004) suggests a weak negative correlation (Spearman coefficient less than –0.5) between environmental fluctuations in the Chew Bahir basin and high-latitude northern hemisphere millennial-scale climate fluctuations that occurred between 46 and 25 ka BP (during the Dansgaard-Oeschger cycles), and between 15 and 5 ka BP (including the Younger Dryas stade). Please note reverse scale of potassium axis.