



Aberystwyth University

Northeast African temperature variability since the Late Pleistocene

Loomis, Shannon E.; Russell, James M.; Lamb, Henry

Published in:

Palaeogeography, Palaeoclimatology, Palaeoecology

DOI:

[10.1016/j.palaeo.2015.02.005](https://doi.org/10.1016/j.palaeo.2015.02.005)

Publication date:

2015

Citation for published version (APA):

Loomis, S. E., Russell, J. M., & Lamb, H. (2015). Northeast African temperature variability since the Late Pleistocene. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 423, 80-90.

<https://doi.org/10.1016/j.palaeo.2015.02.005>

General rights

Copyright and moral rights for the publications made accessible in the Aberystwyth Research Portal (the Institutional Repository) are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Aberystwyth Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Aberystwyth Research Portal

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

tel: +44 1970 62 2400
email: is@aber.ac.uk

1 **Northeast African temperature variability since the Late Pleistocene**

2

3 Shannon E. Loomis^{a,*1}, James M. Russell^a, Henry F. Lamb^b

4

5 *^aBrown University, Department of Earth, Environmental and Planetary Sciences, 324 Brook St.,*

6 *Box 1846, Providence, RI 02912, USA*

7 *^bAberystwyth University, Department of Geography and Earth Sciences, Aberystwyth, SY23*

8 *3DB, UK*

9

10 *Corresponding author

11 *Tel: 1-512-232-5762*

12 *Email address: sloomis@jsg.utexas.edu (S. Loomis)*

13

14 *¹Currently at: University of Texas at Austin, Department of Geological Sciences, 1 University*

15 *Station C1160, Austin, TX 78712, USA*

16

17

18 **Abstract**

19 The development and application of lacustrine paleotemperature proxies based on
20 microbial membrane lipid structures, including the TEX₈₆ and branched glycerol dialkyl
21 glycerol tetraether (brGDGT) paleothermometers, have greatly advanced our
22 understanding of the late-glacial and postglacial temperature history of Africa. However,
23 the currently available records are from equatorial and southern hemisphere sites, limiting
24 our understanding of the spatial patterns of temperature change. Here we use the
25 brGDGT paleotemperature proxy to reconstruct Late Pleistocene and Holocene
26 temperatures from Lake Tana, Ethiopia (12°N, 37°E). Following the termination of
27 Heinrich Stadial 1 at ~15 ka, Lake Tana experienced a 3.7°C oscillation over 1.2 ky.
28 Temperatures then increased abruptly by nearly 7°C between 13.8 and 13.0 ka, followed
29 by a slow warming trend that peaked during the mid Holocene. Temperatures
30 subsequently cooled from ~6 ka to ~0.4 ka. These data indicate that temperature at Lake
31 Tana was sensitive to climate changes caused by variations in the Atlantic Meridional
32 Overturning Circulation during the Late Pleistocene, as well as to regional hydroclimatic
33 changes and reorganizations of the monsoons. Our record suggests that late-glacial
34 temperature changes in northeast Africa were linked to high-latitude northern
35 hemispheric climate processes, but that subsequent post-glacial temperature variations
36 were strongly influenced by tropical hydrology.

37

38 **Keywords:** tropical paleoclimate, east Africa, GDGT, paleotemperature, Holocene, Lake Tana

39

40

41 **1. Introduction**

42 Quantitative paleoclimate reconstructions are crucial for testing global climate models
43 and for understanding the drivers of past and future climate change (Schmittner et al., 2011;
44 Shakun et al., 2012). Despite the importance of tropical temperatures in driving atmospheric
45 convection, continental temperature reconstructions from the tropics are very limited. This is
46 largely due to difficulties in reconstructing tropical continental temperatures using conventional
47 proxies, such as tree rings (e.g. Gebrekirstos et al., 2009), pollen (e.g. Coetsee, 1967), and stable
48 isotopes (e.g. Thompson et al., 2002). In recent years, the development of glycerol dialkyl
49 glycerol tetraether (GDGT) paleothermometry has greatly enhanced our ability to reconstruct
50 terrestrial tropical temperatures and the thermal history of Africa in particular. The TEX₈₆ proxy
51 (TetraEther indeX of tetraethers with 86 carbon atoms; Schouten et al., 2002), based on the
52 relative abundances of isoprenoidal GDGTs produced by mesophilic archaea, has been used to
53 reconstruct past temperature in Lakes Malawi (Powers et al., 2005; Woltering et al., 2011),
54 Tanganyika (Tierney et al., 2008), Turkana (Berke et al., 2012b), Victoria (Berke et al., 2012a),
55 and Albert (Berke et al., 2014). However, TEX₈₆ is only applicable in some large lakes (Powers
56 et al., 2010), limiting its ability as a widespread terrestrial paleotemperature proxy.

57 Branched GDGTs (brGDGTs) are produced by heterotrophic acidobacteria (Weijers et
58 al., 2006, 2010; Sinninghe Damsté et al., 2011, 2014) and their relative abundances are also
59 temperature dependent (Weijers et al., 2007a). brGDGTs are much more abundant than
60 isoprenoidal GDGTs in sediments from smaller lakes (e.g. Tierney and Russell, 2009; Powers et
61 al., 2010; Loomis et al., 2014a), and they have been used to reconstruct paleotemperatures using
62 lake sediments at temperate (Fawcett et al., 2011; Niemann et al., 2012), subtropical (Woltering
63 et al., 2014), and tropical (Loomis et al., 2012) latitudes. GDGT-based temperature records from

64 equatorial East Africa have begun to illuminate the region's thermal history and generally exhibit
65 coherent trends and amplitudes of change on orbital timescales. For instance, these records
66 suggest that, compared to pre-industrial period, temperatures were 3-5°C cooler at the last glacial
67 maximum (LGM; Powers et al., 2005; Tierney et al., 2008; Loomis et al., 2012) and between 1
68 and 3 degrees warmer during the mid-Holocene, ca. 7-5 ka (Powers et al., 2005; Tierney et al.,
69 2008; Berke et al., 2012b; Loomis et al., 2012), similar to findings from TEX₈₆ reconstructions
70 from the region's large lakes.

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

77

78

79 **2. Materials and Methods**

80 *2.1 Site Information*

81 Lake Tana (12.0°N, 37.3°E; 1830 m elevation; Fig. 1) is a large (3156 km²) but shallow
82 (maximum depth = 14 m, mean depth = 9 m) freshwater lake located on the basaltic plateau of
83 northeastern Ethiopia. It is a slightly alkaline (pH = 8), oligo-mesotrophic lake (Wood and
84 Talling, 1988) with four major inflows that contribute >95% of the riverine input, and one
85 outflow, the Blue Nile (Lamb et al., 2007).

86 Mean annual air temperature at Lake Tana is 18.8°C, and total annual precipitation is
87 1450 mm (Kebede et al., 2006). Atmospheric temperature seasonality at Lake Tana is relatively
88 weak, with monthly temperatures ranging from 16.3°C in December to 21.3°C in May (Kebede et
89 al., 2006). Precipitation seasonality, however, is extreme at Lake Tana due to its position near
90 the northern limit of the annual migration of the Intertropical Convergence Zone (ITCZ), with
91 monthly average rainfall ranging from 2 mm in February to 430 mm in July (Kebede et al.,
92 2006). Wind direction also varies seasonally, with southerly flow during boreal summer and
93 northeasterly flow during boreal winter due to the east African and Indian monsoons (Wondie et
94 al., 2007).

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

103

104 *2.2 Core collection, sedimentology, and chronology*

105 In October 2003, a 10.3 m sediment core (03TL3) was recovered from 13.8 m water
106 depth near the center of the lake using a Livingstone piston corer. This core has four distinct
107 lithological units (Lamb et al., 2007). Unit 1 (1030-1000 cm) is a dark gray silt with an organic
108 matter content of 9-22%, and is overlain by Unit 2 (1000-955 cm), a dark brown herbaceous peat

109 with an organic matter content of 30-70%. Unit 3 (955-937) has sharp upper and lower contacts,
110 is comprised of slightly calcareous silt and organics, and diatom evidence suggests that it was
111 likely deposited in waters with higher conductivity (3500 $\mu\text{S}/\text{cm}$) (Lamb et al., 2007). Unit 4
112 (937-0 cm) is a uniform fine gray diatomaceous silt, containing lower organic matter and higher
113 magnetic susceptibility than Units 1-3. Core chronology is derived from mixed effect regression
114 (Heegaard et al., 2005) on 19 radiocarbon ages (Marshall et al., 2011). Errors (1σ) on the age
115 model range from 120 years over the top 200 cm of the core to 500 years at the base of Unit 4.

116

117 *2.3 Sample preparation and GDGT analysis*

118 2 cm-thick subsamples were collected from core 03TL3 every 15 cm (~ 235 yr) and were
119 transported to Brown University for preparation and analysis. Sample preparation followed that
120 of Loomis et al. (2012). Briefly, samples were freeze-dried then homogenized with a mortar and
121 pestle. Lipids were extracted using a Dionex 350 Accelerated Solvent Extractor (ASE) using 9:1
122 dichloromethane (DCM): methanol (MeOH). Extracts were separated into non-polar and polar
123 fractions with an Al_2O_3 column using 9:1 hexane:DCM and 1:1 DCM:MeOH, respectively, as
124 eluents. The polar fractions were filtered through a 0.22 μm glass fiber filter and analyzed using
125 high performance liquid chromatography/atmospheric pressure chemical ionization-mass
126 spectrometry (HPLC/APCI-MS).

127 To explore potential changes in microbial ecology through time, we quantified the
128 relative abundance of branched to isoprenoidal tetraethers (BIT; Hopmans et al., 2004) using the
129 following equation:

$$130 \quad \text{BIT} = (\text{Ia} + \text{IIa} + \text{IIIa}) / (\text{Ia} + \text{IIa} + \text{IIIa} + \text{cren}) \quad (1)$$

131 where the Roman numerals refer to structures in Figure 2. Mean annual air temperature
132 (MAAT) was reconstructed using the East African stepwise forward selection (SFS) calibration:

$$133 \quad \text{MAAT} = 22.7 - 33.58 \cdot \text{IIIa} - 12.88 \cdot \text{IIa} - 418.53 \cdot \text{IIc} + 86.43 \cdot \text{Ib} \quad (2)$$

134 of Loomis et al. (2012).

135 Analytical error was quantified by running 10% of samples in duplicate, and
136 reconstructed MAAT error was determined through bootstrapping the reconstruction with the
137 East African lakes calibration data (Loomis et al., 2012). Duplicate samples show an average
138 analytical BIT error of 0.0009, while the average analytical reconstructed MAAT error is 0.08°C.
139 Bootstrapped MAAT error on individual samples ranges from 0.2-1.3°C, with an average of
140 0.9°C (Fig 3a).

141

142

143 **3. Results and Discussion**

144 *3.1 Production and distribution of GDGTs in Lake Tana*

145 Both branched and isoprenoidal GDGTs were detected in all samples from Lake Tana
146 core 03TL3. BIT values range from 0.29 to 1.00 (mean = 0.71, standard deviation = 0.15; Fig.
147 3b), with the highest values located in the silts and peats that comprise Units 1-3 at the base of
148 the core (BIT = 0.96-1.00). BIT values remain relatively constant from the base of Unit 4 to
149 ~300 cm depth (mean = 0.75, standard deviation = 0.11), but become more variable (standard
150 deviation = 0.17) and have a lower mean (0.55) than the rest of the unit above 300 cm.

151 BrGDGT reconstructed temperatures range from 11.2 to 21.9°C (Fig. 3a). Reconstructed
152 temperatures are lowest below 800 cm, shift to higher temperatures between 800 and 775 cm,
153 and peak near 500 cm. This trend is interrupted by large negative reconstructed temperature

154 excursions in samples with BIT < 0.5 (133-59 cm). The relationship between BIT and
155 reconstructed temperatures could suggest that the environmental conditions and/or ecological
156 changes associated with increased isoprenoidal GDGTs relative to brGDGTs affects the relative
157 abundances of brGDGTs and thereby reconstructed temperatures. Before making paleoclimatic
158 interpretations of the Lake Tana brGDGT temperature record, it is important to understand the
159 environmental controls on the production of brGDGTs and their depositional history.

160

161 3.1.1 Influence of paleolimnology and sediment lithology on brGDGT distributions

162 BrGDGTs have been detected in peat (e.g. Sinninghe Damsté et al., 2000), soil (e.g.
163 Weijers et al., 2007a), lake sediments (e.g. Tierney et al., 2010), and marine sediments (e.g.
164 Weijers et al., 2007b). Although some studies have concluded that brGDGTs in particular lakes
165 are derived from soil runoff (Niemann et al., 2012; Woltering et al., 2014), the majority of
166 studies (Sinninghe Damsté et al., 2009; Tierney and Russell, 2009; Loomis et al., 2011, 2014b;
167 Tierney et al., 2012; Wang et al., 2012; Buckles et al., 2014a,b) – including all of those that have
168 been performed in the tropics – have found that the concentrations and distributions of brGDGTs
169 in lake sediments are substantially different from surrounding soils, indicating that in most
170 lacustrine environments, brGDGTs are predominantly derived from *in situ* production. The
171 differences in brGDGT distributions in lake sediments and surrounding soils can result in
172 differences between reconstructed temperatures in soils and adjacent lake sediments; for
173 instance, offsets of up to 10°C are commonly observed between soils and lake sediment in East
174 Africa (Tierney et al., 2010; Loomis et al., 2012). Thus, changes in catchment hydrology, soil
175 erosion, and lake sedimentation - such as large variations in the inputs of soil-derived organic
176 matter - have the potential to affect reconstructed temperatures from brGDGTs. While the reason

177 for these differences between brGDGTs in lakes and soils is still unknown, it is possible that it is
178 related to changes in water or gas saturation in the environment (Loomis et al., 2011) and/or
179 differences in the microbial ecology between lake and soil environments (Loomis et al., 2014a).

180 The basal units of core 03TL3 include organic-rich silts, peats, and calcareous muds that
181 could signal varying sources of brGDGTs to these sediments, including not only soil vs.
182 lacustrine production, but also *in situ* production of brGDGTs in peat. A greenhouse experiment
183 carried out on peat bogs demonstrated that brGDGT distributions in surface peat layers change in
184 response to variations in mean air temperature (Huguet et al., 2013). However, there is also good
185 evidence of *in situ* production of brGDGTs within deeper peat layers (Weijers et al., 2009;
186 Peterse et al., 2011), which may potentially alter the brGDGT distributions that were present
187 when these sections were exposed and responding to surface air temperatures, thereby biasing
188 the temperature signal. Unfortunately, widespread calibration studies have yet to be carried out
189 on peat, inhibiting our understanding of the temperature/brGDGT relationship in peat samples.

190 To examine the potential for varying brGDGT sources to affect reconstructed
191 temperatures in the Lake Tana core, we compared the fractional abundances of brGDGTs from
192 Units 1-3 to Unit 4 using one way analysis of variance (ANOVA) testing. We find that the
193 fractional abundances of brGDGTs with zero (IIIa, IIa, and Ia) and one cyclopentyl rings (IIIb,
194 IIb, Ib) are significantly different ($p \leq 0.002$) between these stratigraphic units. As several of
195 these compounds are important to our temperature calibration, and in light of the possibility of
196 changing microbial sources of brGDGTs in the variable depositional environments represented
197 by these units, we limit our temperature interpretation of reconstructed temperatures in this core
198 to Unit 4 (937-0 cm).

199 While the lithology and percent organic matter ($9.5 \pm 1.1\%$) remain fairly constant
200 throughout Unit 4 (Marshall et al., 2011), the Ti record shows substantial variability, including
201 an abrupt increase in Ti concentrations at 700 cm (~ 12 ka), a negative Ti oscillation between 515
202 and 575 cm (~ 7 -8.5 ka), and a decrease in Ti concentrations at 400 cm (~ 4.5 ka) (Fig. 4c). These
203 large changes in Ti concentration indicate variations in soil runoff (Marshall et al., 2011), which
204 has the potential to change the relative proportions of allochthonous vs. autochthonous brGDGTs
205 in the lake sediments. However, the large and abrupt shifts in Ti concentrations at 700 cm (12
206 ka) and 400 cm (4.5 ka) do not correspond to large changes in reconstructed temperature (Fig.
207 4a), indicating that the effects of changing delivery of soil-derived brGDGTs from the catchment
208 on our temperature reconstruction is limited. The negative Ti oscillation between 515 and 575
209 (7-8.5 ka), however, is contemporaneous with a negative temperature oscillation (Fig. 4), and
210 thus, we cannot rule out a changing brGDGT source during this interval. In spite of this, we
211 believe that these oscillations are a result of climate variability (see section 3.2.2) rather than a
212 change in runoff, as other large Ti changes are not correlated with temperature variability.

213 Variations in water depth also have the potential to alter brGDGT reconstructed MAAT
214 due to variations in integrated water column temperatures (Loomis et al., 2014b), which could
215 greatly affect lakes that have large differences between epi- and hypolimnetic temperatures.
216 Marginal seismic reflectors are also present at Lake Tana during the periods of lowest Ti (just
217 below 700 cm, 525 and 550 cm, and 400 cm; Marshall et al., 2011), indicating relative lake
218 lowstands during these periods of decreased precipitation. However, given that Lake Tana water
219 column temperatures show $\leq 1^\circ\text{C}$ variability between the surface and the bottom (Dargahi and
220 Setegn, 2011), it is unlikely that changes in the water depth of Lake Tana had a significant
221 impact on brGDGT distributions.

222

223 3.1.2 Influence of changing microbial ecology on brGDGT distributions

224 In addition to brGDGT variations associated with lithological changes, we note that
225 several samples with low BIT values have much lower reconstructed MAAT values than
226 adjacent samples with a high BIT value. The BIT index was initially proposed as a proxy for
227 terrestrial organic matter inputs to marine environments (Hopmans et al., 2004), with higher BIT
228 values (higher relative abundances of brGDGTs) indicating a larger input of soil-derived organic
229 matter relative to aquatically produced organic matter, represented by the relative abundance of
230 crenarchaeol (Sinninghe Damsté et al., 2002). As soil-derived brGDGTs have a different
231 empirical temperature relationship than lacustrine brGDGTs (Tierney et al., 2010; Pearson et al.,
232 2011; Sun et al., 2011; Loomis et al., 2012), large changes in soil-derived organic matter, as
233 defined by the BIT index, have the potential to affect reconstructed temperatures. However,
234 there is strong evidence that brGDGTs in tropical lake sediments are largely derived from
235 production within the lake itself (e.g. Tierney and Russell, 2009; Tierney et al., 2010; Loomis et
236 al., 2011; Buckles et al., 2014b), so BIT values likely record changes in the microbial ecology of
237 lakes, rather than allochthonous vs. autochthonous sources of organic matter in lacustrine
238 environments. Thus, we do not believe that the negative temperature excursions associated with
239 low BIT values are a result of changes soil-derived organic matter; rather, we suggest that the
240 temperature changes in samples with low BIT are tied to changes in the production of brGDGTs
241 and crenarchaeol in the lake itself.

242 BrGDGTs are likely produced by heterotrophic acidobacteria (Weijers et al., 2006, 2010;
243 Sinninghe Damsté et al., 2011, 2014), and there is empirical evidence to suggest that brGDGT
244 production increases in deeper, less oxic lake waters (Sinninghe Damsté et al., 2009; Bechtel et

245 al., 2010; Woltering et al., 2012; Buckles et al., 2014b; Loomis et al., 2014b). Crenarchaeol is
246 produced by an ammonia-oxidizing archaea (Francis et al., 2005), and in lakes, peak production
247 of ammonia-oxidizing archaea takes place near the oxycline (Pouliot et al., 2009; Llíros et al.,
248 2010; Buckles et al., 2013). It seems unlikely that competitive interactions between these two
249 groups could cause changes in the depth of brGDGT production; however, such changes could
250 affect reconstructed temperatures at higher latitudes with large hypolimnetic/epilimnetic
251 temperature gradients. In contrast, water temperature gradients within east African lakes are
252 minimal (<2°C; Loomis et al., 2014a and references therein), and thus, variations in production
253 depth are not the cause of these large temperature excursions.

254 While the mechanism linking low BIT to negative temperature anomalies is unknown, we
255 suggest that it likely involves changes in the microbial flora that produce brGDGTs. BIT values
256 in Lake Tana surface sediments are relatively high, indicating relatively low production of
257 crenarchaeol-producing ammonia-oxidizing archaea. Presently, wind speeds at Lake Tana cause
258 nearly constant mixing (Wondie et al., 2007) resulting in only weak seasonal stratification
259 (Wood and Talling, 1988), thereby inhibiting the formation of an oxycline, which would likely
260 suppress the growth of ammonia-oxidizing archaea. It is possible that in the past, changes in
261 wind speed and/or nitrogen cycling in the lake increased production of crenarchaeol, thereby
262 decreasing BIT values. Moreover, there is evidence of human disturbance in the Lake Tana
263 catchment starting near 1.7 ka (177 cm depth; Marshall et al., 2011), which has the capability to
264 alter the nitrogen cycle of the lake (Russell et al., 2009), potentially increasing crenarchaeol
265 production as well. Changes in water column oxygenation and nutrient concentrations alone are
266 likely not the direct cause of the negative temperature excursions, as nutrient and oxygen
267 concentrations do not significantly control brGDGT distributions in East African lakes (Loomis

268 et al., 2014a). However, it is possible that these changes affect the microbial ecology of the lake,
269 including both the changes in bacterial vs. archaeal populations signified by BIT, as well as the
270 populations of brGDGT-producing bacteria, thereby altering the distributions of brGDGTs
271 deposited in the lake sediments.

272 At Lake Tana, it appears that brGDGT reconstructed temperatures strongly deviate from
273 the reconstructed temperatures of adjacent samples when BIT are less than 0.5 (Fig. 3).
274 Interestingly, TEX₈₆ reconstructed temperatures in global lakes do not accurately record
275 observed temperatures when BIT > 0.5 (Powers et al., 2010), and reconstructed temperatures
276 from surface sediments in East African rift lakes are on average 10°C lower than observed
277 temperatures, which also have low BIT values (mean = 0.35; Loomis et al., 2014a). These data
278 could suggest that the shift in microbial ecology when archaeal and bacterial GDGTs are
279 produced at similar rates (theoretical BIT = 0.5) is a critical threshold when applying GDGT-
280 based paleotemperature proxies; however, the exact threshold should be applied cautiously given
281 that a wide range of BIT values can be obtained for the same sample run in different laboratories
282 (Schouten et al., 2013). Furthermore, given the limited number of lakes with low BIT in the
283 global lacustrine TEX₈₆ dataset (Powers et al., 2010) and the fact that the source organism(s) for
284 brGDGTs are yet unknown, it is difficult to ascertain the reason for reconstructed temperature
285 offsets in samples with low BIT, either in modern or in ancient sediments.

286 Regardless of the mechanism, large changes in BIT do suggest the potential for biases to
287 the brGDGT paleotemperature reconstruction related to changing brGDGT sources. Thus, we
288 will focus our paleoclimatic interpretation of the Lake Tana temperature record only on samples
289 with BIT \geq 0.5.

290

291 *3.2 Temperature variability in Northeast Africa from 15 ka to present*

292 Widespread drought in the Afro-Asian monsoon region during Heinrich Stadial 1 (H1;
293 e.g. Stager et al., 2011 and references therein) led to desiccation of Lake Tana (Lamb et al.,
294 2007; Marshall et al., 2011). Flooding at 15.2 ka returned Lake Tana to a lacustrine environment
295 (Fig. 4a), and our brGDGT data indicate reconstructed temperatures of 12.1°C at this time.
296 Between 15 ka and 13.8 ka, Lake Tana experienced a 3.7°C oscillation, followed by a rapid
297 temperature increase of ~7°C in 0.8 ky, resulting in temperatures of 18.1°C at 13 ka.
298 Temperatures then gradually increased to a maximum of 21.9°C at 6.6 ka, followed by a gradual
299 cooling to 16.7°C in the most recent sample at 0.4 ka. This long-term warming and cooling trend
300 during the Holocene was interrupted by a -3°C temperature oscillation lasting ~1.5 ky and
301 centered at 7.4 ka. Below we discuss this record and its relation to Late Pleistocene and
302 Holocene climate changes on a global and regional scale.

303

304 3.2.1 Late Pleistocene

305 Temperature variability at Lake Tana during the late Pleistocene is broadly consistent
306 with other records of temperature from around North Africa. At the termination of H1, Lake
307 Tana experienced a 3.7°C warming between 15.2 and 14.5 ka. Sea surface temperature (SST)
308 records from the Red Sea (Arz et al., 2003) and Eastern Mediterranean (Castañeda et al., 2010)
309 show an abrupt ~ 5°C warming between 15 ka and 14.5 ka as well (Fig. 5b-c). This warming is
310 consistent with the timing of the Bølling Oscillation recorded in Greenland ice cores (North
311 Greenland Ice Core Project Members, 2004; Fig. 5a), which was driven by the resumption of
312 Atlantic Meridional Overturning Circulation (AMOC) after H1 (McManus et al., 2004),
313 suggesting that abrupt warming observed in much of the northern hemisphere (Shakun et al.,

314 2012) was also felt in northern tropical Africa. In contrast, this abrupt warming is absent from
315 southern and equatorial African continental paleotemperature records (Fig. 6). This could
316 indicate a northern hemispheric temperature history at Lake Tana that is decoupled from that of
317 equatorial and southeastern Africa.

318 Temperatures in the eastern Mediterranean (Castañeda et al., 2010) and the Red Sea (Arz
319 et al., 2003) remain warm during the subsequent Allerød Oscillation, yet temperatures at Lake
320 Tana decrease to near H1 values at 13.8 ka (Fig. 5). These minimum temperatures are coincident
321 with the Older Dryas cooling event identified between the Bølling and Allerød warm periods.
322 Although identification of the Older Dryas has mainly been limited to North Atlantic and
323 northern Eurasian paleoclimate records, contemporaneous climate events have also been
324 identified in the tropics, including decreased temperatures in the Cariaco basin (Lea et al., 2003)
325 and Lake Albert (Berke et al., 2014), decreased biogenic silica production in Lake Tanganyika
326 (Tierney and Russell, 2007), and increased primary productivity in the Cariaco Basin (Hughen et
327 al., 1996). Hughen et al. (1996) postulate that increased primary productivity in the Cariaco
328 Basin is driven by a strengthening of the trade winds associated with North Atlantic cooling,
329 while Tierney and Russell (2007) attribute the decrease in biogenic silica production to a
330 weakening of the southerly winds that drive upwelling in Tanganyika. The strengthening
331 (weakening) of northerly (southerly) winds may also explain temperature decreases at Lake
332 Tana, as strengthened northerly trade winds transport cool, dry air from the Tibetan Plateau over
333 the Arabian Sea and into northeast Africa.

334 Following the temperature minimum at 13.8 ka, temperatures at Lake Tana increased to
335 18.1°C by 13 ka and remained fairly stable (mean = 18.3°C, standard deviation = 0.2°C) into the
336 Holocene (Fig. 6a). The abrupt temperature increase at 13.8 ka is contemporaneous with a 3°C

337 increase at Sacred Lake (Loomis et al., 2012; Fig. 6b), but is not observed in other
338 paleotemperature records from east Africa (Powers et al., 2005; Tierney et al., 2008; Berke et al.,
339 2012a, 2014; Fig. 6c-e). The abrupt (800 year) nature of this event indicates that changes in
340 local insolation are not likely to be the cause of the temperature increase. Greenhouse gas
341 forcing is also likely not the cause of this warming, as atmospheric CO₂ concentrations varied
342 little between 13.8 and 13.0 ka (Monnin et al., 2001). The temperature increase at 13.8 ka,
343 however, is similar in timing to changes in the temperature and circulation of the Arabian Sea.
344 SSTs off the coast of Oman, recorded by foraminiferal assemblages (Naidu and Malmgren,
345 2005; Fig. 7d) and TEX₈₆ (Huguet et al., 2006; Fig. 7c), increased rapidly starting near 14 ka.
346 Foraminiferal assemblage data suggests this increase was mainly driven by increases in winter
347 SSTs (Naidu and Malmgren, 2005). Furthermore, there are large increases in the fractional
348 abundances of dinoflagellates that thrive under high nutrient conditions (Zonneveld et al., 1997;
349 Fig. 7a) along with the foraminifera *Globigerina bulloides* (Naidu and Malmgren, 1996; Fig. 7b),
350 indicating enhanced upwelling at this time. Taken together, these Arabian Sea data indicate an
351 increase in the strength of the Indian Summer Monsoon and a decrease in the intensity of the
352 Indian Winter Monsoon (Naidu and Malmgren, 2005). We hypothesize that the temperature
353 increase at Lake Tana near 14 ka is associated with this shift in Indian Monsoon circulation.

354 The Indian summer and winter monsoons are driven by differential heating/cooling of the
355 Asian continent compared to the ocean (Hastenrath, 1991). During northern hemisphere
356 summer, the Tibetan Plateau warms rapidly compared to the Indian Ocean, resulting in low
357 pressure over the continent, which drives southwesterly winds (Fig 1a) and generates the summer
358 monsoon. Conversely, during the winter months, the Tibetan Plateau cools compared to the
359 ocean, reversing the wind direction over the Arabian Sea to northeasterly (Fig 1b) and generating

360 the winter monsoon. Modern fluctuations in the strength of the monsoons are controlled, in part,
361 by Eurasian snow and ice cover (Hahn and Shukla, 1976; Vernekar et al., 1995). Continental
362 summer temperatures are lower after winters with large snowfall due to the increased albedo and
363 latent heat fluxes associated with snow melt and evaporation. These weaken the summer
364 monsoon, and result in anomalous northeastern winds and a weakening of the Somali Jet.

365 Fluctuations in the Somali Jet alter the transport of moist, warm air from the Congo Basin
366 to northeast Africa, affecting precipitation on the Ethiopian Plateau (Camberlin, 1997).
367 Paleoclimate modeling studies focused on this region show that increased ice cover over Eurasia
368 decreases temperatures and precipitation over Northeast Africa due to a strengthening of the
369 northeasterly winds (deMenocal and Rind, 1993; Otto-Bliesner et al., 2014). The onset of a
370 strong Indian summer monsoon at 14 ka would have weakened the easterly trade winds and
371 strengthened the southwesterly winds and the Somali Jet, transporting warm air to the Ethiopian
372 Plateau.

373 Our hypothesis that large changes in Indian Monsoon circulation trigger changes in
374 temperature at Lake Tana is supported by a leaf wax hydrogen isotope record from Lake Tana
375 (Costa et al., 2014), which shows that the leaf waxes became more D-depleted concomitantly
376 with the rise in temperature (Fig. 4a-b). The temperature increase and the initial onset of the leaf
377 wax δD depletion after 13.8 ka lead increased runoff at Lake Tana (Marshall et al., 2011; Fig. 4c)
378 and in the Nile River catchment (Weldeab et al., 2014) by ~ 2 ky, but peak leaf wax δD depletion
379 is contemporaneous with peak local and regional runoff. This would suggest that the
380 temperature increase/ δD depletion starting at 13.8 ka was caused by an incursion of warm, δD
381 depleted air masses from the Congo Basin (Costa et al., 2014) to the Ethiopian Plateau, which

382 was subsequently followed by an increase in precipitation over ~2 ky, peaking during the early
383 Holocene, causing additional depletion of the leaf wax isotopes through the amount effect.

384 Interestingly, although temperatures at Lake Tana appear to be affected by AMOC-
385 induced global climate events early in the deglacial process, including H1 and the Bølling
386 Oscillation, there is no apparent cooling coincident with the Younger Dryas (YD, 12.8-11.5 ka;
387 Fig. 5). This observation is again consistent with an incursion of Congo Basin air masses onto
388 the Ethiopian Plateau starting at 14 ka, as the Congo Basin temperature record (Weijers et al.,
389 2007b) does not show a temperature decrease associated with the YD.

390 The linkage between Indian Monsoon circulation and temperature at Lake Tana and
391 Sacred Lake (Loomis et al., 2012) contrasts with temperature records from central equatorial
392 Africa (Tierney et al., 2008; Berke et al., 2012a), where variability is more strongly tied to
393 changes in CO₂ and insolation. Furthermore, the temperature changes associated with Indian
394 Monsoon circulation are more pronounced at Lake Tana (~7°C) than at Sacred Lake (~3°C).
395 This would suggest that temperature changes in northeast Africa are more strongly influenced by
396 large changes in atmospheric circulation during the last deglaciation than locations to the south
397 and west.

398

399 3.2.2 Holocene

400 Temperatures at Lake Tana gradually increase from 18.1°C at 13 ka to 21.9°C at 6.6 ka,
401 gradually cool to 19.5°C at 2 ka, and then cool more rapidly to 16.7°C by the most recent sample
402 at 0.4 ka (Fig. 6a). Broadly, the trends in Holocene temperature at Lake Tana are similar to other
403 equatorial east African paleotemperature records, with highest reconstructed temperatures during
404 the mid-Holocene and lowest reconstructed temperatures during the late Holocene (Fig. 5).

405 However, the timing of the mid Holocene thermal maximum differs among the different records,
406 with maxima near 9 ka at Lake Victoria (Berke et al., 2012a), near 7 ka at Lake Tana and Sacred
407 Lake (Loomis et al., 2012), and near 5 ka at Lakes Malawi (Powers et al., 2005) and Tanganyika
408 (Tierney et al., 2008). Peak mid-Holocene temperatures in Africa are not the result of
409 greenhouse gas radiative forcing, as CO₂ reaches a relative minimum during the mid-Holocene
410 (Indermuhle et al., 1999). The thermal maxima are also not a direct result of local insolation
411 forcing, as peak temperatures at Lake Tana and Sacred Lake lag maximum northern hemisphere
412 summer insolation by ~4 ky, while peak temperatures at Lakes Malawi and Tanganyika lead
413 peak southern hemisphere summer insolation by ~3 ky. Furthermore, east African temperature
414 variability during the Holocene does not vary systematically with changes in hydrology, as peak
415 temperatures at Lake Tana, Lake Tanganyika, and Lake Victoria occur during a transition from
416 wet to dry conditions (Tierney et al., 2008; Berke et al., 2012a; Costa et al., 2014), while peak
417 temperatures at Lake Malawi (Powers et al., 2005) occur during a transition from dry to wet
418 conditions (Castañeda et al., 2007). Finally, the relative abruptness of mid-Holocene thermal
419 maxima varies between different locations: Lakes Tanganyika and Malawi record temperature
420 increases of 2-3°C over 2 ky, while temperature maxima at Lake Tana and Sacred Lake are
421 reached through a gradual increase starting at the beginning of the Holocene. Thus, despite the
422 prevalence of warmer mid-Holocene conditions at these sites, the differences in timing, relative
423 abruptness, and hydrological linkages indicate that mid-Holocene thermal maxima at different
424 east African locations are likely driven by different mechanisms.

425 The broad Holocene warming and cooling trend at Lake Tana is interrupted by a 3°C
426 temperature oscillation over 1.5 ky centered at 7.4 ka. While this oscillation could be associated
427 with the 8.2 cooling event identified in the Greenland ice cores (Alley et al., 1997), the event we

428 observe is outside of age model error of 8.2 ka ($\sigma = 0.37$ ky at this time) and appears to have
429 been much longer-lived than the 8.2 ka event observed in Greenland. This cold oscillation is not
430 apparent in either continental (Fig. 6) or marine (Figs. 5, 7) temperature records from the region,
431 but the onset does align with an abrupt leaf wax δD enrichment (Costa et al., 2014; Fig. 4b) and a
432 decrease in Ti (Marshall et al., 2011; Fig. 4c), indicating a concomitant drought. In this context,
433 the Ti record from Lake Tana shows that precipitation gradually decreased after 7 ka (Marshall
434 et al., 2011; Fig. 4c), potentially suggesting that the gradual cooling we observe from 7 ka
435 through the late Holocene is linked to regional hydrological change. Although the mechanisms
436 linking temperature and precipitation at Lake Tana are not known, it is possible that reductions in
437 cloud cover and atmospheric humidity stimulated long-wave and latent heat losses, thereby
438 cooling Lake Tana during drier intervals. In any case, our data suggest that the hydrological and
439 thermal histories of northeastern Africa are more intimately linked than hydrological and
440 temperature histories in equatorial and southern Africa. Such a link is plausible, given the
441 strongly monsoonal nature of precipitation in northeastern Africa.

442

443

444 **4. Conclusions**

445 We present the first quantitative paleotemperature record from northern Africa using the
446 brGDGT lacustrine paleothermometer to investigate the controls on temperature variability in the
447 northern tropics over the past 15 ka. We find that the thermal history of northeast Africa is
448 distinct from the equatorial and southern tropics, and is instead largely tied to variations in the
449 strength of the monsoons and regional hydrology. The Bølling Oscillation induced a large
450 warming at Lake Tana, which is evident in temperature records from the Red Sea (Arz et al.,

451 2003) and eastern Mediterranean (Castañeda et al., 2010) but is not seen in equatorial and
452 southeast African paleotemperature records. After this oscillation, temperatures warmed near 14
453 ka, likely due to large-scale reorganization of wind patterns associated with a weakening of the
454 Indian Winter Monsoon and a strengthening of the Indian Summer Monsoon, which greatly
455 diminished the transport of cold, dry air masses from the Tibetan Plateau. Finally, like other east
456 African paleotemperature locations (Powers et al., 2005; Tierney et al., 2008; Berke et al., 2012a;
457 Loomis et al., 2012), Lake Tana experienced a mid-Holocene thermal maximum. However,
458 existing data suggest discrepancies in the timing and magnitude of the mid-Holocene
459 temperature maximum in different regions of Africa, suggesting this warming arises from
460 diverse causes. Cooling near 7.4 ka, and gradual cooling from the mid-Holocene to present,
461 occur in association with drier conditions, suggesting that, unlike equatorial and southeast
462 Africa, the thermal history of northeast Africa is more directly linked to changes in regional
463 hydrology. Finally, the magnitude of temperature change is larger at Lake Tana compared to
464 other east African locations, potentially due to an amplification of warming at higher latitudes.

465

466

467 **Acknowledgements**

468 We would like to thank B. Konecky for helpful discussions and assistance with core sampling,
469 and K. Costa and R. Tarozo for laboratory assistance. This material is based upon work
470 supported by the National Science Foundation under grant number EAR-1226566 to J. Russell
471 and by a Geological Society of America Graduate Student Research Grant awarded to S. Loomis.

472

473

474 **References**

- 475 Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene
476 climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25, 483-486.
- 477 Arz, H.W., Patzold, J., Muller, P.J., Moammar, M.O., 2003. Influence of Northern Hemisphere
478 climate and global sea level rise on the restricted Red Sea marine environment during
479 termination I. *Paleoceanography* 18.
- 480 Bechtel, A., Smittenberg, R.H., Bernasconi, S.M., Schubert, C.J., 2010. Distribution of branched
481 and isoprenoid tetraether lipids in an oligotrophic and a eutrophic Swiss lake: Insights
482 into sources and GDGT-based proxies. *Organic Geochemistry* 41, 822-832.
- 483 Berke, M.A., Johnson, T.C., Werne, J.P., Grice, K., Schouten, S., Sinninghe Damsté, J.S., 2012a.
484 Molecular records of climate variability and vegetation response since the Late
485 Pleistocene in the Lake Victoria basin, East Africa. *Quaternary Science Reviews* 55, 59-
486 74.
- 487 Berke, M.A., Johnson, T.C., Werne, J.P., Schouten, S., Sinninghe Damsté, J.S., 2012b. A mid-
488 Holocene thermal maximum at the end of the African Humid Period. *Earth and Planetary
489 Science Letters* 351, 95-104.
- 490 Berke, M.A., Johnson, T.C., Werne, J.P., Livingstone, D.A., Grice, K., Schouten, S., Sinninghe
491 Damsté, J.S., 2014. Characterization of the last deglacial transition in tropical East
492 Africa: Insights from Lake Albert. *Palaeogeography Palaeoclimatology Palaeoecology*
493 409, 1-8.
- 494 Blaauw, M., Bakker, R., Christen, J.A., Hall, V.A., van der Plicht, J., 2007. A Bayesian
495 framework for age modeling of radiocarbon-dated peat deposits: Case studies from the
496 Netherlands. *Radiocarbon* 49, 357-367.
- 497 Buckles, L.K., Villanueva, L., Weijers, J.W.H., Verschuren, D., Sinninghe Damsté, J.S., 2013.
498 Linking isoprenoidal GDGT membrane lipid distributions with gene abundances of
499 ammonia-oxidizing Thaumarchaeota and uncultured crenarchaeotal groups in the water
500 column of a tropical lake (Lake Challa, East Africa). *Environmental Microbiology* 15,
501 2445-2462.
- 502 Buckles, L.K., Weijers, J.W.H., Tran, X.M., Waldron, S., Sinninghe Damsté, J.S., 2014a.
503 Provenance of tetraether membrane lipids in a large temperate lake (Loch Lomond, UK):
504 implications for glycerol dialkyl glycerol tetraether (GDGT)-based palaeothermometry.
505 *Biogeosciences* 11, 5539-5563.
- 506 Buckles, L.K., Weijers, J.W.H., Verschuren, D., Sinninghe Damsté, J.S., 2014b. Sources of core
507 and intact branched tetraether membrane lipids in the lacustrine environment: Anatomy
508 of Lake Challa and its catchment, equatorial East Africa. *Geochimica Et Cosmochimica
509 Acta* 140, 106-126.

- 510 Camberlin, P., 1997. Rainfall anomalies in the source region of the Nile and their connection
511 with the Indian summer monsoon. *Journal of Climate* 10, 1380-1392.
- 512 Castañeda, I.S., Werne, J.P., Johnson, T.C., 2007. Wet and arid phases in the southeast African
513 tropics since the Last Glacial Maximum. *Geology* 35, 823-826.
- 514 Castañeda, I.S., Schefuss, E., Patzold, J., Damste, J.S.S., Weldeab, S., Schouten, S., 2010.
515 Millennial-scale sea surface temperature changes in the eastern Mediterranean (Nile
516 River Delta region) over the last 27,000 years. *Paleoceanography* 25.
- 517 Coetzee, J.A., 1967. Pollen analytical studies in East and southern Africa. *Palaeoecology of*
518 *Africa* 3, 1-146.
- 519 Costa, K., Russell, J., Konecky, B., Lamb, H., 2014. Isotopic reconstruction of the African
520 Humid Period and Congo Air Boundary migration at Lake Tana, Ethiopia. *Quaternary*
521 *Science Reviews* 83, 58-67.
- 522 Dargahi, B., Setegn, S.G., 2011. Combined 3D hydrodynamic and watershed modelling of Lake
523 Tana, Ethiopia. *Journal of Hydrology* 398, 44-64.
- 524 deMenocal, P.B., Rind, D., 1993. Sensitivity of Asian and African Climate to Variations in
525 Seasonal Insolation, Glacial Ice Cover, Sea-Surface Temperature, and Asian Orography.
526 *Journal of Geophysical Research-Atmospheres* 98, 7265-7287.
- 527 Fawcett, P.J., Werne, J.P., Anderson, R.S., Heikoop, J.M., Brown, E.T., Berke, M.A., Smith,
528 S.J., Goff, F., Donohoo-Hurley, L., Cisneros-Dozal, L.M., Schouten, S., Sinninghe
529 Damsté, J.S., Huang, Y.S., Toney, J., Fessenden, J., WoldeGabriel, G., Atudorei, V.,
530 Geissman, J.W., Allen, C.D., 2011. Extended megadroughts in the southwestern United
531 States during Pleistocene interglacials. *Nature* 470, 518-521.
- 532 Francis, C.A., Roberts, K.J., Beman, J.M., Santoro, A.E., Oakley, B.B., 2005. Ubiquity and
533 diversity of ammonia-oxidizing archaea in water columns and sediments of the ocean. *P*
534 *Natl Acad Sci USA* 102, 14683-14688.
- 535 Gebrekirstos, A., Worbes, M., Teketay, D., Fetene, M., Mitlohner, R., 2009. Stable carbon
536 isotope ratios in tree rings of co-occurring species from semi-arid tropics in Africa:
537 Patterns and climatic signals. *Global and Planetary Change* 66, 253-260.
- 538 Hahn, D.G., Shukla, J., 1976. Apparent Relationship between Eurasian Snow Cover and Indian
539 Monsoon Rainfall. *J Atmos Sci* 33, 2461-2462.
- 540 Hastenrath, S., 1991. *Climate Dynamics of the Tropics*. Springer, Dordrecht.
- 541 Heegaard, E., Birks, H.J.B., Telford, R.J., 2005. Relationships between calibrated ages and depth
542 in stratigraphical sequences: an estimation procedure by mixed-effect regression.
543 *Holocene* 15, 612-618.

- 544 Hopmans, E.C., Weijers, J.W.H., Schefuß, E., Herfort, L., Sinninghe Damsté, J.S., Schouten, S.,
545 2004. A novel proxy for terrestrial organic matter in sediments based on branched and
546 isoprenoid tetraether lipids. *Earth and Planetary Science Letters* 224, 107-116.
- 547 Huguen, K.A., Overpeck, J.T., Peterson, L.C., Trumbore, S., 1996. Rapid climate changes in the
548 tropical Atlantic region during the last deglaciation. *Nature* 380, 51-54.
- 549 Huguet, A., Fosse, C., Laggoun-Defarge, F., Delarue, F., Derenne, S., 2013. Effects of a short-
550 term experimental microclimate warming on the abundance and distribution of branched
551 GDGTs in a French peatland. *Geochimica Et Cosmochimica Acta* 105, 294-315.
- 552 Huguet, C., Kim, J.H., Sinninghe Damsté, J.S., Schouten, S., 2006. Reconstruction of sea surface
553 temperature variations in the Arabian Sea over the last 23 kyr using organic proxies
554 (TEX₈₆ and U₃₇^{K'}). *Paleoceanography* 21.
- 555 Indermuhle, A., Stocker, T.F., Joos, F., Fischer, H., Smith, H.J., Wahlen, M., Deck, B.,
556 Mastroianni, D., Tschumi, J., Blunier, T., Meyer, R., Stauffer, B., 1999. Holocene
557 carbon-cycle dynamics based on CO₂ trapped in ice at Taylor Dome, Antarctica. *Nature*
558 398, 121-126.
- 559 Kebede, S., Travi, Y., Alemayehu, T., Marc, V., 2006. Water balance of Lake Tana and its
560 sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of Hydrology* 316,
561 233-247.
- 562 Lamb, H.F., Bates, C.R., Coombes, P.V., Marshall, M.H., Umer, M., Davies, S.J., Dejen, E.,
563 2007. Late Pleistocene desiccation of Lake Tana, source of the Blue Nile. *Quaternary*
564 *Science Reviews* 26, 287-299.
- 565 Lea, D.W., Pak, D.K., Peterson, L.C., Huguen, K.A., 2003. Synchronicity of tropical and high-
566 latitude Atlantic temperatures over the last glacial termination. *Science* 301, 1361-1364.
- 567 Llirós, M., Gich, F., Plasencia, A., Auguet, J.C., Darchambeau, F., Casamayor, E.O., Descy, J.P.,
568 Borrego, C., 2010. Vertical Distribution of Ammonia-Oxidizing Crenarchaeota and
569 Methanogens in the Epipelagic Waters of Lake Kivu (Rwanda-Democratic Republic of
570 the Congo). *Applied and Environmental Microbiology* 76, 6853-6863.
- 571 Loomis, S.E., Russell, J.M., Sinninghe Damsté, J.S., 2011. Distributions of branched GDGTs in
572 soils and lake sediments from western Uganda: Implications for a lacustrine
573 paleothermometer. *Organic Geochemistry* 42, 739-751.
- 574 Loomis, S.E., Russell, J.M., Ladd, B., Street-Perrott, F.A., Sinninghe Damsté, J.S., 2012.
575 Calibration and application of the branched GDGT temperature proxy on East African
576 lake sediments. *Earth and Planetary Science Letters* 357-358, 277-288.
- 577 Loomis, S.E., Russell, J.M., Eggermont, H., Verschuren, D., Sinninghe Damsté, J.S., 2014a.
578 Effects of temperature, pH and nutrient concentration on branched GDGT distributions in
579 East African lakes: Implications for paleoenvironmental reconstruction. *Organic*
580 *Geochemistry* 66, 25-37.

- 581 Loomis, S.E., Russell, J.M., Heurreux, A.M., D'Andrea, W.J., Damste, J.S.S., 2014b. Seasonal
582 variability of branched glycerol dialkyl glycerol tetraethers (brGDGTs) in a temperate
583 lake system. *Geochimica Et Cosmochimica Acta* 144, 173-187.
- 584 Marshall, M.H., Lamb, H.F., Huws, D., Davies, S.J., Bates, R., Bloemendal, J., Boyle, J., Leng,
585 M.J., Umer, M., Bryant, C., 2011. Late Pleistocene and Holocene drought events at Lake
586 Tana, the source of the Blue Nile. *Global and Planetary Change* 78, 147-161.
- 587 McManus, J.F., Francois, R., Gherardi, J.M., Keigwin, L.D., Brown-Leger, S., 2004. Collapse
588 and rapid resumption of Atlantic meridional circulation linked to deglacial climate
589 changes. *Nature* 428, 834-837.
- 590 Monnin, E., Indermuhle, A., Dallenbach, A., Fluckiger, J., Stauffer, B., Stocker, T.F., Raynaud,
591 D., Barnola, J.M., 2001. Atmospheric CO₂ concentrations over the last glacial
592 termination. *Science* 291, 112-114.
- 593 Naidu, P.D., Malmgren, B.A., 1996. A high-resolution record of late quaternary upwelling along
594 the Oman Margin, Arabian Sea based on planktonic foraminifera. *Paleoceanography* 11,
595 129-140.
- 596 Naidu, P.D., Malmgren, B.A., 2005. Seasonal sea surface temperature contrast between the
597 Holocene and last glacial period in the western Arabian Sea (Ocean Drilling Project Site
598 723A): Modulated by monsoon upwelling. *Paleoceanography* 20.
- 599 Niemann, H., Stadnitskaia, A., Wirth, S.B., Gilli, A., Anselmetti, F.S., Sinninghe Damsté, J.S.,
600 Schouten, S., Hopmans, E.C., Lehmann, M.F., 2012. Bacterial GDGTs in Holocene
601 sediments and catchment soils of a high Alpine lake: application of the MBT/CBT-
602 paleothermometer. *Climate of the Past* 8, 889-906.
- 603 North Greenland Ice Core Project Members, 2004. High-resolution record of Northern
604 Hemisphere climate extending into the last interglacial period. *Nature* 431, 147-151.
- 605 Otto-Bliesner, B.L., Russell, J.M., Clark, P.U., Liu, Z.Y., Overpeck, J.T., Konecky, B.,
606 deMenocal, P., Nicholson, S.E., He, F., Lu, Z.Y., 2014. Coherent changes of southeastern
607 equatorial and northern African rainfall during the last deglaciation. *Science* 346, 1223-
608 1227.
- 609 Pearson, E.J., Juggins, S., Talbot, H.M., Weckstrom, J., Rosen, P., Ryves, D.B., Roberts, S.J.,
610 Schmidt, R., 2011. A lacustrine GDGT-temperature calibration from the Scandinavian
611 Arctic to Antarctic: Renewed potential for the application of GDGT-paleothermometry in
612 lakes. *Geochimica et Cosmochimica Acta* 75, 6225-6238.
- 613 Peterse, F., Hopmans, E.C., Schouten, S., Mets, A., Rijpstra, W.I.C., Sinninghe Damsté, J.S.,
614 2011. Identification and distribution of intact polar branched tetraether lipids in peat and
615 soil. *Organic Geochemistry* 42, 1007-1015.

- 616 Pouliot, J., Galand, P.E., Lovejoy, C., Vincent, W.F., 2009. Vertical structure of archaeal
617 communities and the distribution of ammonia monooxygenase A gene variants in two
618 meromictic High Arctic lakes. *Environmental Microbiology* 11, 687-699.
- 619 Powers, L.A., Johnson, T.C., Werne, J.P., Castañeda, I.S., Hopmans, E.C., Sinninghe Damsté,
620 J.S., Schouten, S., 2005. Large temperature variability in the southern African tropics
621 since the Last Glacial Maximum. *Geophysical Research Letters* 32, L08706.
- 622 Powers, L.A., Werne, J.P., Vanderwoude, A.J., Sinninghe Damsté, J.S., Hopmans, E.C.,
623 Schouten, S., 2010. Applicability and calibration of the TEX₈₆ paleothermometer in lakes.
624 *Organic Geochemistry* 41, 404-413.
- 625 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E.,
626 Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H.,
627 Hajdas, I., Hatte, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser,
628 K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M.,
629 Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. Intcal13 and
630 Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years Cal Bp. *Radiocarbon* 55,
631 1869-1887.
- 632 Russell, J.M., McCoy, S.J., Verschuren, D., Bessems, I., Huang, Y., 2009. Human impacts,
633 climate change, and aquatic ecosystem response during the past 2000 yr at Lake
634 Wandakara, Uganda. *Quaternary Research* 72, 315-324.
- 635 Schmittner, A., Urban, N.M., Shakun, J.D., Mahowald, N.M., Clark, P.U., Bartlein, P.J., Mix,
636 A.C., Rosell-Mele, A., 2011. Climate Sensitivity Estimated from Temperature
637 Reconstructions of the Last Glacial Maximum. *Science* 334, 1385-1388.
- 638 Schouten, S., Hopmans, E.C., Schefuß, E., Sinninghe Damsté, J.S., 2002. Distributional
639 variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing
640 ancient sea water temperatures? *Earth and Planetary Science Letters* 204, 265-274.
- 641 Schouten, S., Hopmans, E.C., Rosell-Mele, A., Pearson, A., Adam, P., Bauersachs, T., Bard, E.,
642 Bernasconi, S.M., Bianchi, T.S., Brocks, J.J., Carlson, L.T., Castaneda, I.S., Derenne, S.,
643 Selver, A.D., Dutta, K., Eglinton, T., Fosse, C., Galy, V., Grice, K., Hinrichs, K.U.,
644 Huang, Y.S., Huguet, A., Huguet, C., Hurley, S., Ingalls, A., Jia, G., Keely, B., Knappy,
645 C., Kondo, M., Krishnan, S., Lincoln, S., Lipp, J., Mangelsdorf, K., Martinez-Garcia, A.,
646 Menot, G., Mets, A., Mollenhauer, G., Ohkouchi, N., Ossebaar, J., Pagani, M., Pancost,
647 R.D., Pearson, E.J., Peterse, F., Reichart, G.J., Schaeffer, P., Schmitt, G., Schwark, L.,
648 Shah, S.R., Smith, R.W., Smittenberg, R.H., Summons, R.E., Takano, Y., Talbot, H.M.,
649 Taylor, K.W.R., Tarozo, R., Uchida, M., van Dongen, B.E., Van Mooy, B.A.S., Wang,
650 J.X., Warren, C., Weijers, J.W.H., Werne, J.P., Woltering, M., Xie, S.C., Yamamoto, M.,
651 Yang, H., Zhang, C.L., Zhang, Y.G., Zhao, M.X., Sinninghe Damsté, J.S., 2013. An
652 interlaboratory study of TEX₈₆ and BIT analysis of sediments, extracts, and standard
653 mixtures. *Geochemistry Geophysics Geosystems* 14, 5263-5285.

- 654 Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z.Y., Otto-Bliesner, B.,
655 Schmittner, A., Bard, E., 2012. Global warming preceded by increasing carbon dioxide
656 concentrations during the last deglaciation. *Nature* 484, 49-54.
- 657 Sinninghe Damsté, J.S., Hopmans, E.C., Pancost, R.D., Schouten, S., Geenevasen, J.A.J., 2000.
658 Newly discovered non-isoprenoid glycerol dialkyl glycerol tetraether lipids in sediments.
659 *Chemical Communications*, 1683-1684.
- 660 Sinninghe Damsté, J.S., Schouten, S., Hopmans, E.C., van Duin, A.C.T., Geenevasen, J.A.J.,
661 2002. Crenarchaeol: the characteristic core glycerol dibiphytanyl glycerol tetraether
662 membrane lipid of cosmopolitan pelagic crenarchaeota. *Journal of Lipid Research* 43,
663 1641-1651.
- 664 Sinninghe Damsté, J.S., Ossebaar, J., Abbas, B., Schouten, S., Verschuren, D., 2009. Fluxes and
665 distribution of tetraether lipids in an equatorial African lake: Constraints on the
666 application of the TEX₈₆ palaeothermometer and BIT index in lacustrine settings.
667 *Geochimica et Cosmochimica Acta* 73, 4232-4249.
- 668 Sinninghe Damsté, J.S., Rijpstra, W.I.C., Hopmans, E.C., Weijers, J.W.H., Foesel, B.U.,
669 Overman, J., Dedysh, S.N., 2011. 13,16-Dimethyl octacosanedionic acid (iso-diabolic
670 acid): A common membrane-spanning lipid of Acidobacteria subdivisions 1 and 3.
671 *Applied and Environmental Microbiology* 77, 4147-4154.
- 672 Sinninghe Damsté, J.S., Rijpstra, W.I.C., Hopmans, E.C., Foesel, B.U., Wüst, P.K., Overman, J.,
673 Tank, M., Bryant, D.A., Dunfield, P.F., Houghton, K., Stott, M.B., 2014. Ether- and
674 ester-bound iso-diabolic acid and other lipids in members of Acidobacteria subdivision 4.
675 *Applied and Environmental Microbiology* 80, 5207-5218.
- 676 Stager, J.C., Ryves, D.B., Chase, B.M., Pausata, F.S.R., 2011. Catastrophic Drought in the Afro-
677 Asian Monsoon Region During Heinrich Event 1. *Science* 331, 1299-1302.
- 678 Sun, Q., Chu, G., Liu, M., Xie, M., Li, S., Ling, Y., Wang, X., Shi, L., Jia, G., Lü, H., 2011.
679 Distributions and temperature dependence of branched glycerol dialkyl glycerol tetraethers
680 in recent lacustrine sediments from China and Nepal. *Journal of Geophysical Research*
681 116, G01008.
- 682 Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H.,
683 Zagorodnov, V.S., Mashiotta, T.A., Lin, P.N., Mikhalenko, V.N., Hardy, D.R., Beer, J.,
684 2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical
685 Africa. *Science* 298, 589-593.
- 686 Tierney, J.E., Russell, J.M., 2007. Abrupt climate change in southeast tropical Africa influenced
687 by Indian monsoon variability and ITCZ migration. *Geophysical Research Letters* 34.
- 688 Tierney, J.E., Russell, J.M., Huang, Y., Sinninghe Damsté, J.S., Hopmans, E.C., Cohen, A.S.,
689 2008. Northern hemisphere controls on tropical southeast African climate during the past
690 60,000 years. *Science* 322, 252-255.

- 691 Tierney, J.E., Russell, J.M., 2009. Distributions of branched GDGTs in a tropical lake system:
692 Implications for lacustrine application of the MBT/CBT paleoproxy. *Organic*
693 *Geochemistry* 40, 1032-1036.
- 694 Tierney, J.E., Russell, J.M., Eggermont, H., Hopmans, E.C., Verschuren, D., Sinninghe Damsté,
695 J.S., 2010. Environmental controls on branched tetraether lipid distributions in tropical
696 East African lake sediments. *Geochimica et Cosmochimica Acta* 74, 4902-4918.
- 697 Tierney, J.E., Schouten, S., Pitcher, A., Hopmans, E.C., Sinninghe Damsté, J.S., 2012. Core and
698 intact polar glycerol dialkyl glycerol tetraethers (GDGTs) in Sand Pond, Warwick, Rhode
699 Island (USA): Insights into the origin of lacustrine GDGTs. *Geochimica et*
700 *Cosmochimica Acta* 77, 561-581.
- 701 Vernekar, A.D., Zhou, J., Shukla, J., 1995. The Effect of Eurasian Snow Cover on the Indian
702 Monsoon. *Journal of Climate* 8, 248-266.
- 703 Wang, H.Y., Liu, W.G., Zhang, C.L.L., Wang, Z., Wang, J.X., Liu, Z.H., Dong, H.L., 2012.
704 Distribution of glycerol dialkyl glycerol tetraethers in surface sediments of Lake Qinghai
705 and surrounding soil. *Organic Geochemistry* 47, 78-87.
- 706 Weijers, J.W.H., Schouten, S., Hopmans, E.C., Geenevasen, J.A.J., David, O.R.P., Coleman,
707 J.M., Pancost, R.D., Sinninghe Damsté, J.S., 2006. Membrane lipids of mesophilic
708 anaerobic bacteria thriving in peats have typical archaeal traits. *Environmental*
709 *Microbiology* 8, 648-657.
- 710 Weijers, J.W.H., Schouten, S., van den Donker, J.C., Hopmans, E.C., Sinninghe Damsté, J.S.,
711 2007a. Environmental controls on bacterial tetraether membrane lipid distribution in
712 soils. *Geochimica et Cosmochimica Acta* 71, 703-713.
- 713 Weijers, J.W.H., Schefuß, E., Schouten, S., Sinninghe Damsté, J.S., 2007b. Coupled thermal and
714 hydrological evolution of tropical Africa over the last deglaciation. *Science* 315, 1701-
715 1704.
- 716 Weijers, J.W.H., Panoto, E., van Bleijswijk, J., Schouten, S., Rijpstra, W.I.C., Balk, M., Stams,
717 A.J.M., Sinninghe Damsté, J.S., 2009. Constraints on the biological source(s) of the
718 orphan branched tetraether membrane lipids. *Geomicrobiology Journal* 26, 402-414.
- 719 Weijers, J.W.H., Wiesenberg, G.L.B., Bol, R., Hopmans, E.C., Pancost, R.D., 2010. Carbon
720 isotopic composition of branched tetraether membrane lipids in soils suggest a rapid
721 turnover and a heterotrophic life style of their source organism(s). *Biogeosciences*
722 *Discussions* 7, 3691-3734.
- 723 Weldeab, S., Menke, V., Schmiedl, G., 2014. The pace of East African monsoon evolution
724 during the Holocene. *Geophysical Research Letters* 41, 1724-1731.
- 725 Woltering, M., Johnson, T.C., Werne, J.P., Schouten, S., Sinninghe Damsté, J.S., 2011. Late
726 Pleistocene temperature history of Southeast Africa: A TEX₈₆ temperature record from
727 Lake Malawi. *Palaeogeography Palaeoclimatology Palaeoecology* 303, 93-102.

- 728 Woltering, M., Werne, J.P., Kish, J.L., Hicks, R., Sinninghe Damsté, J.S., Schouten, S., 2012.
729 Vertical and temporal variability in concentration and distribution of thaumarchaeotal
730 tetraether lipids in Lake Superior and the implications for the application of the TEX₈₆
731 temperature proxy. *Geochimica et Cosmochimica Acta* 87, 136-153.
- 732 Woltering, M., Atahan, P., Grice, K., Heijnis, H., Taffs, K., Dodson, J., 2014. Glacial and
733 Holocene terrestrial temperature variability in subtropical east Australia as inferred from
734 branched GDGT distributions in a sediment core from Lake McKenzie. *Quaternary*
735 *Research* 82, 132-145.
- 736 Wondie, A., Mengistu, S., Vijverberg, J., Dejen, E., 2007. Seasonal variation in primary
737 production of a large high altitude tropical lake (Lake Tana, Ethiopia): effects of nutrient
738 availability and water transparency. *Aquat Ecol* 41, 195-207.
- 739 Wood, R.B., Talling, J.F., 1988. Chemical and algal relationships in a salinity series of Ethiopian
740 inland waters. *Hydrobiologia* 158, 29-67.
- 741 Zonneveld, K.A.F., Ganssen, G., Troelstra, S., Versteegh, G.J.M., Visscher, H., 1997.
742 Mechanisms forcing abrupt fluctuations of the Indian Ocean summer monsoon during the
743 last deglaciation. *Quaternary Science Reviews* 16, 187-201.
- 744

745 **Figures**

746

747 *Figure 1:* Map of average surface winds and air temperatures at 850 mb. a) June, July, and
748 August (JJA), b) December, January, and February (DJF). White dot (1) marks the location of
749 Lake Tana core 03TL3 (this study, Marshall et al., 2011, and Costa et al., 2014), and gray boxes
750 mark the locations of other paleoclimate records mentioned in the text. 2: Sacred Lake, (Loomis
751 et al., 2012); 3: Lake Victoria (Berke et al., 2012a); 4: Lake Tanganyika (Tierney et al., 2008); 5:
752 Lake Malawi (Powers et al., 2005); 6: Red Sea, GeoB 5844-2 (Arz et al., 2003); 7: Eastern
753 Mediterranean, GeoB 7702-3 (Castañeda et al., 2010); 8: Arabian Sea, 905P (Zonneveld et al.,
754 1997); 9: Arabian Sea, 74KL (Huguet et al., 2006); 10: Arabian Sea, ODP 723A (Naidu and
755 Malmgren, 1996, 2005).

756

757 *Figure 2:* Structures of GDGTs discussed in the text, including the isoprenoidal crenarchaeol
758 (cren) and the brGDGTs (IIIa-Ic).

759

760 *Figure 3:* GDGT records from Lake Tana core 03TL3. a) Reconstructed mean annual air
761 temperature (MAAT). Black circles are samples with BIT values ≥ 0.5 , open circles are samples
762 with BIT values < 0.5 . Bootstrapped 1σ errors on reconstructed temperatures are indicated by
763 the gray lines. b) BIT record. Black triangles along the x-axis mark the depths of age control
764 points (Marshall et al., 2011). Background is shaded to represent the different lithological units
765 (Lamb et al., 2007) described in the text: medium gray for Unit 1 (dark gray silt; organic matter
766 = 9-22%), light gray for Unit 2 (dark brown herbaceous peat; organic matter = 30-70%), dark

767 gray for Unit 3 (calcareous silt; deposition conductivity = 3500 $\mu\text{S}/\text{cm}$), and white for Unit 4
768 (uniform fine gray diatomaceous silt; low organic matter and magnetic susceptibility).

769

770 *Figure 4:* Temperature and precipitation records from Lake Tana core 03TL3. a) Mean annual
771 air temperature (MAAT; this study), b) δD of leaf waxes (Costa et al., 2014), c) low pass filter of
772 Ti counts (Marshall et al., 2011).

773

774 *Figure 5:* Comparison of North African temperature records with the Greenland ice core record.
775 a) $\delta^{18}\text{O}$ of the NGRIP ice core (North Greenland Ice Core Project Members, 2004), b) Eastern
776 Mediterranean sea surface temperature (SST; Castañeda et al., 2010), c) Red Sea SST (Arz et al.,
777 2003), and d) Lake Tana mean annual air temperature (MAAT; this study). Gray shading marks
778 the Bølling Oscillation as defined by the NGRIP ice core.

779

780 *Figure 6:* Comparison of continental East African paleotemperature records. a) Mean annual air
781 temperature (MAAT) at Lake Tana (12.0°N; this study), b) MAAT at Sacred Lake (0°N; Loomis
782 et al., 2012), c) lake surface temperature (LST) at Lake Victoria (1°S; Berke et al., 2012a), d)
783 LST at Lake Tanganyika (7°S; Tierney et al., 2008), and e) LST at Lake Malawi (10°S; Powers et
784 al., 2005).

785

786 *Figure 7:* Comparison of paleoclimate records influenced by the Indian Monsoon. Strength of
787 upwelling in the western Arabian Sea measured by a) the relative abundance of dinoflagellate
788 species with highest relative abundance during the Indian Summer Monsoon at 905P (Zonneveld
789 et al., 1997) and b) the relative abundance of *G. bulloides* at ODP 723A (Naidu and Malmgren,

790 1996); sea surface temperature (SST) in the western Arabian Sea reconstructed using c) the
791 TEX₈₆ proxy at 74KL (Huguet et al., 2006) and d) foraminifera at ODP 723A (Naidu and
792 Malmgren, 2005); e) mean annual air temperature (MAAT) at Lake Tana (this study). ¹⁴C ages
793 from 905P were converted to calendar years using the Marine13 radiocarbon curve (Reimer et
794 al., 2013), and the new age model was constructed using Bacon 2.2 (Blaauw et al., 2007).

1 **Northeast African temperature variability since the Late Pleistocene**

2

3 Shannon E. Loomis^{a*1}, James M. Russell^a, Henry F. Lamb^b

4

5 *^aBrown University, Department of Earth, Environmental and Planetary Sciences, 324 Brook St.,*
6 *Box 1846, Providence, RI 02912, USA*

7 *^bAberystwyth University, ~~Institute~~Department of Geography and Earth Sciences, Aberystwyth,*
8 *SY23 3DB, UK*

9

10 ***Corresponding author**

Formatted: Font: Times

11 *Tel: 1-512-232-5762*

12 *Email address: sloomis@jsg.utexas.edu (S. Loomis)*

13

14 *¹Currently at: University of Texas at Austin, Department of Geological Sciences, 1 University*
15 *Station C1160, Austin, TX 78712, USA*

Formatted: Indent: Left: 0 cm, First line: 0 cm

16

17

18 **Abstract**

19 The development and application of lacustrine paleotemperature proxies based
20 upon microbial membrane lipid structures, including the TEX₈₆ and branched glycerol
21 dialkyl glycerol tetraether (brGDGT) paleothermometers, have greatly advanced our
22 understanding of the ~~deglacial~~late-glacial and postglacial temperature history of Africa,
23 ~~but current.~~ However, the currently available records are ~~limited to~~from equatorial and
24 southern hemisphere sites, limiting our understanding of the spatial patterns of
25 temperature change. Here we use the brGDGT paleotemperature proxy to reconstruct
26 Late Pleistocene and Holocene temperatures from Lake Tana, Ethiopia (12°N, 37°E).
27 Following the termination of Heinrich ~~Event~~Stadial 1 at ~15 ka, Lake Tana experienced a
28 3.7°C oscillation over 1.2 ky. Temperatures then increased abruptly by nearly 7°C ~~deg~~
29 between 13.8 and 13.0 ka, followed by a slow warming trend that peaked during the mid
30 Holocene. Temperatures subsequently cooled from ~6 ka to ~0.4 ka. These data indicate
31 that temperature at Lake Tana ~~is highly~~was sensitive to ~~global~~-climate changes caused by
32 variations in the Atlantic Meridional Overturning Circulation ~~in~~during the Late
33 Pleistocene, as well as to regional ~~climate~~hydroclimatic changes ~~caused by hydrologic~~
34 ~~variability and reorganization~~and reorganizations of the monsoons. ~~This~~Our record
35 suggests that ~~de~~late-glacial temperature changes in northeast Africa were ~~strongly~~
36 ~~linked~~to high-latitude northern hemispheric ~~glacial~~-climate processes, but ~~following~~
37 ~~deglaciation, temperature variability was strongly~~that subsequent post-glacial
38 temperature variations were strongly influenced by tropical hydrology.

39

40 **Keywords:** tropical paleoclimate, ~~East~~east Africa, GDGT, paleotemperature, Holocene, Lake

Formatted: Font: Times

Formatted: Font: Times

41 | Tana
42 |
43 |

1. Introduction

Quantitative paleoclimate reconstructions are crucial ~~to test the output from~~ for testing global climate models and for understanding the ~~amplitudedrivers~~ of ~~and mechanisms that cause~~ past and future climate change (Schmittner et al., 2011; Shakun et al., 2012). Despite the importance of tropical temperatures in driving atmospheric convection, continental ~~paleo~~temperature reconstructions ~~in~~ from the tropics are very limited. This is largely due to difficulties in reconstructing tropical continental temperatures using conventional proxies, such as tree rings (e.g. Gebrekirstos et al., 2009) ~~and~~ , pollen (e.g. Coetsee, 1967) , ~~and stable isotopes~~ (e.g. Thompson et al., 2002). In recent years, the development of glycerol dialkyl glycerol tetraether (GDGT) paleothermometry has greatly enhanced our ability to reconstruct terrestrial tropical ~~paleotemperatures~~ temperatures and the thermal history of Africa in particular. The TEX₈₆ proxy (TetraEther indeX of tetraethers with 86 carbon atoms; Schouten et al., 2002), based on the relative abundances of isoprenoidal GDGTs produced by mesophilic archaea, has been used to reconstruct past temperature in Lakes Malawi (Powers et al., 2005; Woltering et al., 2011), Tanganyika (Tierney et al., 2008), Turkana (Berke et al., 2012b), Victoria (Berke et al., 2012a), and Albert (Berke et al., 2014). However, TEX₈₆ is only applicable in some large lakes (Powers et al., 2010), limiting its ability as a widespread terrestrial paleotemperature proxy.

~~The relative abundances of branched~~ Branched GDGTs (brGDGTs) ~~—which~~ are produced by heterotrophic acidobacteria (Weijers et al., 2006, 2010; Sinninghe Damsté et al., 2011, ~~in~~ press) ~~—2014~~ and their relative abundances are also temperature dependent (Weijers et al., 2007a) ~~and~~ , brGDGTs are much more abundant than isoprenoidal GDGTs in sediments from smaller lakes (e.g. Tierney and Russell, 2009; Powers et al., 2010; Loomis et al., ~~2011~~) ~~—~~ BrGDGTs ~~2014a~~ , ~~and they~~ have been used to reconstruct paleotemperatures using lake

67 | sediments at ~~both~~-temperate (Fawcett et al., 2011; Niemann et al., 2012), subtropical (Woltering
68 | et al., 2014), and tropical (Loomis et al., 2012) latitudes.

69 | _GDGT-based temperature records from equatorial East Africa have begun to illuminate
70 | the region's thermal history and generally exhibit coherent trends and amplitudes of change on
71 | orbital timescales. ~~Compared~~For instance, these records suggest that, ~~compared~~ to present-
72 | industrial period, temperatures were 3-5°C cooler at the last glacial maximum (LGM; Powers et
73 | al., 2005; Tierney et al., 2008; Loomis et al., 2012) and between 1 and 3 degrees warmer during
74 | the mid-Holocene, ca. 7-5 ka (Powers et al., 2005; Tierney et al., 2008; Berke et al., 2012b;
75 | Loomis et al., 2012)-), similar to findings from TEX₈₆ reconstructions from the region's large
76 | lakes.

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

83

84

85 | **2. Materials and Methods**

86 | *2.1 Site Information*

87 | Lake Tana (12.0°N, 37.~~25~~3°E; 1830 m elevation; Fig. 1) is a large (3156 km²) but
88 | shallow (maximum depth = 14 m, mean depth = 9 m) freshwater lake located on the basaltic
89 | plateau of northeastern Ethiopia. It is a slightly alkaline (pH = 8), oligo-mesotrophic lake (Wood

90 and Talling, 1988) with weak seasonal stratification (Wood and Talling, 1988). Lake Tana has
91 four major inflows, which that contribute >95% of the riverine input, and one outflow, the Blue
92 Nile (Lamb et al., 2007).

93 Mean annual air temperature at Lake Tana is 18.8°C, and total annual precipitation is
94 1450 mm. Temperature (Kebede et al., 2006). Atmospheric temperature seasonality at Lake
95 Tana is relatively weak, with monthly temperatures ranging from 16.3°C in December to 21.3°C
96 in May. (Kebede et al., 2006). Precipitation seasonality, however, is extreme at Lake Tana due
97 to its position near the northern limit of the annual migration of the Intertropical Convergence
98 Zone (ITCZ), with monthly average rainfall ranging from 2 mm in February to 430 mm in July.
99 (Kebede et al., 2006). Wind direction also varies seasonally, with southerly flow during boreal
100 summer and northeasterly flow during boreal winter, due to the east African and Indian
101 monsoons. (Wondie et al., 2007).

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

110

111 *2.2 Core collection, sedimentology, and chronology*

112 | In October 2003, a 10.3 m ~~lake~~-sediment core (03TL3) was recovered from 13.88 m
113 | water depth near the center of the lake using a Livingstone piston corer. This core has four
114 | distinct lithological units (Lamb et al., 2007). Unit 1 (1030-1000 cm) is a dark gray silt with an
115 | organic matter content of 9-22%, and is overlain by Unit 2 (1000-955 cm) ~~is-~~ a dark brown
116 | herbaceous peat with an organic matter content of 30-70%. Unit 3 (955-937) has sharp upper
117 | and lower contacts, is comprised of slightly calcareous silt and organics, and diatom evidence
118 | suggests that it was likely deposited in waters with higher conductivity (3500 $\mu\text{S}/\text{cm}$) (Lamb et
119 | al., 2007). Unit 4 (937-0 cm) is a uniform fine gray diatomaceous silt, containing lower organic
120 | matter and higher magnetic susceptibility than Units 1-3. Core chronology is derived from mixed
121 | effect regression (Heegaard et al., 2005) on 4719 radiocarbon ages (Marshall et al., 2011).
122 | Errors (1σ) on the age model range from 120 years over the top 200 cm of the core to 500 years
123 | at the base of Unit 4.

125 | 2.3 Sample preparation and GDGT analysis

126 | ~~Core~~ 2 cm-thick subsamples were collected from core 03TL3 ~~was subsampled~~ every 15
127 | cm (~235 yr) and ~~subsamples~~ were transported to Brown University for preparation and analysis.
128 | Sample preparation followed that of Loomis et al. (2012). Briefly, samples were freeze-dried
129 | then homogenized with a mortar and pestle. Lipids were extracted using a Dionex 350
130 | Accelerated Solvent Extractor (ASE) using 9:1 dichloromethane (DCM): methanol (MeOH).
131 | Extracts were separated into non-polar and polar fractions with an Al_2O_3 column using 9:1
132 | hexane:DCM and 1:1 DCM:MeOH, respectively, as eluents. The polar fractions were filtered
133 | through a 0.22 μm glass fiber filter and analyzed using high performance liquid

134 chromatography/atmospheric pressure chemical ionization-mass spectrometry (HPLC/ACPI-
135 MS).

136 To explore potential changes in microbial ecology through time, we quantified the
137 relative abundance of branched to isoprenoidal tetraethers (BIT; Hopmans et al., 2004) using the
138 following equation:

$$139 \quad \text{BIT} = (\text{Ia} + \text{IIa} + \text{IIIa}) / (\text{Ia} + \text{IIa} + \text{IIIa} + \text{cren}) \quad (1)$$

140 where the Roman numerals refer to structures in Figure 2. Mean annual air temperatures
141 (MAAT) ~~were~~ reconstructed using the East African stepwise forward selection (SFS)
142 calibration:

$$143 \quad \text{MAAT} = 22.7 - 33.58 * \text{IIIa} - 12.88 * \text{IIa} - 418.53 * \text{IIc} + 86.43 * \text{Ib} \quad (2)$$

144 of Loomis et al. (2012).

145
146
147 Analytical error was quantified by running 10% of samples in duplicate, and
148 reconstructed MAAT error was determined through bootstrapping the reconstruction with the
149 East African lakes calibration data (Loomis et al., 2012). Duplicate samples show an average
150 analytical BIT error of 0.0009, while the average analytical reconstructed MAAT error is 0.08°C.
151 Bootstrapped MAAT error on individual samples ranges from 0.2-1.3°C, with an average of
152 0.9°C (Fig 3a).

Formatted: Font: Not Bold

155 **3. Results and Discussion**

156 *3.1 Production and Distributional Variations in distribution of GDGTs in Lake Tana*

157 Both branched and isoprenoidal GDGTs were detected in all samples ~~examined~~ from
158 Lake Tana core 03TL3. BIT values ~~average 0.71, and~~ range from 0.29 to 1.00 (mean = 0.71,
159 standard deviation = 0.15; Fig. 3b), with the highest values located in the silts and peats that
160 comprise Units 1-3 at the base of the core (BIT = 0.96-1.00). BIT values remain relatively
161 constant from the base of Unit 4 to ~300 cm depth (mean = 0.75, standard deviation = 0.11), but
162 become more variable (standard deviation = 0.17) and have a lower mean (0.55) than the rest of
163 the unit above 300 cm.

164 BrGDGT reconstructed temperatures range from 11.2- ~~to~~ 21.9°C (Fig. 3a). Reconstructed
165 temperatures are lowest below 800 cm, shift to higher temperatures between 800 and 775 cm,
166 and peak near 500 cm. This trend is interrupted by large negative reconstructed temperature
167 excursions in samples with BIT < 0.5 (133-59 cm). ~~This~~ The relationship between BIT and
168 reconstructed temperatures could suggest that the environmental conditions and/or ecological
169 changes associated with increased isoprenoidal GDGTs relative to brGDGTs ~~may affect~~ affects
170 the relative abundances of brGDGTs, ~~and~~ thereby ~~affecting~~ reconstructed temperatures. Before
171 making paleoclimatic interpretations of the Lake Tana brGDGT temperature record, it is
172 important to understand the environmental controls on the production of brGDGTs and their
173 depositional history.

174 175 3.1.1 Influence of paleolimnology and sediment lithology on brGDGT distributions

176 BrGDGTs have been detected in peat (e.g. Sinninghe Damsté et al., 2000), soil (e.g.
177 Weijers et al., 2007a), lake sediments (e.g. Tierney et al., 2010), and marine sediments (e.g.
178 Weijers et al., 2007b). ~~Laeustrine brGDGTs were originally thought to be derived solely from~~
179 ~~soil runoff, but numerous studies have found that the concentrations and distributions of~~

Formatted: Normal, No widow/orphan control, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

180 ~~brGDGTs in lake sediments are different from surrounding soils (e.g. Although some studies~~
181 ~~have concluded that brGDGTs in particular lakes are derived from soil runoff (Niemann et al.,~~
182 ~~2012; Woltering et al., 2014), the majority of studies~~ (Sinninghe Damsté et al., 2009; Tierney
183 and Russell, 2009; Loomis et al., 2011), ~~indicating that lacustrine brGDGTs are largely derived~~
184 ~~from an in situ source that has a different temperature response than soil-derived brGDGT~~
185 ~~producers, 2014b; Tierney et al., 2012; Wang et al., 2012; Buckles et al., 2014a,b) – including~~
186 ~~all of those that have been performed in the tropics – have found that the concentrations and~~
187 ~~distributions of brGDGTs in lake sediments are substantially different from surrounding soils,~~
188 ~~indicating that in most lacustrine environments, brGDGTs are predominantly derived from in~~
189 ~~situ production.~~ The differences in brGDGT distributions in lake sediments and surrounding
190 soils can result in ~~offsets in differences between~~ reconstructed temperatures in soils and adjacent
191 lake sediments; ~~for instance,~~ offsets of up to 10°C are commonly observed between soils and
192 lake sediment in East Africa, ~~for instance~~ (Tierney et al., 2010; Loomis et al., 2012). Thus,
193 ~~drastic~~ changes in catchment hydrology, ~~soil erosion,~~ and lake sedimentation - such as large
194 variations in the inputs of soil-derived organic matter - have the potential to affect reconstructed
195 temperatures from brGDGTs. While the reason for these differences between brGDGTs in lakes
196 and soils is still unknown, it is possible that it is related to changes in water or gas saturation ~~of in~~
197 the ~~production~~ environment (Loomis et al., 2011) ~~and/or~~ differences in the microbial ecology
198 between lake and soil environments (Loomis et al., 2014a).

Formatted: Border: : (No border)

Formatted: Border: : (No border)

Formatted: Border: : (No border)

Formatted: Border: : (No border)

199 The basal units of core 03TL3 include organic-rich silts, peats, and calcareous muds that
200 could signal varying sources of brGDGTs to these sediments, including not only soil vs.
201 lacustrine production, but also *in situ* production of brGDGTs in peat. A greenhouse experiment
202 carried out on peat bogs ~~has~~ demonstrated ~~that~~ brGDGT distributions in surface peat layers

203 change in response to variations in mean air temperature (Huguet et al., 2013). However, there is
204 also good evidence of *in situ* production of brGDGTs within deeper peat layers (Weijers et al.,
205 2009; Peterse et al., 2011), which may potentially alter the brGDGT distributions that were
206 present when these sections were exposed and responding to surface air temperatures, thereby
207 biasing the temperature signal. Unfortunately, widespread calibration studies have yet to be
208 carried out on peat, inhibiting our understanding of the temperature/brGDGT relationship in peat
209 samples. To examine the potential for varying brGDGT sources to affect reconstructed
210 temperatures in the Lake Tana core, we compared the fractional abundances of brGDGTs from
211 Units 1-3 to Unit 4 using one way analysis of variance (ANOVA) testing. We find that the
212 fractional abundances of brGDGTs with zero (IIIa, IIa, and Ia) and one cyclopentyl rings (IIIb,
213 IIb, Ib) are significantly different ($p \leq 0.002$) between these stratigraphic units. As several of
214 these compounds are important to our temperature calibration, and in light of the possibility of
215 changing microbial sources of brGDGTs in the variable depositional environments represented
216 by these units, we limit our temperature interpretation of reconstructed temperatures in this core
217 to Unit 4 (937-0 cm).

Formatted: Font: Italic

218 ~~—— In addition to brGDGT variations associated with these lithological changes, we note that~~
219 ~~several samples with low BIT values have large negative temperature changes. While the~~
220 ~~lithology and percent organic matter ($9.5 \pm 1.1\%$) remain fairly constant throughout Unit 4~~
221 ~~(Marshall et al., 2011), the Ti record shows substantial variability, including an abrupt increase~~
222 ~~in Ti concentrations at 700 cm (~12 ka), a negative Ti oscillation between 515 and 575 cm (~7-~~
223 ~~8.5 ka), and a decrease in Ti concentrations at 400 cm (~4.5 ka) (Fig. 4c). These large changes in~~
224 ~~Ti concentration indicate variations in soil runoff (Marshall et al., 2011), which has the potential~~
225 ~~to change the relative proportions of allochthonous vs. autochthonous brGDGTs in the lake~~

226 sediments. However, the large and abrupt shifts in Ti concentrations at 700 cm (12 ka) and 400
227 cm (4.5 ka) do not correspond to large changes in reconstructed temperature (Fig. 4a), indicating
228 that the effects of changing delivery of soil-derived brGDGTs from the catchment on our
229 temperature reconstruction is limited. The negative Ti oscillation between 515 and 575 (7-8.5
230 ka), however, is contemporaneous with a negative temperature oscillation (Fig. 4), and thus, we
231 cannot rule out a changing brGDGT source during this interval. In spite of this, we believe that
232 these oscillations are a result of climate variability (see section 3.2.2) rather than a change in
233 runoff, as other large Ti changes are not correlated with temperature variability.

234 Variations in water depth also have the potential to alter brGDGT reconstructed MAAT
235 due to variations in integrated water column temperatures (Loomis et al., 2014b), which could
236 greatly affect lakes that have large differences between epi- and hypolimnetic temperatures.
237 Marginal seismic reflectors are also present at Lake Tana during the periods of lowest Ti (just
238 below 700 cm, 525 and 550 cm, and 400 cm; Marshall et al., 2011), indicating relative lake
239 lowstands during these periods of decreased precipitation. However, given that Lake Tana water
240 column temperatures show $\leq 1^{\circ}\text{C}$ variability between the surface and the bottom (Dargahi and
241 Setegn, 2011), it is unlikely that changes in the water depth of Lake Tana had a significant
242 impact on brGDGT distributions.

244 3.1.2 Influence of changing microbial ecology on brGDGT distributions

245 In addition to brGDGT variations associated with lithological changes, we note that
246 several samples with low BIT values have much lower reconstructed MAAT values than
247 adjacent samples with a high BIT value. The BIT index was initially proposed as a proxy for
248 terrestrial organic matter inputs to marine environments (Hopmans et al., 2004), with higher BIT

249 values (higher relative abundances of brGDGTs) indicating a larger input of soil-derived organic
250 matter relative to aquatically produced organic matter-, represented by the relative abundance of
251 crenarchaeol (Sinninghe Damsté et al., 2002). As soil-derived brGDGTs have a different
252 empirical temperature relationship than lacustrine brGDGTs (Tierney et al., 2010; Pearson et al.,
253 2011; Sun et al., 2011; Loomis et al., 2012), large changes in soil-derived organic matter, as
254 defined by the BIT index, have the potential to affect reconstructed temperatures. However,
255 there is strong evidence that brGDGTs in tropical lake sediments are largely derived from
256 production within the lake itself (e.g. Tierney and Russell, 2009; Tierney et al., 2010; Loomis et
257 al., 2011; Buckles et al., 2014**b**), so BIT values likely record changes in the microbial ecology of
258 lakes, rather than allochthonous vs. autochthonous sources of organic matter in lacustrine
259 environments. Thus, we do not ~~think~~believe that the negative temperature excursions associated
260 with low BIT values are a result of changes soil-derived organic matter-~~Rather, rather,~~ we
261 suggest that the temperature changes in samples with low BIT are tied to changes in the
262 production of brGDGTs and crenarchaeol in the lake itself.

263 BrGDGTs are likely produced by heterotrophic acidobacteria (Weijers et al., 2006, 2010;
264 Sinninghe Damsté et al., 2011, ~~in press~~2014), and there is empirical evidence to suggest that
265 brGDGT production increases in deeper, less oxic lake waters (Sinninghe Damsté et al., 2009;
266 Bechtel et al., 2010; Woltering et al., 2012; ~~Loomis, 2013;~~ Buckles et al., 2014**b**; Loomis et al.,
267 2014b). Crenarchaeol is produced by an ammonia-oxidizing archaea (Francis et al., 2005), and
268 in lakes, peak production of ammonia-oxidizing archaea takes place near the oxycline (Pouliot et
269 al., 2009; Llíros et al., 2010; Buckles et al., 2013). It seems unlikely that ~~these~~ competitive
270 interactions between these two groups could cause changes in the depth of brGDGT production;
271 however, such changes could affect reconstructed temperatures at higher latitudes with large

272 | hypo-limnetic/epilimnetic temperature gradients. In contrast, water temperature gradients within
273 | ~~East~~ African lakes are minimal (<2°C; Loomis et al., 2014a and references therein), and
274 | thus, variations in production depth are not the cause of these large temperature excursions.

275 | While the mechanisms linking low BIT to negative temperature anomalies is unknown,
276 | we suggest that ~~they~~ it likely involves changes in the microbial flora that produce brGDGTs.
277 | BIT values in Lake Tana surface sediments are relatively high, indicating relatively low
278 | production of ~~the~~ crenarchaeol-producing ammonia-oxidizing archaea. Presently, wind speeds at
279 | Lake Tana cause nearly constant mixing (Wondie et al., 2007) resulting in only weak seasonal
280 | stratification (Wood and Talling, 1988), thereby inhibiting the formation of an oxycline, which
281 | would likely suppress the growth of ammonia-oxidizing archaea. It is possible that in the past,
282 | changes in wind speed and/or nitrogen cycling in the lake increased production of crenarchaeol,
283 | thereby decreasing BIT values. Moreover, there is evidence of human disturbance in the Lake
284 | Tana catchment starting near 1.7 ka (177 cm depth; Marshall et al., 2011), which has the
285 | ~~potential~~ capability to alter the nitrogen cycle of the lake (Russell et al., 2009), potentially
286 | increasing crenarchaeol production as well. Changes in water column oxygenation and nutrient
287 | concentrations alone are likely not the direct cause of the negative temperature excursions, as
288 | nutrient and oxygen concentrations do not significantly control brGDGT distributions in East
289 | African lakes (Loomis et al., 2014a). However, it is possible that these changes affect the
290 | microbial ecology of the lake, including both the changes in bacterial vs. archaeal populations
291 | signified by BIT, as well as the populations of brGDGT-producing bacteria, thereby altering the
292 | distributions of brGDGTs deposited in the lake sediments.

293 | ~~Interestingly, At Lake Tana,~~ it appears that brGDGT reconstructed temperatures ~~begin~~
294 | ~~to~~ strongly deviate from ~~observed~~ the reconstructed temperatures ~~of adjacent samples~~ when BIT <

295 ~~0.5, while are less than 0.5 (Fig. 3). Interestingly,~~ TEX₈₆ reconstructed temperatures in global
296 lakes do not accurately record observed temperatures when BIT > 0.5 (Powers et al., 2010).
297 ~~Moreover, and~~ reconstructed temperatures from surface sediments in East African rift lakes are
298 on average 10°C lower than observed temperatures, which also have low BIT values (mean =
299 0.35; Loomis et al., 2014a). These data could suggest that the shift in microbial ecology
300 ~~near when archaeal and bacterial GDGTs are produced at similar rates (theoretical BIT = 0.5)~~ is
301 a critical threshold when applying GDGT-based paleotemperature proxies. ~~However, without~~
302 ~~knowing which organisms produce brGDGTs; however, the exact threshold should be applied~~
303 ~~cautiously given that a wide range of BIT values can be obtained for the same sample run in~~
304 ~~different laboratories (Schouten et al., 2013). Furthermore, given the limited number of lakes~~
305 ~~with low BIT in the global lacustrine TEX₈₆ dataset (Powers et al., 2010) and the fact that the~~
306 ~~source organism(s) for brGDGTs are yet unknown,~~ it is difficult to ascertain the reason for
307 reconstructed temperature offsets in samples with low BIT, either in modern or in ancient
308 sediments.

309 Regardless of the mechanism, large changes in BIT do suggest the potential for biases to
310 the brGDGT paleotemperature reconstruction related to changing brGDGT sources. Thus, we
311 will focus our paleoclimatic interpretation of the Lake Tana temperature record only on samples
312 with BIT \geq 0.5.

313

314 *3.2 Temperature variability in Northeast Africa from 15 ka to present*

315 Widespread drought in the Afro-Asian monsoon region during Heinrich ~~Event~~Stadial 1
316 (H1; e.g. Stager et al., 2011 and references therein) led to desiccation of Lake Tana (Lamb et al.,
317 2007; Marshall et al., 2011). Flooding at 15.2 ka returned Lake Tana to a lacustrine environment

318 | (Fig. [4d4a](#)), and our brGDGT data indicate reconstructed temperatures of 12.1°C at this time.
319 | Between 15 ka and 13.8 ka, Lake Tana experienced a 3.7°C oscillation, followed by a rapid
320 | temperature increase of ~7°C in 0.8 ky, resulting in temperatures of 18.1°C at 13 ka.
321 | Temperatures then gradually increased to a maximum of 21.9°C at 6.6 ka, followed by a gradual
322 | cooling to 16.7°C in the most recent sample at 0.4 ka. This long-term warming and cooling trend
323 | during the Holocene was interrupted by a -3°C temperature oscillation lasting ~1.5 ky and
324 | centered at 7.4 ka. Below we discuss this record and its relation to Late Pleistocene and
325 | Holocene climate changes on a global and regional scale.

326

327 | 3.2.1 Late Pleistocene

328 | Temperature variability at Lake Tana during the late Pleistocene is broadly consistent
329 | with other records of temperature from around North Africa. At the termination of H1, Lake
330 | Tana experienced a 3.7°C warming between 15.2 and 14.5 ka. Sea surface temperature (SST)
331 | records from the Red Sea (Arz et al., 2003) and Eastern Mediterranean (Castañeda et al., 2010)
332 | show an abrupt ~ 5°C warming between 15 ka and 14.5 ka as well (Fig. [4b5b-c](#)). This warming
333 | is consistent with the timing of the Bølling Oscillation recorded in Greenland ice cores (North
334 | Greenland Ice Core Project Members, 2004; Fig. [4a5a](#)), which was driven by the resumption of
335 | Atlantic Meridional Overturning Circulation (AMOC) after H1 (McManus et al., 2004),
336 | suggesting that abrupt warming observed in much of the northern hemisphere (Shakun et al.,
337 | 2012) was also felt in northern tropical Africa. In contrast, this abrupt warming is absent from
338 | southern and equatorial African continental paleotemperature records (Fig. [56](#)). This could
339 | indicate a northern hemispheric temperature history at Lake Tana that is decoupled from that of
340 | equatorial and southeastern Africa.

341 Temperatures in the eastern Mediterranean (Castañeda et al., 2010) and the Red Sea (Arz
342 et al., 2003) remain warm during the subsequent Allerød Oscillation, yet temperatures at Lake
343 Tana decrease to near H1 values at 13.8 ka (Fig. 5). These minimum temperatures are
344 ~~concomitant~~ coincident with the Older Dryas cooling event identified between the Bølling and
345 Allerød warm periods. Although identification of the Older Dryas has mainly been limited to
346 North Atlantic and northern Eurasian paleoclimate records, contemporaneous climate events
347 have also been identified in the tropics, including decreased temperatures in the Cariaco basin
348 (Lea et al., 2003) and Lake Albert (Berke et al., 2014) ~~as well as~~, decreased biogenic silica
349 production in Lake Tanganyika (Tierney and Russell, 2007), and increased primary productivity
350 in the Cariaco Basin (Hughen et al., 1996) ~~in the Cariaco Basin~~. Hughen et al. (1996) postulate
351 that increased primary productivity in the Cariaco Basin is driven by a strengthening of the trade
352 winds associated with North Atlantic cooling. ~~While the resolution of our record is inadequate to~~
353 ~~unequivocally link, while Tierney and Russell (2007) attribute the cooling observed at this time~~
354 ~~to decrease in biogenic silica production to a weakening of the Older Dryas event, this~~
355 ~~mechanism~~ southerly winds that drive upwelling in Tanganyika. The strengthening (weakening)
356 of northerly (southerly) winds may also explain temperature decreases at Lake Tana, as
357 strengthened northerly trade winds transport cool, dry air from the Tibetan Plateau over the
358 Arabian Sea and into northeast Africa.

359 Following the temperature minimum at 13.8 ka, temperatures at Lake Tana increased to
360 18.1°C by 13 ka and remained fairly stable (mean = 18.3°C, standard deviation = 0.2°C) into the
361 Holocene (Fig. 5a6a). The abrupt temperature increase at 13.8 ka is contemporaneous with a 3°C
362 increase at Sacred Lake (Loomis et al., 2012; Fig. 5b), ~~and occurs shortly after large and abrupt~~
363 ~~warmings in Lakes Malawi and Victoria~~6b), but is not observed in other paleotemperature

364 records from ~~East~~East Africa (Powers et al., 2005; Tierney et al., 2008; Berke et al., 2012a; ~~Berke~~
365 ~~et al.~~, 2014; Fig. 6c-e). The abrupt (800 year) nature of this event indicates that changes in local
366 insolation are not likely to be the cause of the temperature increase. Greenhouse gas forcing is
367 also likely not the cause of this warming, as atmospheric CO₂ concentrations varied little
368 between 13.8 and 13.0 ka (Monnin et al., 2001). The temperature increase at 13.8 ka, however,
369 is similar in timing to changes in the temperature and circulation of the Arabian Sea. SSTs off
370 the coast of Oman, recorded by foraminiferal assemblages (Naidu and Malmgren, 2005; Fig.
371 ~~6e7d~~) and ~~the~~TEX₈₆ proxy (Huguet et al., 2006; Fig. ~~6d7c~~), increased rapidly starting at
372 ~~about~~near 14 ka. Foraminiferal assemblage data suggests this increase was mainly driven by
373 increases in winter SSTs (Naidu and Malmgren, 2005). Furthermore, there are large increases in
374 the fractional abundances of dinoflagellates that thrive under high nutrient conditions (Zonneveld
375 et al., 1997; Fig. ~~6a7a~~) along with the foraminifera *Globigerina bulloides* (Naidu and Malmgren,
376 1996; Fig. ~~6b7b~~), indicating enhanced upwelling at this time. Taken together, these Arabian Sea
377 data indicate an increase in the strength of the Indian Summer Monsoon and a decrease in the
378 intensity of the Indian Winter Monsoon (Naidu and Malmgren, 2005). We hypothesize that the
379 temperature increase at Lake Tana near 14 ka is associated with this shift in ~~the~~Indian Monsoon
380 circulation.

381 The Indian summer and winter monsoons are driven by differential heating/cooling of the
382 Asian continent compared to the ocean (Hastenrath, 1991). During northern hemisphere
383 summer, the Tibetan Plateau warms rapidly compared to the Indian Ocean, resulting in low
384 pressure over the continent, which drives southwesterly winds (Fig 1a) and generates the summer
385 monsoon. Conversely, during the winter months, the Tibetan Plateau cools compared to the
386 ocean, reversing the wind direction over the Arabian Sea to northeasterly (Fig 1b) and generating

387 the winter monsoon. Modern fluctuations in the strength of the monsoons are controlled, in part,
388 by Eurasian snow and ice cover (Hahn and Shukla, 1976; Vernekar et al., 1995). Continental
389 summer temperatures are lower after winters with large snowfall due to the increased albedo and
390 latent heat fluxes associated with snow melt and evaporation. These weaken the summer
391 monsoon, and result in anomalous northeastern winds and a weakening of the Somali Jet.

392 Fluctuations in the Somali Jet alter the transport of moist, warm air from the Congo Basin
393 to northeast Africa, affecting precipitation on the Ethiopian Plateau (Camberlin, 1997).
394 Paleoclimate modeling studies focused on this region show that increased ice cover over Eurasia
395 decreases temperatures and precipitation over Northeast Africa due to a strengthening of the
396 northeasterly winds (deMenocal and Rind, 1993; [Otto-Bliesner et al., 2014](#)). The onset of a
397 strong Indian summer monsoon at 14 ka would have weakened the easterly trade winds and
398 strengthened the southwesterly winds and the Somali Jet, transporting warm, ~~moist~~ air to the
399 Ethiopian Plateau.

400 Our hypothesis that large changes in Indian Monsoon circulation trigger changes in
401 temperature at Lake Tana is supported by a leaf wax hydrogen isotope record from Lake Tana
402 (Costa et al., 2014), which shows that the leaf waxes became more D-depleted concomitantly
403 with the rise in temperature (Fig. 7c). ~~This depletion is likely a result of increased precipitation~~
404 ~~triggered by a strengthening of the monsoon (Costa et al., 2014). The 4a-b). The temperature~~
405 ~~increase and the initial onset of the leaf wax δD depletion after 13.8 ka lead increased runoff at~~
406 ~~Lake Tana (Marshall et al., 2011; Fig. 4c) and in the Nile River catchment (Weldeab et al., 2014)~~
407 ~~by ~2 ky, but peak leaf wax δD depletion is contemporaneous with peak local and regional~~
408 ~~runoff. This would suggest that the temperature increase/ δD depletion starting at 13.8 ka was~~
409 ~~caused by an incursion of warm, δD depleted air masses from the Congo Basin (Costa et al.,~~

410 2014) to the Ethiopian Plateau, which was subsequently followed by an increase in precipitation
411 over ~2 ky, peaking during the early Holocene, causing additional depletion of the leaf wax
412 isotopes through the amount effect.

413 Interestingly, although temperatures at Lake Tana appear to be affected by AMOC-
414 induced global climate events early in the deglacial process, including H1 and the Bølling
415 Oscillation, there is no apparent cooling coincident with the Younger Dryas (YD, 12.8-11.5 ka;
416 Fig. 5). This observation is again consistent with an incursion of Congo Basin air masses onto
417 the Ethiopian Plateau starting at 14 ka, as the Congo Basin temperature record (Weijers et al.,
418 2007b) does not show a temperature decrease associated with the YD.

419 The linkage between Indian Monsoon circulation and temperature at Lake Tana and
420 Sacred Lake (Loomis et al., 2012) contrasts with temperature records from central equatorial
421 Africa (Tierney et al., 2008; Berke et al., 2012a), where variability is more strongly tied to
422 changes in CO₂ and insolation. Furthermore, the temperature changes associated with Indian
423 Monsoon circulation are more pronounced at Lake Tana (~7°C) than at Sacred Lake (~3°C).
424 This would suggest that temperature changes in northeast Africa are more strongly influenced by
425 large changes in atmospheric circulation during the last deglaciation than locations to the south
426 and west.

427

428 3.2.2 Holocene

429 Temperatures at Lake Tana gradually increase from 18.1°C at 13 ka to 21.9°C at 6.6 ka,
430 gradually cool to 19.5°C at 2 ka, and then cool more rapidly to 16.7°C by the most recent sample
431 at 0.4 ka- (Fig. 6a). Broadly, the trends in Holocene temperature at Lake Tana are similar to
432 other equatorial East African paleotemperature records, with highest reconstructed

Formatted: Indent: First line: 1.27 cm

433 temperatures during the mid-Holocene and lowest reconstructed temperatures during the late
434 Holocene (Fig. 5). However, the timing of the mid Holocene thermal maximum differs
435 ~~substantially~~ among the different records, with maxima near 9 ka at Lake Victoria (Berke et al.,
436 2012a), near 7 ka at Lake Tana and Sacred Lake (Loomis et al., 2012), and near 5 ka at Lakes
437 Malawi (Powers et al., 2005) and Tanganyika (Tierney et al., 2008). Peak mid-Holocene
438 temperatures in Africa are not the result of greenhouse gas radiative forcing, as ~~the timing at~~
439 ~~different locations differs and~~ CO₂ reaches a relative ~~minimamimum~~ during the mid-Holocene
440 (Indermuhle et al., 1999). The thermal maxima are also not a direct result of local insolation
441 forcing, as peak temperatures at Lake Tana and Sacred Lake lag maximum northern hemisphere
442 summer insolation by ~4 ky, while peak temperatures at Lakes Malawi and Tanganyika lead
443 peak southern hemisphere summer insolation by ~3 ky. Furthermore, ~~Easteast~~ African
444 temperature variability during the Holocene does not vary systematically with changes in
445 hydrology, as peak temperatures at Lake Tana, Lake Tanganyika, and Lake Victoria occur during
446 a transition from wet to dry conditions (Tierney et al., 2008; Berke et al., 2012a; Costa et al.,
447 2014), while peak temperatures at Lake Malawi (Powers et al., 2005) occur during a transition
448 from dry to wet conditions (Castañeda et al., 2007). Finally, the relative abruptness of mid-
449 Holocene thermal maxima varies between different locations: Lakes Tanganyika and Malawi
450 record temperature increases of 2-3°C over 2 ky, while temperature maxima at Lake Tana and
451 Sacred Lake are reached through a gradual increase starting at the beginning of the Holocene.
452 Thus, despite the prevalence of warmer mid-Holocene conditions at these sites, the differences in
453 timing, relative abruptness, and hydrological linkages indicate that mid-Holocene thermal
454 maxima at different ~~East Africa~~ ~~east African~~ locations are likely driven by different mechanisms.

455 The broad Holocene warming and cooling trend at Lake Tana is interrupted by a 3°C
456 temperature oscillation over 1.5 ky centered at 7.4 ka. While this oscillation could be associated
457 with the 8.2 cooling event identified in the Greenland ice cores (Alley et al., 1997), the event we
458 observe is outside of age model error of 8.2 ka ($\sigma = 0.37$ ky at this time) and appears to have
459 been much longer-lived than the 8.2 ka event observed in Greenland. This cold oscillation is not
460 apparent in either continental (Fig. 56) or marine (Figs. 45, 7) temperature records from the
461 region, but the onset does align with an abrupt leaf wax δD enrichment (Costa et al., 2014; Fig.
462 7e4b) and a decrease in Ti (Marshall et al., 2011; Fig. 7d4c), indicating a concomitant drought.
463 In this context, the Ti record from Lake Tana shows that precipitation gradually decreased after 7
464 ka (Marshall et al., 2011; Fig. 7d4c), potentially suggesting that the gradual cooling we observe
465 from 7 ka through the late Holocene is linked to regional hydrological change. Although the
466 mechanisms linking temperature and precipitation at Lake Tana are not known, it is possible that
467 reductions in cloud cover and atmospheric humidity stimulated long-wave and latent heat losses,
468 thereby cooling Lake Tana during drier intervals. In any case, our data suggest that the
469 hydrological and thermal histories of northeastern Africa are more intimately linked than
470 hydrological and temperature histories in equatorial and southern Africa. Such a link is
471 plausible, given the strongly monsoonal nature of precipitation in northeastnortheastern Africa.

472

473

474 4. Conclusions

475 We present the first quantitative paleotemperature record from North-northern Africa
476 using the brGDGT lacustrine paleothermometer to investigate the controls on temperature
477 variability in the northern tropics over the past 15 ka. We find that the thermal history of North

478 | Eastnortheast Africa is distinct from the equatorial and southern tropics, and is instead largely
479 | tied to variations in the strength of the monsoons and regional hydrology. The Bølling
480 | Oscillation induced a large warming at Lake Tana, which is evident in temperature records from
481 | the Red Sea (Arz et al., 2003) and eastern Mediterranean (Castañeda et al., 2010) but is not seen
482 | in equatorial and southeast African paleotemperature records. After this oscillation,
483 | temperatures warmed near 14 ka, likely due to large-scale reorganization of wind patterns
484 | associated with a weakening of the Indian Winter Monsoon and a strengthening of the Indian
485 | Summer Monsoon, which greatly diminished the transport of cold, dry air masses from the
486 | Tibetan Plateau. Finally, like other Easteast African paleotemperature locations (Powers et al.,
487 | 2005; Tierney et al., 2008; Berke et al., 2012a; Loomis et al., 2012), Lake Tana experienced a
488 | mid-Holocene thermal maximum. However, existing data suggest discrepancies in the timing
489 | and magnitude of the mid-Holocene temperature maximum in different regions of Africa,
490 | suggesting this warming arises from diverse causes. Cooling near 7.4 ka, and gradual cooling
491 | from the mid-Holocene to present, occur in association with drier conditions, suggesting that,
492 | unlike equatorial and southeast Africa, the thermal history of northeast Africa is more directly
493 | linked to changes in regional hydrology. Finally, the magnitude of temperature change is larger
494 | at Lake Tana compared to other Easteast African locations, potentially due to an amplification of
495 | warming at higher latitudes.

496

497

498 **Acknowledgements**

499 | We would like to thank B. Konecky for helpful discussions and assistance with core sampling,
500 | and K. Costa and R. Tarozo for laboratory assistance. This material is based upon work

501 supported by the National Science Foundation under grant number EAR-1226566 to J. Russell
502 and by a Geological Society of America Graduate Student Research Grant awarded to S. Loomis.
503
504

505 **References**

506 Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene
507 climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25, 483-486.

508 Arz, H.W., Patzold, J., Muller, P.J., Moammar, M.O., 2003. Influence of Northern Hemisphere
509 climate and global sea level rise on the restricted Red Sea marine environment during
510 termination I. *Paleoceanography* 18.

511 [Bechtel, A., Smittenberg, R.H., Bernasconi, S.M., Schubert, C.J., 2010. Distribution of branched
512 and isoprenoid tetraether lipids in an oligotrophic and a eutrophic Swiss lake: Insights
513 into sources and GDGT-based proxies. *Organic Geochemistry* 41, 822-832.](#)

514 Berke, M.A., Johnson, T.C., Werne, J.P., Grice, K., Schouten, S., Sinninghe Damsté, J.S., 2012a.
515 Molecular records of climate variability and vegetation response since the Late
516 Pleistocene in the Lake Victoria basin, East Africa. *Quaternary Science Reviews* 55, 59-
517 74.

518 Berke, M.A., Johnson, T.C., Werne, J.P., Schouten, S., Sinninghe Damsté, J.S., 2012b. A mid-
519 Holocene thermal maximum at the end of the African Humid Period. *Earth and Planetary
520 Science Letters* 351, 95-104.

521 Berke, M.A., Johnson, T.C., Werne, J.P., Livingstone, D.A., Grice, K., Schouten, S., Sinninghe
522 Damsté, J.S., 2014. Characterization of the last deglacial transition in tropical East
523 Africa: Insights from Lake Albert. *Palaeogeography Palaeoclimatology Palaeoecology*
524 409, 1-8.

525 Blaauw, M., Bakker, R., Christen, J.A., Hall, V.A., van der Plicht, J., 2007. A Bayesian
526 framework for age modeling of radiocarbon-dated peat deposits: Case studies from the
527 Netherlands. *Radiocarbon* 49, 357-367.

528 [Buckles, L.K., Villanueva, L., Weijers, J.W.H., Verschuren, D., Sinninghe Damsté, J.S.,
529 2014-2013. Linking isoprenoidal GDGT membrane lipid distributions with gene
530 abundances of ammonia-oxidizing Thaumarchaeota and uncultured crenarchaeotal
531 groups in the water column of a tropical lake \(Lake Challa, East Africa\). *Environmental
532 Microbiology* 15, 2445-2462.](#)

533 [Buckles, L.K., Weijers, J.W.H., Tran, X.M., Waldron, S., Sinninghe Damsté, J.S., 2014a.
534 Provenance of tetraether membrane lipids in a large temperate lake \(Loch Lomond, UK\):
535 implications for glycerol dialkyl glycerol tetraether \(GDGT\)-based palaeothermometry.
536 *Biogeosciences* 11, 5539-5563.](#)

537 [Buckles, L.K., Weijers, J.W.H., Verschuren, D., Sinninghe Damsté, J.S., 2014b.](#) Sources of core
538 and intact branched tetraether membrane lipids in the lacustrine environment: Anatomy
539 of Lake Challa and its catchment, equatorial East Africa. *Geochimica Et Cosmochimica
540 Acta* 140, 106-126.

Formatted: English (U.S.), Border: :
(No border)

Formatted: English (U.S.), Border: :
(No border)

Formatted: Border: : (No border)

- 541 Camberlin, P., 1997. Rainfall anomalies in the source region of the Nile and their connection
542 with the Indian summer monsoon. *Journal of Climate* 10, 1380-1392.
- 543 Castañeda, I.S., Werne, J.P., Johnson, T.C., 2007. Wet and arid phases in the southeast African
544 tropics since the Last Glacial Maximum. *Geology* 35, 823-826.
- 545 Castañeda, I.S., Schefuss, E., Patzold, J., Damste, J.S.S., Weldeab, S., Schouten, S., 2010.
546 Millennial-scale sea surface temperature changes in the eastern Mediterranean (Nile
547 River Delta region) over the last 27,000 years. *Paleoceanography* 25.
- 548 Coetzee, J.A., 1967. Pollen analytical studies in East and southern Africa. *Palaeoecology of*
549 *Africa* 3, 1-146.
- 550 Costa, K., Russell, J., Konecky, B., Lamb, H., 2014. Isotopic reconstruction of the African
551 Humid Period and Congo Air Boundary migration at Lake Tana, Ethiopia. *Quaternary*
552 *Science Reviews* 83, 58-67.
- 553 [Dargahi, B., Setegn, S.G., 2011. Combined 3D hydrodynamic and watershed modelling of Lake](#)
554 [Tana, Ethiopia. *Journal of Hydrology* 398, 44-64.](#)
- 555 deMenocal, P.B., Rind, D., 1993. Sensitivity of Asian and African Climate to Variations in
556 Seasonal Insolation, Glacial Ice Cover, Sea-Surface Temperature, and Asian Orography.
557 *Journal of Geophysical Research-Atmospheres* 98, 7265-7287.
- 558 Fawcett, P.J., Werne, J.P., Anderson, R.S., Heikoop, J.M., Brown, E.T., Berke, M.A., Smith,
559 S.J., Goff, F., Donohoo-Hurley, L., Cisneros-Dozal, L.M., Schouten, S., Sinninghe
560 Damsté, J.S., Huang, Y.S., Toney, J., Fessenden, J., WoldeGabriel, G., Atudorei, V.,
561 Geissman, J.W., Allen, C.D., 2011. Extended megadroughts in the southwestern United
562 States during Pleistocene interglacials. *Nature* 470, 518-521.
- 563 Francis, C.A., Roberts, K.J., Beman, J.M., Santoro, A.E., Oakley, B.B., 2005. Ubiquity and
564 diversity of ammonia-oxidizing archaea in water columns and sediments of the ocean. *P*
565 *Natl Acad Sci USA* 102, 14683-14688.
- 566 Gebrekirstos, A., Worbes, M., Teketay, D., Fetene, M., Mitlohner, R., 2009. Stable carbon
567 isotope ratios in tree rings of co-occurring species from semi-arid tropics in Africa:
568 Patterns and climatic signals. *Global and Planetary Change* 66, 253-260.
- 569 Hahn, D.G., Shukla, J., 1976. Apparent Relationship between Eurasian Snow Cover and Indian
570 Monsoon Rainfall. *J Atmos Sci* 33, 2461-2462.
- 571 Hastenrath, S., 1991. *Climate Dynamics of the Tropics*. Springer, Dordrecht.
- 572 Heegaard, E., Birks, H.J.B., Telford, R.J., 2005. Relationships between calibrated ages and depth
573 in stratigraphical sequences: an estimation procedure by mixed-effect regression.
574 *Holocene* 15, 612-618.

- 575 Hopmans, E.C., Weijers, J.W.H., Schefuß, E., Herfort, L., Sinninghe Damsté, J.S., Schouten, S.,
576 2004. A novel proxy for terrestrial organic matter in sediments based on branched and
577 isoprenoid tetraether lipids. *Earth and Planetary Science Letters* 224, 107-116.
- 578 Huguen, K.A., Overpeck, J.T., Peterson, L.C., Trumbore, S., 1996. Rapid climate changes in the
579 tropical Atlantic region during the last deglaciation. *Nature* 380, 51-54.
- 580 Huguet, A., Fosse, C., Laggoun-Defarge, F., Delarue, F., Derenne, S., 2013. Effects of a short-
581 term experimental microclimate warming on the abundance and distribution of branched
582 GDGTs in a French peatland. *Geochimica Et Cosmochimica Acta* 105, 294-315.
- 583 Huguet, C., Kim, J.H., Sinninghe Damsté, J.S., Schouten, S., 2006. Reconstruction of sea surface
584 temperature variations in the Arabian Sea over the last 23 kyr using organic proxies
585 (TEX₈₆ and U₃₇^K). *Paleoceanography* 21.
- 586 Indermuhle, A., Stocker, T.F., Joos, F., Fischer, H., Smith, H.J., Wahlen, M., Deck, B.,
587 Mastroianni, D., Tschumi, J., Blunier, T., Meyer, R., Stauffer, B., 1999. Holocene
588 carbon-cycle dynamics based on CO₂ trapped in ice at Taylor Dome, Antarctica. *Nature*
589 398, 121-126.
- 590 ~~Konecky, B.L., Russell, J.M., Johnson, T.C., Brown, E.T., Berke, M.A., Werne, J.P., Huang,~~
591 ~~Y.S., 2011. Atmospheric circulation patterns during late Pleistocene climate changes at~~
592 ~~Lake Malawi, Africa. *Earth and Planetary Science Letters* 312, 318-326.~~
- 593 ~~Kebede, S., Travi, Y., Alemayehu, T., Marc, V., 2006. Water balance of Lake Tana and its~~
594 ~~sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of Hydrology* 316,~~
595 ~~233-247.~~
- 596 Lamb, H.F., Bates, C.R., Coombes, P.V., Marshall, M.H., Umer, M., Davies, S.J., Dejen, E.,
597 2007. Late Pleistocene desiccation of Lake Tana, source of the Blue Nile. *Quaternary*
598 *Science Reviews* 26, 287-299.
- 599 Lea, D.W., Pak, D.K., Peterson, L.C., Huguen, K.A., 2003. Synchronicity of tropical and high-
600 latitude Atlantic temperatures over the last glacial termination. *Science* 301, 1361-1364.
- 601 ~~Llirós, M., Gich, F., Plasencia, A., Auguet, J.C., Darchambeau, F., Casamayor, E.O., Descy, J.P.,~~
602 ~~Borrego, C., 2010. Vertical Distribution of Ammonia-Oxidizing Crenarchaeota and~~
603 ~~Methanogens in the Epipelagic Waters of Lake Kivu (Rwanda-Democratic Republic of~~
604 ~~the Congo). *Applied and Environmental Microbiology* 76, 6853-6863.~~
- 605 ~~Loomis, S.E., Russell, J.M., Sinninghe Damsté, J.S., 2011. Distributions of branched GDGTs in~~
606 ~~soils and lake sediments from western Uganda: Implications for a lacustrine~~
607 ~~paleothermometer. *Organic Geochemistry* 42, 739-751.~~
- 608 Loomis, S.E., Russell, J.M., Ladd, B., Street-Perrott, F.A., Sinninghe Damsté, J.S., 2012.
609 Calibration and application of the branched GDGT temperature proxy on East African
610 lake sediments. *Earth and Planetary Science Letters* 357-358, 277-288.

611 | [Loomis, S.E., 2013. On Branched Glycerol Dialkyl Glycerol Tetraethers: Development and](#)
612 | [Application of a Paleotemperature Proxy, Department of Geological Sciences, Brown](#)
613 | [University, p. 254.](#)

614 | Loomis, S.E., Russell, J.M., Eggermont, H., Verschuren, D., Sinninghe Damsté, J.S., 2014-[a.](#)
615 | Effects of temperature, pH and nutrient concentration on branched GDGT distributions in
616 | East African lakes: Implications for paleoenvironmental reconstruction. *Organic*
617 | *Geochemistry* 66, 25-37.

618 | ~~[Mareott, Loomis, S.A., Shakun, E., Russell, J.D., Clark, P.U., Mix, A.C., 2013. A Reconstruction](#)~~
619 | ~~[of Regional and Global Temperature for the Past 11,300 Years. *Science* 339, 1198-](#)~~
620 | ~~[1201.](#)~~ ~~[M., Heurreux, A.M., D'Andrea, W.J., Damste, J.S.S., 2014b. Seasonal variability of](#)~~
621 | ~~[branched glycerol dialkyl glycerol tetraethers \(brGDGTs\) in a temperate lake system.](#)~~
622 | ~~[Geochimica Et Cosmochimica Acta 144, 173-187.](#)~~

623 | Marshall, M.H., Lamb, H.F., Huws, D., Davies, S.J., Bates, R., Bloemendal, J., Boyle, J., Leng,
624 | M.J., Umer, M., Bryant, C., 2011. Late Pleistocene and Holocene drought events at Lake
625 | Tana, the source of the Blue Nile. *Global and Planetary Change* 78, 147-161.

626 | ~~[McGee, D., Donohoe, A., Marshall, J., Ferreira, D., 2014. Changes in ITCZ location and cross-](#)~~
627 | ~~[equatorial heat transport at the Last Glacial Maximum, Heinrich Stadial 1, and the mid-](#)~~
628 | ~~[Holocene. *Earth and Planetary Science Letters* 390, 69-79.](#)~~

629 | ~~[McManus, J.F., Francois, R., Gherardi, J.M., Keigwin, L.D., Brown-Leger, S., 2004. Collapse](#)~~
630 | ~~[and rapid resumption of Atlantic meridional circulation linked to deglacial climate](#)~~
631 | ~~[changes. *Nature* 428, 834-837.](#)~~

632 | Monnin, E., Indermuhle, A., Dallenbach, A., Fluckiger, J., Stauffer, B., Stocker, T.F., Raynaud,
633 | D., Barnola, J.M., 2001. Atmospheric CO2 concentrations over the last glacial
634 | termination. *Science* 291, 112-114.

635 | Naidu, P.D., Malmgren, B.A., 1996. A high-resolution record of late quaternary upwelling along
636 | the Oman Margin, Arabian Sea based on planktonic foraminifera. *Paleoceanography* 11,
637 | 129-140.

638 | Naidu, P.D., Malmgren, B.A., 2005. Seasonal sea surface temperature contrast between the
639 | Holocene and last glacial period in the western Arabian Sea (Ocean Drilling Project Site
640 | 723A): Modulated by monsoon upwelling. *Paleoceanography* 20.

641 | Niemann, H., Stadnitskaia, A., Wirth, S.B., Gilli, A., Anselmetti, F.S., Sinninghe Damsté, J.S.,
642 | Schouten, S., Hopmans, E.C., Lehmann, M.F., 2012. Bacterial GDGTs in Holocene
643 | sediments and catchment soils of a high Alpine lake: application of the MBT/CBT-
644 | paleothermometer. *Climate of the Past* 8, 889-906.

645 | North Greenland Ice Core Project Members, 2004. High-resolution record of Northern
646 | Hemisphere climate extending into the last interglacial period. *Nature* 431, 147-151.

647 | ~~[Otto-Bliesner, B.L., Russell, J.M., Clark, P.U., Liu, Z.Y., Overpeck, J.T., Konecky, B.,](#)~~

Formatted: Normal, No widow/orphan control, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers, Tab stops: Not at 0.99 cm + 1.98 cm + 2.96 cm + 3.95 cm + 4.94 cm + 5.93 cm + 6.91 cm + 7.9 cm + 8.89 cm + 9.88 cm + 10.86 cm + 11.85 cm

Formatted: Font: Border: : (No border)

Formatted: Font: Border: : (No border)

Formatted: Font: Border: : (No border)

- 648 [deMenocal, P., Nicholson, S.E., He, F., Lu, Z.Y., 2014. Coherent changes of southeastern](#)
649 [equatorial and northern African rainfall during the last deglaciation. *Science* 346, 1223-](#)
650 [1227.](#)
- 651 [Pearson, E.J., Juggins, S., Talbot, H.M., Weckstrom, J., Rosen, P., Ryves, D.B., Roberts, S.J.,](#)
652 [Schmidt, R., 2011. A lacustrine GDGT-temperature calibration from the Scandinavian](#)
653 [Arctic to Antarctic: Renewed potential for the application of GDGT-paleothermometry in](#)
654 [lakes. *Geochimica et Cosmochimica Acta* 75, 6225-6238.](#)
- 655 [Peterse, F., Hopmans, E.C., Schouten, S., Mets, A., Rijpstra, W.I.C., Sinninghe Damsté, J.S.,](#)
656 [2011. Identification and distribution of intact polar branched tetraether lipids in peat and](#)
657 [soil. *Organic Geochemistry* 42, 1007-1015.](#)
- 658 Pouliot, J., Galand, P.E., Lovejoy, C., Vincent, W.F., 2009. Vertical structure of archaeal
659 communities and the distribution of ammonia monooxygenase A gene variants in two
660 meromictic High Arctic lakes. *Environmental Microbiology* 11, 687-699.
- 661 Powers, L.A., Johnson, T.C., Werne, J.P., Castañeda, I.S., Hopmans, E.C., Sinninghe Damsté,
662 J.S., Schouten, S., 2005. Large temperature variability in the southern African tropics
663 since the Last Glacial Maximum. *Geophysical Research Letters* 32, L08706.
- 664 Powers, L.A., Werne, J.P., Vanderwoude, A.J., Sinninghe Damsté, J.S., Hopmans, E.C.,
665 Schouten, S., 2010. Applicability and calibration of the TEX₈₆paleothermometer in lakes.
666 *Organic Geochemistry* 41, 404-413.
- 667 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E.,
668 Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H.,
669 Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser,
670 K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M.,
671 Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. Intcal13 and
672 Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years Cal Bp. *Radiocarbon* 55,
673 1869-1887.
- 674 Russell, J.M., McCoy, S.J., Verschuren, D., Bessems, I., Huang, Y., 2009. Human impacts,
675 climate change, and aquatic ecosystem response during the past 2000 yr at Lake
676 Wandakara, Uganda. *Quaternary Research* 72, 315-324.
- 677 Schmittner, A., Urban, N.M., Shakun, J.D., Mahowald, N.M., Clark, P.U., Bartlein, P.J., Mix,
678 A.C., Rosell-Mele, A., 2011. Climate Sensitivity Estimated from Temperature
679 Reconstructions of the Last Glacial Maximum. *Science* 334, 1385-1388.
- 680 Schouten, S., Hopmans, E.C., Schefuß, E., Sinninghe Damsté, J.S., 2002. Distributional
681 variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing
682 ancient sea water temperatures? *Earth and Planetary Science Letters* 204, 265-274.
- 683 [Schouten, S., Hopmans, E.C., Rosell-Mele, A., Pearson, A., Adam, P., Bauersachs, T., Bard, E.,](#)
684 [Bernasconi, S.M., Bianchi, T.S., Brocks, J.J., Carlson, L.T., Castaneda, I.S., Derenne, S.,](#)
685 [Selver, A.D., Dutta, K., Eglinton, T., Fosse, C., Galy, V., Grice, K., Hinrichs, K.U.,](#)

- 686 [Huang, Y.S., Huguet, A., Huguet, C., Hurley, S., Ingalls, A., Jia, G., Keely, B., Knappy,](#)
687 [C., Kondo, M., Krishnan, S., Lincoln, S., Lipp, J., Mangelsdorf, K., Martinez-Garcia, A.,](#)
688 [Menot, G., Mets, A., Mollenhauer, G., Ohkouchi, N., Ossebaar, J., Pagani, M., Pancost,](#)
689 [R.D., Pearson, E.J., Peterse, F., Reichart, G.J., Schaeffer, P., Schmitt, G., Schwark, L.,](#)
690 [Shah, S.R., Smith, R.W., Smittenberg, R.H., Summons, R.E., Takano, Y., Talbot, H.M.,](#)
691 [Taylor, K.W.R., Tarozo, R., Uchida, M., van Dongen, B.E., Van Mooy, B.A.S., Wang,](#)
692 [J.X., Warren, C., Weijers, J.W.H., Werne, J.P., Woltering, M., Xie, S.C., Yamamoto, M.,](#)
693 [Yang, H., Zhang, C.L., Zhang, Y.G., Zhao, M.X., Sinninghe Damsté, J.S., 2013. An](#)
694 [interlaboratory study of TEX₈₆ and BIT analysis of sediments, extracts, and standard](#)
695 [mixtures. *Geochemistry Geophysics Geosystems* 14, 5263-5285.](#)
- 696 [Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z.Y., Otto-Bliesner, B.,](#)
697 [Schmittner, A., Bard, E., 2012. Global warming preceded by increasing carbon dioxide](#)
698 [concentrations during the last deglaciation. *Nature* 484, 49-54.](#)
- 699 Sinninghe Damsté, J.S., Hopmans, E.C., Pancost, R.D., Schouten, S., Geenevasen, J.A.J., 2000.
700 Newly discovered non-isoprenoid glycerol dialkyl glycerol tetraether lipids in sediments.
701 *Chemical Communications*, 1683-1684.
- 702 [Sinninghe Damsté, J.S., Schouten, S., Hopmans, E.C., van Duin, A.C.T., Geenevasen, J.A.J.,](#)
703 [2002. Crenarchaeol: the characteristic core glycerol dibiphytanyl glycerol tetraether](#)
704 [membrane lipid of cosmopolitan pelagic crenarchaeota. *Journal of Lipid Research* 43,](#)
705 [1641-1651.](#)
- 706 Sinninghe Damsté, J.S., Ossebaar, J., Abbas, B., Schouten, S., Verschuren, D., 2009. Fluxes and
707 distribution of tetraether lipids in an equatorial African lake: Constraints on the
708 application of the TEX₈₆ palaeothermometer and BIT index in lacustrine settings.
709 *Geochimica et Cosmochimica Acta* 73, 4232-4249.
- 710 Sinninghe Damsté, J.S., Rijpstra, W.I.C., Hopmans, E.C., Weijers, J.W.H., Foesel, B.U.,
711 Overman, J., Dedysh, S.N., 2011. 13,16-Dimethyl octacosanedionic acid (iso-diabolic
712 acid): A common membrane-spanning lipid of Acidobacteria subdivisions 1 and 3.
713 *Applied and Environmental Microbiology* 77, 4147-4154.
- 714 Sinninghe Damsté, J.S., Rijpstra, W.I.C., Hopmans, E.C., Foesel, B.U., Wüst, P.K., Overman, J.,
715 Tank, M., Bryant, D.A., Dunfield, P.F., Houghton, K., Stott, M.B., [in press-2014](#). Ether-
716 and ester-bound iso-diabolic acid and other lipids in members of Acidobacteria
717 subdivision 4. *Applied and Environmental Microbiology* [80](#), 5207-5218.
- 718 Stager, J.C., Ryves, D.B., Chase, B.M., Pausata, F.S.R., 2011. Catastrophic Drought in the Afro-
719 Asian Monsoon Region During Heinrich Event 1. *Science* 331, 1299-1302.
- 720 [Sun, Q., Chu, G., Liu, M., Xie, M., Li, S., Ling, Y., Wang, X., Shi, L., Jia, G., Lü, H., 2011.](#)
721 [Distributions and temperature dependence of branched glycerol dialkyl glycerol tetraethers](#)
722 [in recent lacustrine sediments from China and Nepal. *Journal of Geophysical Research*](#)
723 [116, G01008.](#)
- 724 [Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H.,](#)

- 725 [Zagorodnov, V.S., Mashiotta, T.A., Lin, P.N., Mikhalenko, V.N., Hardy, D.R., Beer, J.,](#)
726 [2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical](#)
727 [Africa. Science 298, 589-593.](#)
- 728 [Tierney, J.E., Russell, J.M., 2007. Abrupt climate change in southeast tropical Africa influenced](#)
729 [by Indian monsoon variability and ITCZ migration. Geophysical Research Letters 34.](#)
- 730 Tierney, J.E., Russell, J.M., Huang, Y., Sinninghe Damsté, J.S., Hopmans, E.C., Cohen, A.S.,
731 2008. Northern hemisphere controls on tropical southeast African climate during the past
732 60,000 years. Science 322, 252-255.
- 733 Tierney, J.E., Russell, J.M., 2009. Distributions of branched GDGTs in a tropical lake system:
734 Implications for lacustrine application of the MBT/CBT paleoproxy. Organic
735 Geochemistry 40, 1032-1036.
- 736 Tierney, J.E., Russell, J.M., Eggermont, H., Hopmans, E.C., Verschuren, D., Sinninghe Damsté,
737 J.S., 2010. Environmental controls on branched tetraether lipid distributions in tropical
738 East African lake sediments. Geochimica et Cosmochimica Acta 74, 4902-4918.
- 739 [Tierney, J.E., Schouten, S., Pitcher, A., Hopmans, E.C., Sinninghe Damsté, J.S., 2012. Core and](#)
740 [intact polar glycerol dialkyl glycerol tetraethers \(GDGTs\) in Sand Pond, Warwick, Rhode](#)
741 [Island \(USA\): Insights into the origin of lacustrine GDGTs. Geochimica et](#)
742 [Cosmochimica Acta 77, 561-581.](#)
- 743 [Vernekar, A.D., Zhou, J., Shukla, J., 1995. The Effect of Eurasian Snow Cover on the Indian](#)
744 [Monsoon. Journal of Climate 8, 248-266.](#)
- 745 [Wang, H.Y., Liu, W.G., Zhang, C.L.L., Wang, Z., Wang, J.X., Liu, Z.H., Dong, H.L., 2012.](#)
746 [Distribution of glycerol dialkyl glycerol tetraethers in surface sediments of Lake Qinghai](#)
747 [and surrounding soil. Organic Geochemistry 47, 78-87.](#)
- 748 Weijers, J.W.H., Schouten, S., Hopmans, E.C., Geenevasen, J.A.J., David, O.R.P., Coleman,
749 J.M., Pancost, R.D., Sinninghe Damsté, J.S., 2006. Membrane lipids of mesophilic
750 anaerobic bacteria thriving in peats have typical archaeal traits. Environmental
751 Microbiology 8, 648-657.
- 752 Weijers, J.W.H., Schouten, S., van den Donker, J.C., Hopmans, E.C., Sinninghe Damsté, J.S.,
753 2007a. Environmental controls on bacterial tetraether membrane lipid distribution in
754 soils. Geochimica et Cosmochimica Acta 71, 703-713.
- 755 Weijers, J.W.H., Schefuß, E., Schouten, S., Sinninghe Damsté, J.S., 2007b. Coupled thermal and
756 hydrological evolution of tropical Africa over the last deglaciation. Science 315, 1701-
757 1704.
- 758 Weijers, J.W.H., Panoto, E., van Bleijswijk, J., Schouten, S., Rijpstra, W.I.C., Balk, M., Stams,
759 A.J.M., Sinninghe Damsté, J.S., 2009. Constraints on the biological source(s) of the
760 orphan branched tetraether membrane lipids. Geomicrobiology Journal 26, 402-414.

761 | Weijers, J.W.H., Wiesenberg, G.L.B., Bol, R., Hopmans, E.C., Pancost, R.D., 2010. Carbon
762 isotopic composition of branched tetraether membrane lipids in soils suggest a rapid
763 turnover and a heterotropic life style of their source organism(s). *Biogeosciences*
764 *Discussions* 7, 3691-3734.

765 | [Weldeab, S., Menke, V., Schmiidl, G., 2014. The pace of East African monsoon evolution](#)
766 [during the Holocene. *Geophysical Research Letters* 41, 1724-1731.](#)

767 | Woltering, M., Johnson, T.C., Werne, J.P., Schouten, S., Sinninghe Damsté, J.S., 2011. Late
768 Pleistocene temperature history of Southeast Africa: A TEX₈₆ temperature record from
769 Lake Malawi. *Palaeogeography Palaeoclimatology Palaeoecology* 303, 93-102.

770 | [Woltering, M., Werne, J.P., Kish, J.L., Hicks, R., Sinninghe Damsté, J.S., Schouten, S., 2012.](#)
771 [Vertical and temporal variability in concentration and distribution of thaumarchaeotal](#)
772 [tetraether lipids in Lake Superior and the implications for the application of the TEX₈₆](#)
773 [temperature proxy. *Geochimica et Cosmochimica Acta* 87, 136-153.](#)

774 | [Woltering, M., Atahan, P., Grice, K., Hejnis, H., Taffs, K., Dodson, J., 2014. Glacial and](#)
775 [Holocene terrestrial temperature variability in subtropical east Australia as inferred from](#)
776 [branched GDGT distributions in a sediment core from Lake McKenzie. *Quaternary*](#)
777 [Research 82, 132-145.](#)

778 | Wondie, A., Mengistu, S., Vijverberg, J., Dejen, E., 2007. Seasonal variation in primary
779 production of a large high altitude tropical lake (Lake Tana, Ethiopia): effects of nutrient
780 availability and water transparency. *Aquat Ecol* 41, 195-207.

781 | Wood, R.B., Talling, J.F., 1988. Chemical and algal relationships in a salinity series of Ethiopian
782 inland waters. *Hydrobiologia* 158, 29-67.

783 | Zonneveld, K.A.F., Ganssen, G., Troelstra, S., Versteegh, G.J.M., Visscher, H., 1997.
784 Mechanisms forcing abrupt fluctuations of the Indian Ocean summer monsoon during the
785 last deglaciation. *Quaternary Science Reviews* 16, 187-201.

786 |

787 |

Formatted: Tab stops: Not at 0.99 cm + 1.98 cm + 2.96 cm + 3.95 cm + 4.94 cm + 5.93 cm + 6.91 cm + 7.9 cm + 8.89 cm + 9.88 cm + 10.86 cm + 11.85 cm

Formatted: Subscript

788 **Figures**

789

790 | *Figure 1:* Map of average surface winds and air temperatures at 850 mb ~~in~~ a) June, July, and
791 | August (JJA) ~~and~~ b) December, January, and February (DJF). White dot (1) marks the location
792 | of Lake Tana core 03TL3 (this study, [Marshall et al., 2011](#), and Costa et al., 2014), and gray
793 | boxes mark the locations of other paleoclimate records mentioned in the text. 2: Sacred Lake,
794 | ~~SL1~~ (Loomis et al., 2012); 3: Lake Victoria (Berke et al., 2012a); 4: Lake Tanganyika (Tierney
795 | et al., 2008); 5: Lake Malawi (Powers et al., 2005); 6: Red Sea, GeoB 5844-2 (Arz et al., 2003);
796 | 7: Eastern Mediterranean, GeoB 7702-3 (Castañeda et al., 2010); 8: Arabian Sea, 905P
797 | (Zonneveld et al., 1997); 9: Arabian Sea, 74KL (Huguet et al., 2006); [910](#): Arabian Sea, ODP
798 | 723A (Naidu and Malmgren, 1996, 2005).

799

800 |

801 *Figure 2:* Structures of GDGTs discussed in the text, including the isoprenoidal crenarchaeol
802 (cren) and the brGDGTs (IIIa-Ic).

803

804 |

805 ~~Figure 3: a) Reconstructed temperatures from Lake Tana.~~ Figure 3: GDGT records from Lake
806 Tana core 03TL3. a) Reconstructed mean annual air temperature (MAAT). Black circles are
807 samples with BIT values ≥ 0.5 , open circles are samples with BIT values < 0.5 . Bootstrapped
808 1σ errors on reconstructed temperatures are indicated by the gray lines. b) BIT record ~~from Lake~~
809 Tana. ~~The background.~~ Black triangles along the x-axis mark the depths of age control points
810 (Marshall et al., 2011). Background is shaded to represent the different lithological units (Lamb
811 et al., 2007) described in the text: medium gray for Unit 1 (dark gray silt; organic matter = 9-
812 22%), light gray for Unit 2 (dark brown herbaceous peat; organic matter = 30-70%), dark gray
813 for Unit 3 (calcareous silt; deposition conductivity = 3500 $\mu\text{S}/\text{cm}$), and white for Unit 4 (uniform
814 fine gray diatomaceous silt; low organic matter and magnetic susceptibility).

815

816

817 Figure 4: Comparison of climate records with Northern Hemispheric forcing.
818 Temperature and precipitation records from Lake Tana core 03TL3. a) Mean annual air
819 temperature (MAAT; this study), b) δD of leaf waxes (Costa et al., 2014), c) low pass filter of Ti
820 counts (Marshall et al., 2011).

821
822 Figure 5: Comparison of North African temperature records with the Greenland ice core record.
823 a) $\delta^{18}O$ of the NGRIP ice core (North Greenland Ice Core Project Members, 2004), b) Eastern
824 Mediterranean sea surface temperature (SST- δ ; Castañeda et al., 2010), c) Red Sea SST (Arz et
825 al., 2003), and d) Lake Tana mean annual air temperature (MAAT- δ ; this study). Gray shading
826 marks the Bølling Oscillation as defined by the NGRIP ice core.

827

828

829 | *Figure 56*: Comparison of continental East African paleotemperature records. a) Mean annual air
830 | temperature (MAAT) at Lake Tana (12.0°N; this study), b) MAAT at Sacred Lake (0°N; Loomis
831 | et al., 2012), c) lake surface temperature (LST) at Lake Victoria (1°S; Berke et al., 2012a), d)
832 | LST at Lake Tanganyika (7°S; Tierney et al., 2008), and e) LST at Lake Malawi (10°S; Powers et
833 | al., 2005).

834

835 |

836 | *Figure 6Z*: Comparison of paleoclimate records influenced by the Indian Monsoon. Strength of
837 | upwelling in the western Arabian Sea measured by a) the relative abundance of dinoflagellate
838 | species with highest relative abundance during the Indian Summer Monsoon at 905P (Zonneveld
839 | et al., 1997) and b) the relative abundance of *G. bulloides* at ODP 723A (Naidu and Malmgren,
840 | 1996); sea surface temperature (SST) in the western Arabian Sea reconstructed using c) the
841 | TEX₈₆ proxy at 74KL (Huguet et al., 2006) and d) foraminifera at ODP 723A (Naidu and
842 | Malmgren, 2005); ~~and~~; e) mean annual air temperature (MAAT) at Lake Tana (this study). ¹⁴C
843 | ages from 905P were converted to calendar years using the Marine13 radiocarbon curve (Reimer
844 | et al., 2013), and the new age model was constructed using Bacon 2.2 (Blaauw et al., 2007).

845

846

847 *Figure 7: Comparison of temperature and precipitation records at Lake Tana with globally*
848 *averaged records of temperature change. a) Anomalies in northern hemisphere temperatures, b)*
849 *MAAT from Lake Tana (this study), c) δD from Lake Tana (Costa et al., 2014), d) low pass filter*
850 *of Ti record from Lake Tana (Marshall et al., 2011), and e) mean northern hemisphere minus*
851 *southern hemisphere temperature anomalies as a proxy for global mean position of the ITCZ*
852 *(after McGee et al., 2014). Data from (a) and (e) are derived from deglacial (dashed lines;*
853 *Shakun et al., 2012) and Holocene (solid lines; Marcott et al., 2013) global reconstructed*
854 *temperature stacks normalized to mid-Holocene temperatures.*

855

Formatted: Font: Times

Formatted: No Spacing

Highlights

- We present the first terrestrial temperature record from northern Africa (Lake Tana)
- Temperature change at Lake Tana is affected by changes in the Indian Monsoon
- Magnitude of temperature changes are larger than lower latitude sites in Africa

Figure 1

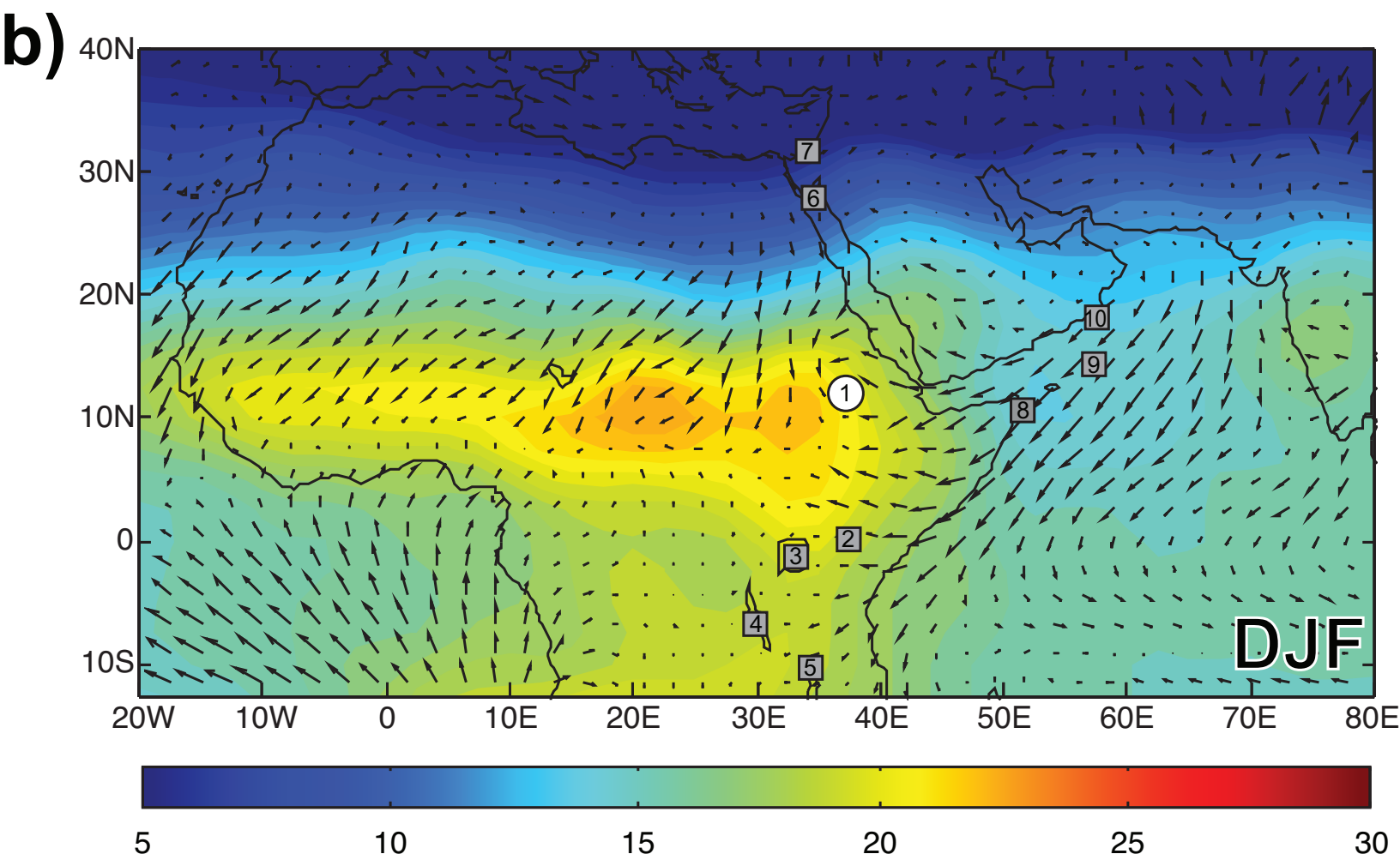
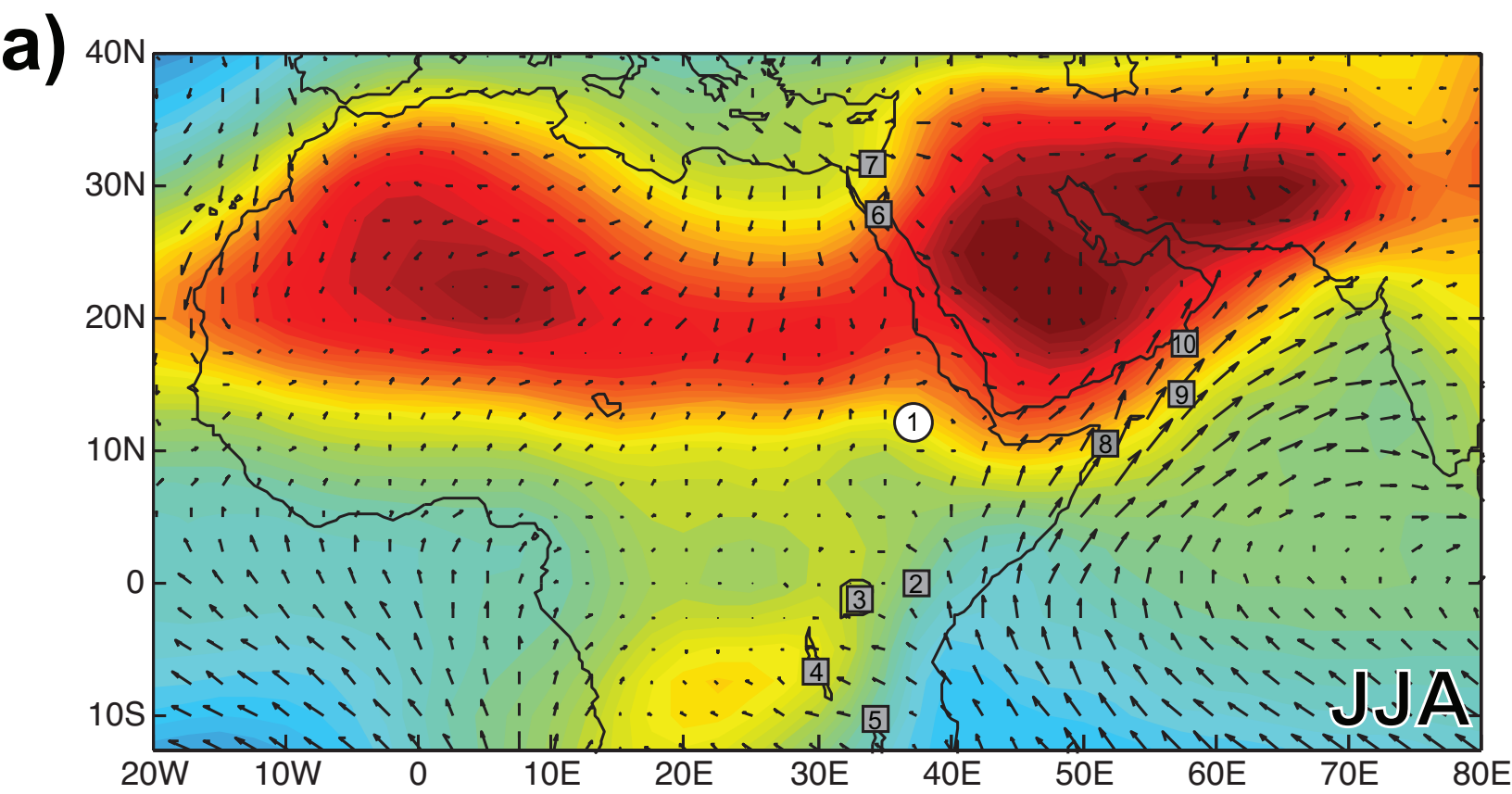


Figure 2

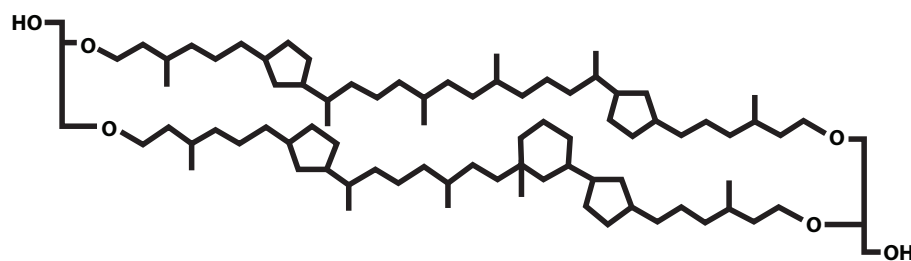
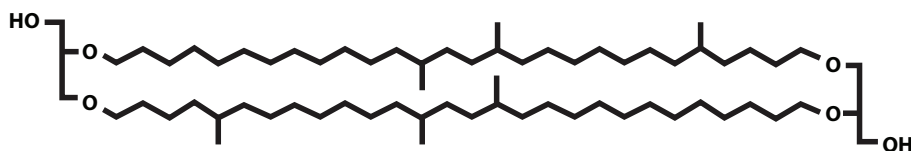
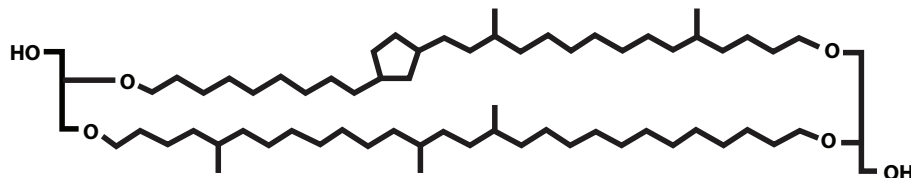
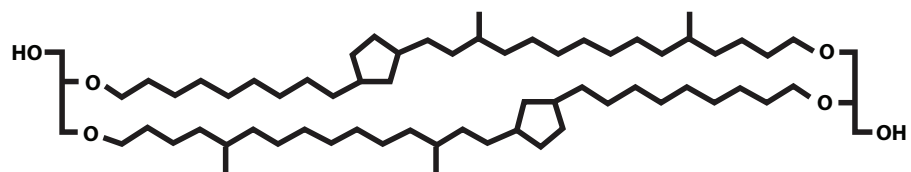
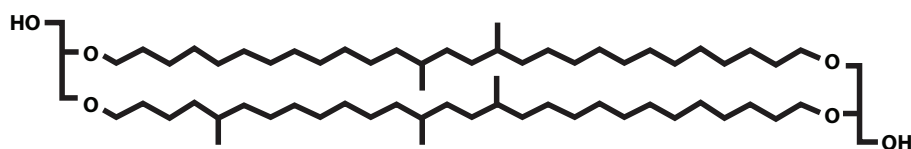
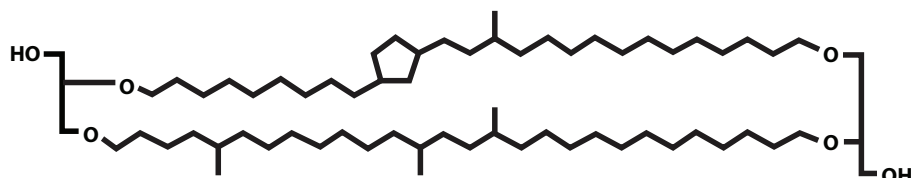
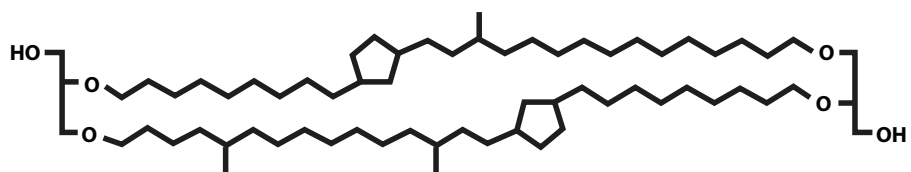
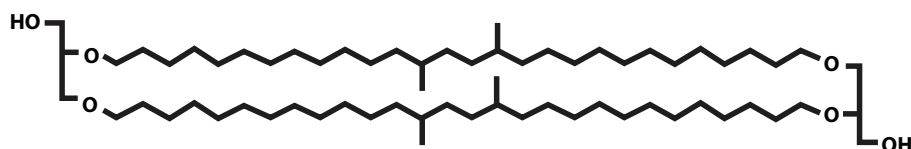
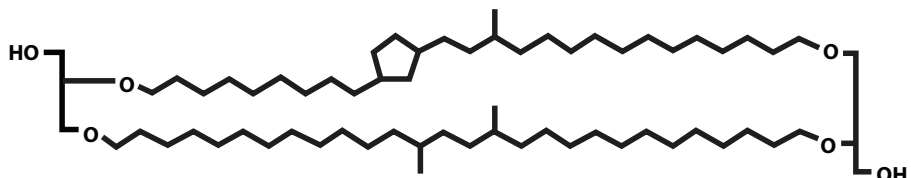
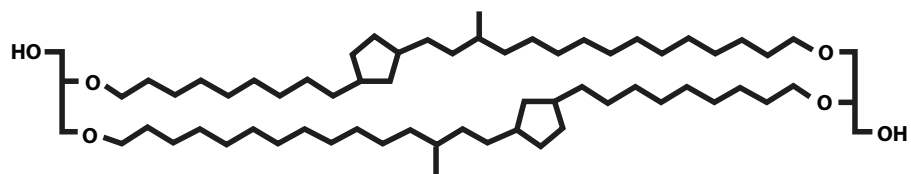
 m/z **Cren***1292***IIIa***1050***IIIb***1048***IIIc***1046***IIa***1036***IIb***1034***IIc***1032***Ia***1022***Ib***1020***Ic***1018*

Figure 3

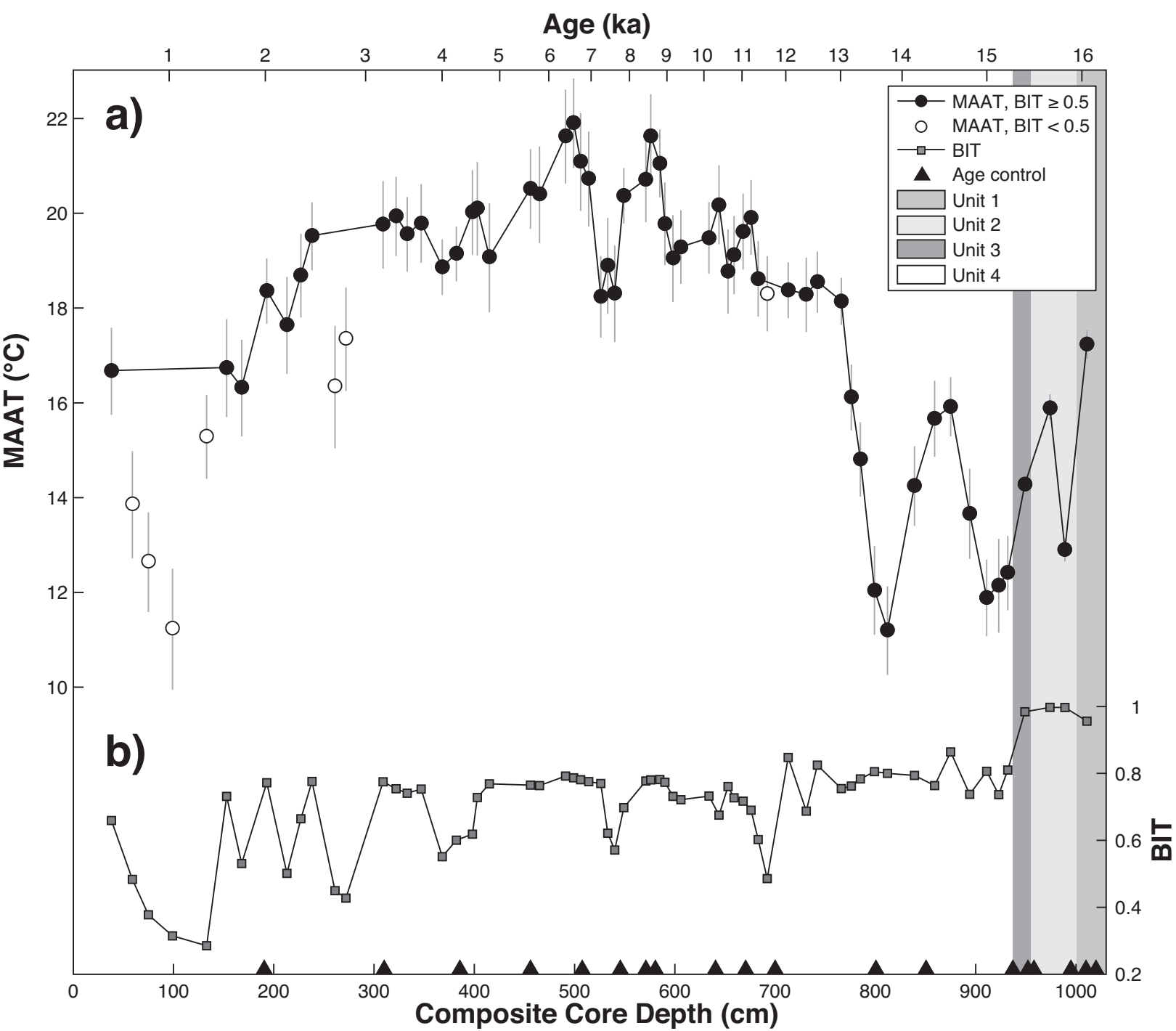


Figure 4

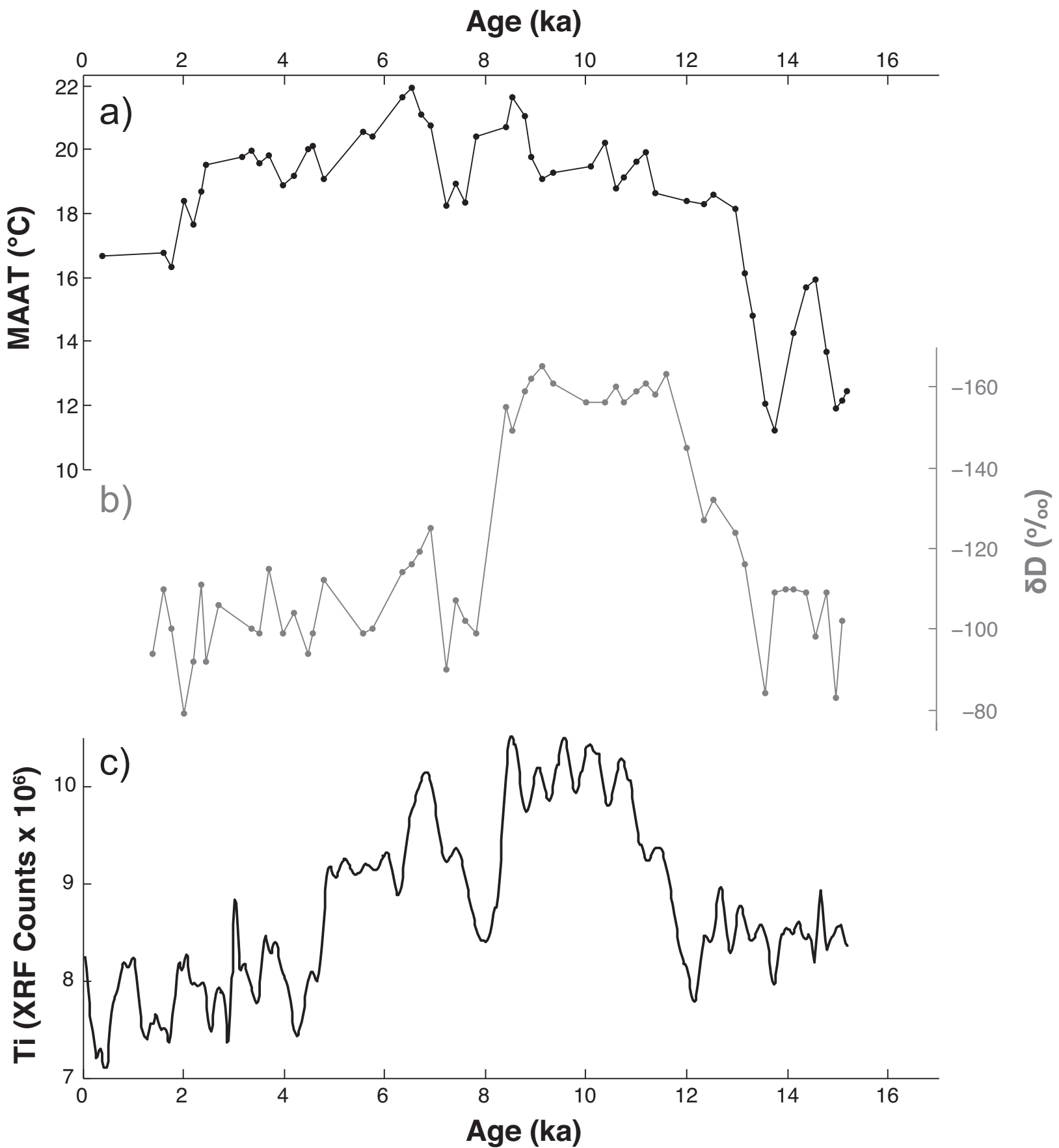


Figure 5

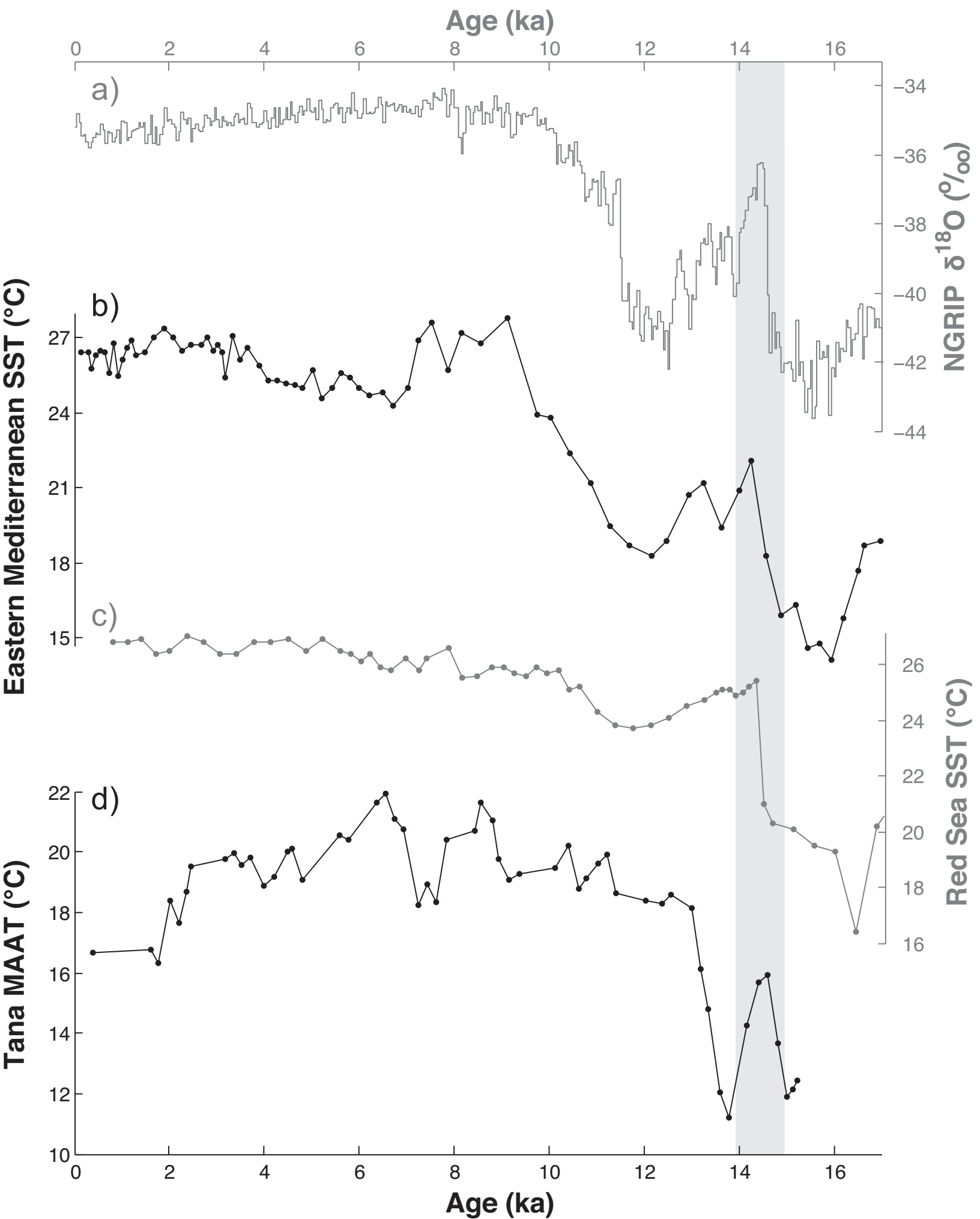


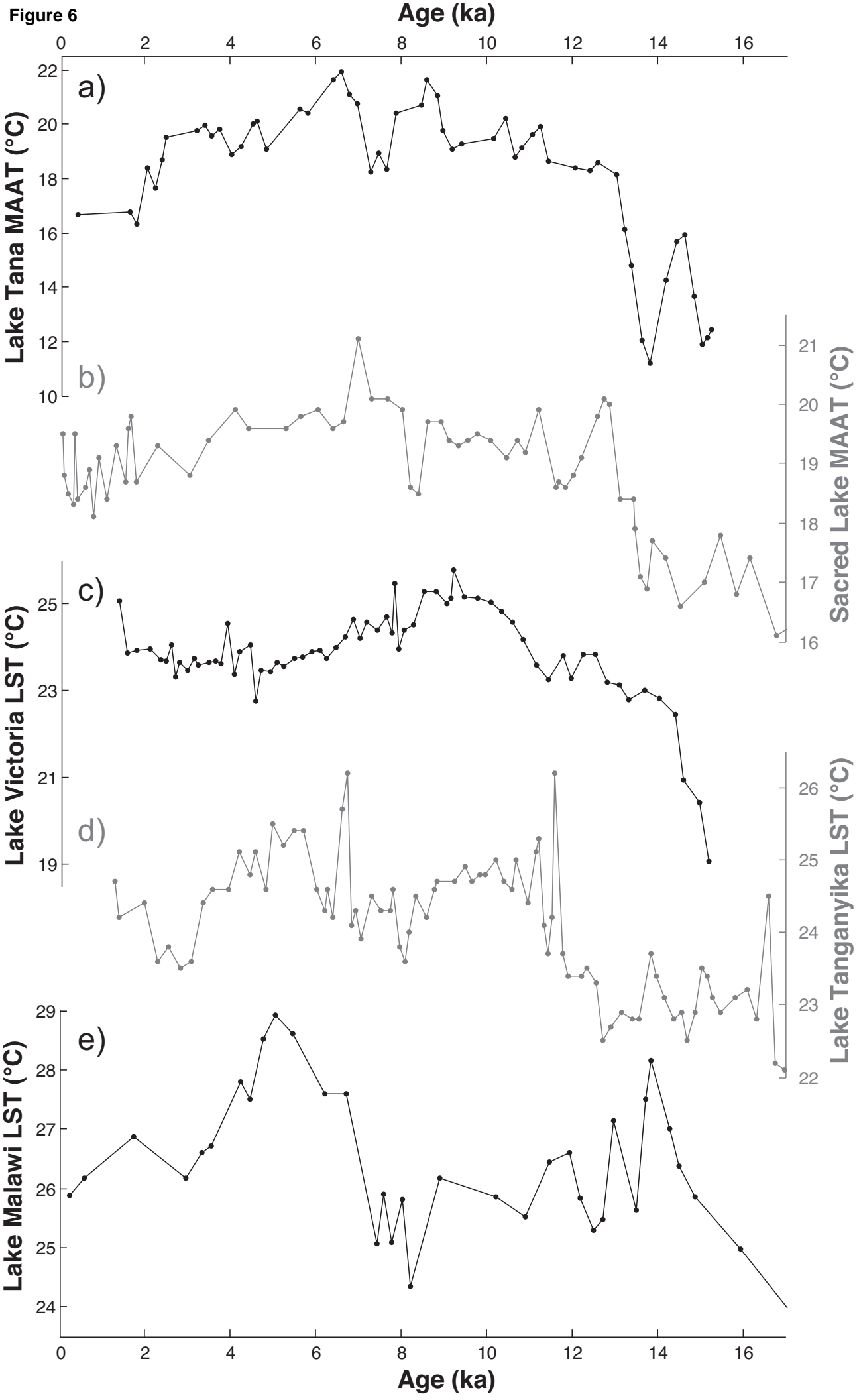
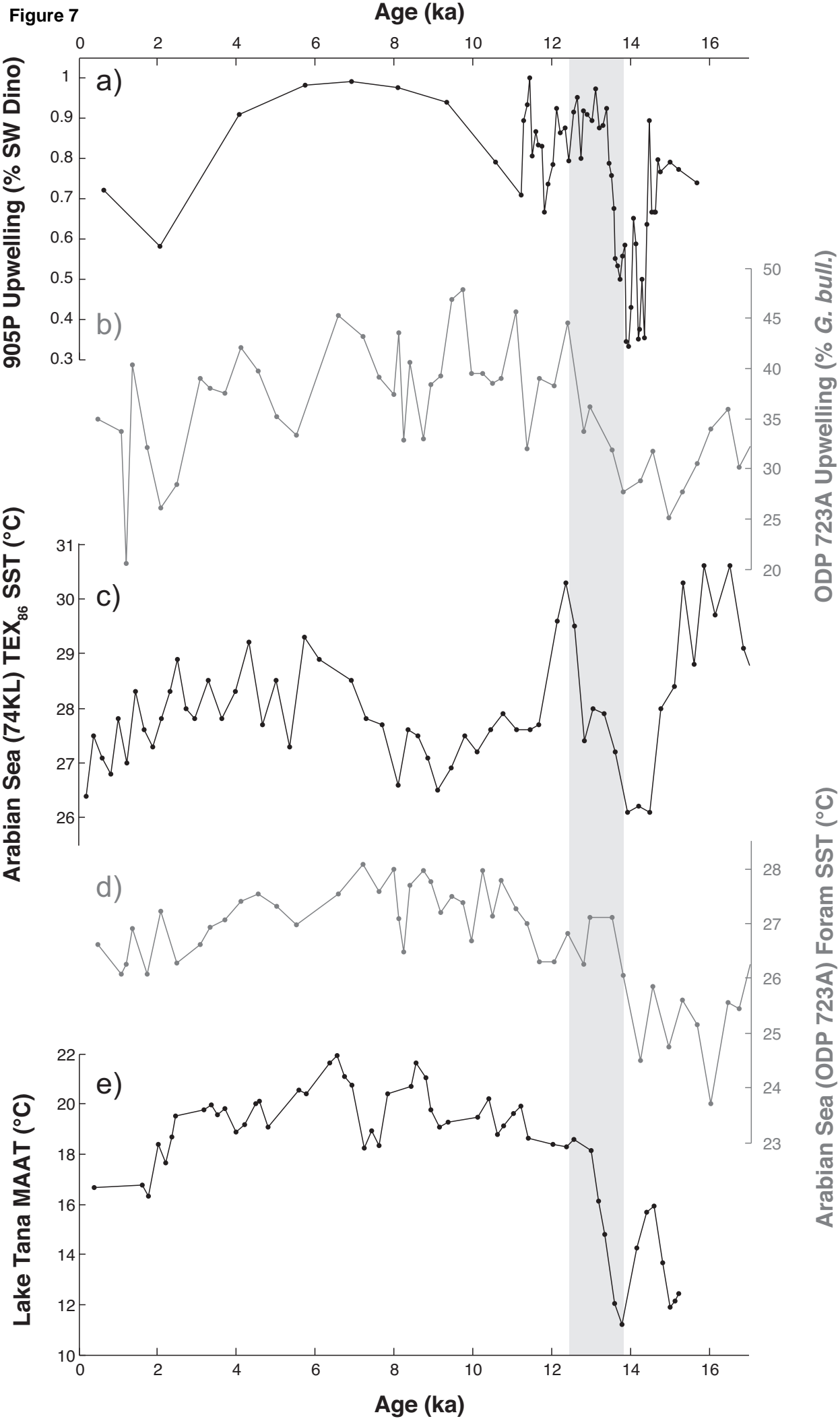
Figure 6

Figure 7

Supplemental Material

[Click here to download Background dataset for online publication only: Loomis_2015_TanaSupp.xlsx](#)