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*Published in:*  
Quaternary Research

*DOI:*  
[10.1017/qua.2018.30](https://doi.org/10.1017/qua.2018.30)

*Publication date:*  
2018

*Citation for published version (APA):*

Trauth, M., Foerster, V., Junginger, A., Asrat, A., Lamb, H., & Schaebitz, F. (2018). Abrupt or gradual? Change point analysis of the late Pleistocene–Holocene climate record from Chew Bahir, southern Ethiopia. *Quaternary Research*, 90(2), 321-330. <https://doi.org/10.1017/qua.2018.30>

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

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15

16 **ABSTRACT**

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

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

31

## 32 INTRODUCTION

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

41 Testing hypotheses concerning the relationship between climate and human cultural change is complicated  
42 by the complex interplays between climate, environment, and human behaviour, and relies largely on  
43 archaeological datasets and modelling (e.g., [Widlok et al., 2012](#)). The reconstruction of the climatic  
44 component on which we have focused can be compromised by uncertainties in the interpretation of climate  
45 proxies, the dating of climate archives, and the validation of modelling results. For example, while consensus  
46 prevails on the causes and nature of the African Humid Period (~14,800–5,500 a BP; [deMenocal et al.,](#)  
47 [2000](#)), the precise timing of this interval and the relative abruptness of its onset and termination in different  
48 regions remain a matter of debate (e.g., [Kröpelin et al., 2008a, b](#); [Brovkin and Claussen, 2008](#); [Junginger](#)  
49 [and Trauth, 2013](#); [Tierney and deMenocal, 2013](#); [Shanahan et al., 2015](#); [Tierney et al., 2017](#)). Furthermore,  
50 evaluating the response of the tropical and subtropical African climate to North Atlantic cold events such as  
51 the Heinrich Events and the Younger Dryas stadial has proved controversial, with a general acceptance that  
52 the Younger Dryas had a drying effect on the African climate but with different interpretations of its timing  
53 ([Roberts et al., 1993](#); [Garcin et al., 2007](#); [Tierney and deMenocal, 2013](#); [Berke et al., 2014](#)). The impacts of  
54 the Dansgaard-Oeschger (D-O) cycles and the Heinrich events of the northern hemisphere high latitudes on  
55 East African moisture availability are also subject to debate (e.g. [Brown et al., 2007](#); [Lamb et al., 2007](#);  
56 [Garcin, 2008](#); [Tierney and deMenocal, 2013](#)).

57 In this paper we present the results of a change point analysis on high-resolution environmental records from  
58 the Chew Bahir, which we used to determine the abruptness of climatic transitions. We then discuss the  
59 possible impact of such transitions on human cultural evolution. The Chew Bahir is a 30 x 70 km saline  
60 mudflat within a tectonically bounded basin, located in a transition zone between the Main Ethiopian Rift and  
61 the Omo-Turkana basin (Fig. 1). In the Omo-Turkana basin the fossils of one of the oldest (~196 ka,  
62 McDougall et al., 2005) known anatomically modern humans have been found, although recent discoveries  
63 in Jebel Irhoud, Morocco, suggest that our species actually appears much earlier (~315 ka, Richter et al.,  
64 2017; Hublin et al., 2017). The south-western Ethiopian Highlands, which are within the 32,400 km<sup>2</sup> Chew  
65 Bahir catchment, may have been a refugium for groups of *H. sapiens* during times of climatic stress  
66 (Ambrose et al., 1998; Brandt and Hildebrand, 2005) as well as a possible hotspot of cultural innovation  
67 (Brandt et al., 2012). The several km thick deposits of the Chew Bahir basin therefore present a promising  
68 archive of past environmental changes, containing clues to their possible influence on human expansion and  
69 cultural innovation (Campisano et al., 2017).

70 Our environmental record is based on a comprehensive multi-proxy analysis of six sediment cores up to 18.8  
71 m long, collected along an approximately 20 km long NW-SE transect across the western half of the basin  
72 (Fig. 1). Three of these cores (CB-01, CB-03 and CB-05), which were collected in a pilot study for the  
73 Hominin Sites and Paleolakes Drilling Project (HSPDP; HSPDP-CHB deep coring site in Fig.1) (Cohen et al.,  
74 2016; Campisano et al., 2017) and the Collaborative Research Center CRC-806, have been described in  
75 previous publications (Foerster et al., 2012, 2015; Trauth et al., 2015). By incorporating new data from CB-  
76 02, CB-04 and CB-06 we can make a definitive contribution to the discussion on the timing of the onset and  
77 termination of the AHP, the YD, and earlier dry-wet-dry cycles, as well as the rates of change involved. As in  
78 our previous publications, we use potassium concentrations (standardized counts of XRF scans) as a proxy  
79 for aridity in the Chew Bahir (Foerster et al., 2012, 2015; Trauth et al., 2015). The potassium record spans  
80 the last 45,280 years, including the last two orbitally-driven dry-wet-dry climate alternations in north-east  
81 Africa. A dynamic time warping algorithm was used to compare and correlate proxy time series from the six  
82 sediment cores, and a principal component analysis to unmix the records and help us to separate regional  
83 from local influences. Since this continuous high-resolution record from the 32,400 km<sup>2</sup> large Chew Bahir

84 catchment can be considered to be representative of the whole of the southern Ethiopian Plateau region, it is  
85 a promising dataset against which to test hypotheses concerning human responses to climatic changes in  
86 north-east Africa over the last ~45 ka.

## 87 REGIONAL SETTING

88 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  
89 to the west by the Hammar Range. It therefore forms a terminal sink for weathering products from its 32,400  
90 km<sup>2</sup> catchment. The perennial Weyto and Segen rivers drain from the north/north-west and north-east,  
91 respectively, to feed the playa lake. Large alluvial fans reach into the Chew Bahir basin from the flanks of the  
92 southern Ethiopian Rift and are activated during arid intervals, when the vegetation cover is sparse ([Foerster  
93 et al., 2012](#)). The Hammar Range to the west and the highlands to the north and north-east consist of Late  
94 Proterozoic granitic and mafic gneisses with minor occurrences of meta-sedimentary rocks, whereas the  
95 eastern part of the catchment is dominated by Miocene basaltic lava flows with subordinate rhyolite-trachyte  
96 and felsic tuff intercalations. Oligocene basalt flows with subordinate rhyolites, trachytes, tuffs and  
97 ignimbrites cover the Precambrian basement units in the distal north-eastern, northern, and north-western  
98 parts of the catchment ([Moore and Davidson, 1978](#); [Davidson, 1983](#); [Fig. 1](#)).

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

109 in the relative strength of these Pacific and Indian Ocean anomalies may also explain the continuous decline  
110 of the intensity of the long rains in recent decades (Nicholson, 2017).

## 111 **MATERIALS AND METHODS**

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

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

130 We used a principal component analysis (PCA), included in the MATLAB function `pca` (Mathworks, 2017b),  
131 to unmix (or separate) the mixed regional and local environmental signals in cores CB01 to CB06 (Pearson,  
132 1901; Hotelling, 1931) (Fig. 4). More than 94% of the total variance of the data set is contained in the first  
133 principal component (PC1), which we interpret to represent the regional climate signal. However, complete

134 unmixing of the regional and site-specific signal components (including noise) was not possible since the K  
135 values from the CB01 to CB06 cores are not perfectly Gaussian distributed (Fig. 4). The temporal resolution  
136 of the climate proxy record in CB01 has a mean of approximately 16 years, ranging from ~4 years up to  
137 almost 2,000 years between about 41 and 42 ka BP. The K record after DTW alignment and PCA-based  
138 unmixing was interpolated to an evenly spaced time axis running from 0 to 45,350 a BP at 15 year intervals,  
139 which is close to the mean interval in the original data (~16 years).

140 In order to test the synchronicity of the African Humid Period across tropical and subtropical Africa and the  
141 relative abruptness of its onset and termination, we applied a change point search algorithm from Killick et al.  
142 (2012) to the standardized K record, i.e. the mean K values were subtracted from the individual K values and  
143 then divided by the standard deviation. The algorithm, which has recently been included in MATLAB as the  
144 `findchangepts` function (MathWorks, 2017a), detects change points by minimizing a cost function over all  
145 possible numbers and locations of change points. The `findchangepts` function yields the number of  
146 significant changes in the mean, the standard deviation, and the trend of a time series (not exceeding a  
147 maximum number of permissible changes defined by the user) that minimize the sum of the residual error  
148 and an internal fixed penalty for each change.

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

## 156 RESULTS

157 The micro X-ray fluorescence ( $\mu\text{XRF}$ ) scans provided data on the elemental content of six cores CB01 to  
158 CB06 (for 26 to 47 elements, depending on the setting of the core scanner) (Figs. 2 to 4). Of all the elements



159 analyzed we only made statistical analyses of the K records, as these have been shown to reflect past  
160 climate variability on millennial to centennial time scales (Foerster et al., 2012, 2015; Trauth et al., 2015)  
161 (Figs. 2 to 4). After DTW alignment and PCA-based unmixing the application of the change point search  
162 algorithm to the data means yielded about 15 significant transitions during the last ~45 ka (Fig. 5a).  
163 Increasing the maximum number of changes permitted in `findchangepts` yielded additional transitions  
164 bounding narrow minima (i.e. short wet episodes, based on interpretation of the K record) to the series of  
165 change points. Reducing the maximum number of changes to 10, however, resulted in the gradual increase  
166 in K concentrations at the end of the AHP being defined by just a single change point (at 4,860 a BP).  
167 Adjusting the maximum number of change points to an intermediate value placed the termination of the AHP  
168 between ~4,875 to 3,885 a BP, as suggested by two significant change points, one at the beginning of this  
169 climate transition and one at the end. The transition from wet to dry at the end of the AHP therefore appears  
170 to have lasted ~990 years in the Chew Bahir basin.

171 A second set of important transitions is the one defining the episode of higher K concentrations that  
172 coincides with the Younger Dryas stade. According to our analysis the onset of this ~1,500 year long dry  
173 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  
174 was a transition from dry to wet evident in the CB01–CB04 and CB06 cores, but not in the central core  
175 (CB05). This very abrupt transition is dated at 15,640 a BP, most likely marking the onset of the AHP in the  
176 Chew Bahir basin. Earlier transitions from an even drier to a wetter climate (as indicated by changes from  
177 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  
178 the cores, there are numerous rapid shifts from dry (high K) to wet (low K) and back within less than a  
179 thousand years; the pattern of these rapid transitions resembles the D-O cycles of high latitudes, as  
180 discussed below.

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

185 ~7.15 and ~5 ka BP interrupted by at least fourteen distinct dry events, each lasting between ~20 and 80  
186 years (Figs. 2 to 4); this episode is followed by a relatively dry and stable climate after ~5 ka BP (Fig. 3a in  
187 Trauth et al., 2015). The Younger Dryas dry period is also bounded by two transitions in the standard  
188 deviation (from wet to dry and then back again), at 13,260 and 11,730 a BP, which are the same dates as  
189 the transitions in the mean. The onset of the AHP, as defined by a change in the mean K concentration at  
190 15,640 a BP, is also associated with a change point in the standard deviation at about the same date.  
191 Similarly, the older step-wise dry-wet transitions in the mean K concentration are associated with changes in  
192 the standard deviation at more or less the same times.

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

204 Correlating the entire K record from CB01 with the  $\delta^{18}\text{O}$  record from the NorthGRIP ice core (North  
205 Greenland Ice Core Project members, 2004) yields a Pearson correlation coefficient of  $-0.61$ , which is  
206 similar to the Spearman correlation coefficient ( $-0.60$ ) but differs from the Kendall correlation coefficient ( $-$   
207  $0.42$ ), i.e. high negative  $\delta^{18}\text{O}$  values correlate with high positive K values (Fig. 6). These results suggest a  
208 weak but consistently negative correlation, i.e., cold climates in the high northern latitudes correlate with (but  
209 do not necessarily cause) dry climates in the Chew Bahir basin. Piecewise cross correlation using the  
210 Spearman coefficient with a window size of 100 data points (corresponding to  $100 \times 15 \text{ a} = 1,500 \text{ a}$ ) reveals

211 that this negative correlation is not stationary. In fact periods of negative and positive correlation alternate  
212 with each other, interrupted at times by periods with no correlation. It is interesting to note that episodes with  
213 a correlation below  $-0.5$  occur prior to  $\sim 25$  ka BP, briefly at about 20 ka BP, and between 15 and 10 ka BP,  
214 i.e. at the same times as D-O cycles and the YD stadial in Greenland, whereas the correlation is positive or  
215 absent (values of  $0-0.5$ ) during relatively wet climatic episodes. Qualitatively similar results were obtained  
216 from correlation analyses using Pearson's and Kendall's correlation coefficients instead of the Spearman's  
217 coefficient.

## 218 **DISCUSSION AND CONCLUSIONS**

### 219 *Climatic transitions in the Chew Bahir record*

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

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

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

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

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

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

282 Understanding how the east and northeast African climate switched from dry to wet and back to dry is  
283 essential for deciphering the effect that environmental instability may have had on human behaviour (e.g.,  
284 Bradtmöller et al., 2012; Widlok et al., 2012; Foerster et al., 2015). The K record in Chew Bahir lake  
285 sediments provides detailed information on how the environment responded to the gradual changes in  
286 insolation that occurred in a nonlinear, saddle-node bifurcation type of transition at the end of the AHP  
287 (Trauth et al., 2015). This high-resolution (~15 a) record provides an important basis for discussions on the

288 nature of, and reasons for, the human cultural transition in this region from fishing to herding (Ambrose,  
289 1998; Marshall and Hildebrand, 2002; Scheinfeldt et al., 2010). The record clearly shows that the climate  
290 evolved from rather stable wet conditions prior to ~7.15 ka BP towards rather stable dry conditions after ~3.8  
291 ka BP.

292 Most of the intermediate interval between 7.15 and 3.8 ka BP is characterized by rather wet conditions but  
293 these are interrupted by at least 14 dry events that recurred every  $160\pm 40$  years and lasted between 20 and  
294 80 years (Figs. 5 and 6), which may have had a major influence on the livelihoods and life decisions of the  
295 human population. The final transition to predominantly dry conditions, and hence the actual termination of  
296 the AHP in the Chew Bahir basin, occurred over a relatively long time period of about 990 years. The impact  
297 that this prolonged transition from wet to dry conditions had on the livelihood of humans compared to that of  
298 a series of precursor droughts that occurred prior to the termination of the AHP is a matter of considerable  
299 interest for future investigation. In contrast, the transition from wet to dry within ~45 years (at ~13,260 a BP,  
300 within the errors of the age model) at the onset of the dry episode coinciding with the YD stadial must have  
301 certainly affected humans living in the area. Our record suggests that this change in climate was likely to  
302 have had a much more dramatic effect on human behaviour than the drought events that occurred just  
303 before the end of the AHP.

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

313 triggered dry-wet-dry fluctuations are likely to provide additional insights into early human behaviour during  
314 periods of rapid climate change.

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

## 322 **ACKNOWLEDGEMENTS**

323 This project was funded by German Research Foundation (DFG) grants to M.H.T. and F.S. through the  
324 Priority Program SPP 1006 ICDP and the CRC 806 Research Project at the University of Cologne. We thank  
325 C. Ohlendorf and S. Stahl from the Geomorphology and Polar Research Group at the University of Bremen  
326 and for the XRF scans. The previously published XRF scan results for the CB01, CB03 and CB05 cores  
327 were supported by V. Wennrich at the University of Cologne. This research is part of a pilot study for the  
328 Hominin Sites and Paleolakes Drilling Project (HSPDP), within the framework of the International Continental  
329 Scientific Drilling Program (ICDP) and the DFG Priority Program SPP 1006 ICDP. This paper is publication  
330 number ### of the Hominin Sites and Paleolakes Drilling Project (HSPDP).

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530 Map ([Davidson, 1983](#)), Geology of the Sabarei Area ([Key, 1987](#)), Geology of the Yabello Area ([Hailemeskel  
531 and Fekadu, 2004](#)), and Geology of the Agere Maryam Area ([Hassen et al., 1997](#)). (B) Topographic map of  
532 the Chew Bahir basin, showing the outline of the catchment, the drainage network, the location of the short  
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534 Figure 2 | Variation in the K concentration of the CB01–06 cores (in standardized counts per second, cps)  
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536 molybdenum tube, all records were standardized (mean=0, standard deviation=1). Please note reverse scale  
537 of potassium axis.

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

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

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

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

554 Figure 6 | Comparing the K record after DTW alignment and PCA-based unmixing with the  $\delta^{18}\text{O}$  data from  
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556 correlation (Spearman coefficient less than  $-0.5$ ) between environmental fluctuations in the Chew Bahir  
557 basin and high-latitude northern hemisphere millennial-scale climate fluctuations that occurred between 46  
558 and 25 ka BP (during the Dansgaard-Oeschger cycles), and between 15 and 5 ka BP (including the Younger  
559 Dryas stage). Please note reverse scale of potassium axis.