

# Large temperature variability in the southern African tropics since the Last Glacial Maximum

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[1] The role of the tropics in global climate change is actively debated, particularly in regard to the timing and magnitude of thermal and hydrological response. Continuous, high-resolution temperature records through the Last Glacial Maximum (LGM) from tropical oceans have provided much insight but surface temperature reconstructions do not exist from tropical continental environments. Here we used the TEX<sub>86</sub> paleotemperature proxy to reconstruct mean annual lake surface temperatures through the Last Glacial Maximum (LGM) in Lake Malawi, East Africa (9°–14°S). We find a ~3.5°C overall warming since the LGM, with temperature reversals of ~2°C during the Younger Dryas (12.5 ka BP) and at 8.2 ka BP. Maximum Holocene temperatures of ~29°C were found at 5 ka BP, a period preceding severe drought in Africa. These results suggest a substantial thermal response of southeastern tropical Africa to deglaciation and to varying conditions during the Holocene. **Citation:** Powers, L. A., T. C. Johnson, J. P. Werne, I. S. Castañeda, E. C. Hopmans, J. S. Sinninghe Damsté, and S. Schouten (2005), Large temperature variability in the southern African tropics since the Last Glacial Maximum, *Geophys. Res. Lett.*, 32, L08706, doi:10.1029/2004GL022014.

## 1. Introduction

[2] The thermal history of tropical Africa since the LGM is not as well known as its hydrological past. The LGM in the African tropics was clearly cooler than today, but quantitative estimates of cooling are highly variable. Pollen records from tropical Africa [Chalie, 1995; Coetzee, 1967] estimate LGM temperatures to have been 2–8°C cooler than modern. Oxygen isotope analyses of speleothems from the Transvaal (~23°S) of southern Africa suggest temperatures to have been as much as 8°C cooler [Talma et al., 1974], while Late Pleistocene (24 ka) temperatures from noble gas analyses of groundwater in the Stampriet Aquifer in Namibia (~24°S) suggest temperatures  $5.2 \pm 1.5^\circ\text{C}$  cooler than today [Kulongoski et al., 2004], however these sites are substantially farther south of the equator than Lake Malawi. Tropical sea surface temperature (SST) estimates of LGM temperatures range from 2 to 5°C [Lea et al., 2003;

Rosell-Melé et al., 2004; Visser et al., 2003] cooler than present, but may not necessarily be representative of the continental environment. All of the biological or carbonate-based continental paleotemperature proxies are potentially confounded by changes in the hydrologic cycle, and noble gas temperature records are severely limited by their low temporal resolution.

[3] Recent application of the marine paleotemperature proxy, TEX<sub>86</sub> (TetraEther indeX of tetraethers with 86 carbon atoms) [Schouten et al., 2002], to lacustrine sediments [Powers et al., 2004] has provided a new continental paleotemperature tool, allowing us to reconstruct tropical African temperatures. Crenarchaeota, the organisms that produce the tetraether membrane lipids on which the TEX<sub>86</sub> index is based, are widely distributed in lacustrine and marine environments [Karner et al., 2001; Keough et al., 2003; Powers et al., 2004; Schouten et al., 2002]. The TEX<sub>86</sub> paleotemperature proxy is believed to be solely dependent upon growth temperature and is not confounded by changes in hydrologic budget, nutrient availability or salinity [Schouten et al., 2002; Wuchter et al., 2004]. Here we apply this improved TEX<sub>86</sub> paleotemperature proxy to lacustrine sediments from Lake Malawi, East Africa, to reconstruct a continuous record of tropical temperature, independent of hydrological variability, for the last 24 ka.

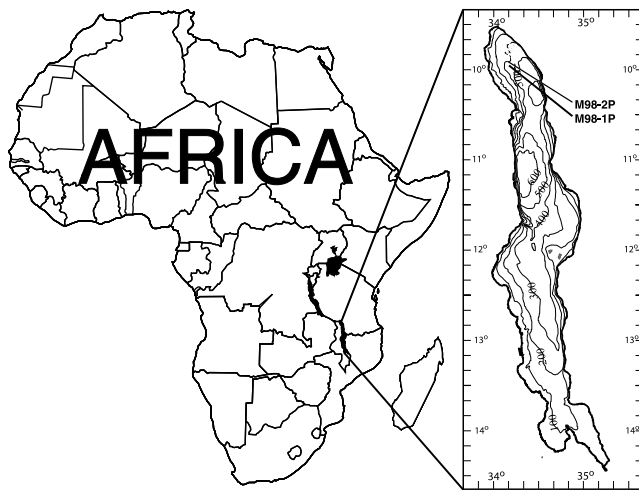
[4] Lake Malawi, the southernmost lake in the western branch of the East African Rift Valley, spans approximately 9–14°S and sits at an elevation of 474 m (Figure 1). Surface water temperatures in the north basin of Lake Malawi presently range from 25 to 29°C annually [Patterson and Kachinjika, 1995]. Sediments recovered from the northern basin of Lake Malawi record a significant response of the lake to global climatic events [Barker and Gasse, 2003; Johnson et al., 2002]. We have analyzed sediments from two piston cores, M98-1P and M98-2P, that span the past 24 ka, collected from the northern basin of Lake Malawi (Figure 1) during the 1998 expedition of the International Decade for East African Lakes (IDEAL).

## 2. Methodology

[5] The age models for the two cores are available as auxiliary material<sup>1</sup>. Sediments (1–3 g dry mass) were freeze-dried and homogenized by mortar and pestle. Sedi-

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<sup>1</sup>Auxiliary material is available at <ftp://ftp.agu.org/apend/gl/2004GL022014>.



**Figure 1.** Lake Malawi, East Africa. Coring locations of M98-1P ( $10^{\circ}15.9'S$ ,  $34^{\circ}19.1'E$ , 403 m water depth) and M98-2P ( $9^{\circ}58.6'S$ ,  $34^{\circ}13.8'E$ , 363 m) taken from the North Basin of the Lake.

ments were then extracted with dichloromethane (DCM)/methanol (2:1) by using Soxhlet or Dionex<sup>TM</sup> accelerated solvent extraction (ASE) techniques, to acquire the total lipid fraction. The extracts were separated by  $Al_2O_3$  column chromatography using hexane/DCM (9:1) and DCM/methanol (1:1) as subsequent eluents. The polar fraction (DCM/methanol) was condensed by rotary evaporation, dissolved in hexane/isopropanol (99:1), and filtered prior to injection. Analyses were performed using an HP (Palo-Alto, CA, USA) 1100 series LC-MS equipped with an auto-injector and Chemstation chromatography manager software. Separation was achieved on a Prevail Cyano column ( $2.1 \times 150$  mm,  $3 \mu m$ ; Alltech, Deerfield, IL, USA), maintained at  $30^{\circ}C$ . Injection volumes varied from 1 to  $5 \mu l$ . Tetraethers were eluted isocratically with 99% A and 1% B for 5 min, followed by a linear gradient to 1.8% B in 45 min, where A = hexane and B = propanol. Flow rate was 0.2 ml/min. After each analysis the column was cleaned by back-flushing hexane/propanol (90:10, v/v) at 0.2 ml/min for 10 min. Detection was achieved using atmospheric pressure positive ion chemical ionization mass spectrometry (APCI-MS) of the eluent. Conditions for APCI-MS were as follows: nebulizer pressure 60 psi, vaporizer temperature  $400^{\circ}C$ , drying gas ( $N_2$ ) flow 6 l/min and temperature  $200^{\circ}C$ , capillary voltage  $-3$  kV, corona  $5 \mu A$  ( $\sim 3.2$  kV). GDGTs were detected by Single Ion Monitoring (SIM) of their  $[M + H]^+$  ions (dwell time = 234 ms) and quantified by integration of the peak areas. All samples were measured at least in duplicate and half of the samples were measured at least in triplicate.

[6] We have recently improved the  $TEX_{86}$  calibration for mean annual lake surface temperatures (LST) [Powers *et al.*, 2004] by adding five lakes to our dataset, which results in the linear equation  $TEX_{86} = 0.017LST + 0.25$  ( $r^2 = 0.96$ ) (L. A. Powers, unpublished results, 2005) which is similar to the marine  $TEX_{86}$  calibration curve [Schouten *et al.*, 2002]. The standard error of the regression is 0.034 resulting in a calibration error of  $\pm 2.0^{\circ}C$ . In addition, the analytical method has been modified resulting in an improved analytical precision in  $TEX_{86}$  determinations,

and which has resulted in an analytical error in LST reconstructions of  $\pm 1^{\circ}C$ . This substantial improvement in analytical reproducibility compared to a previous report [Schouten *et al.*, 2002] is mainly due to improved chromatographic conditions and the use of SIM instead of mass scanning.

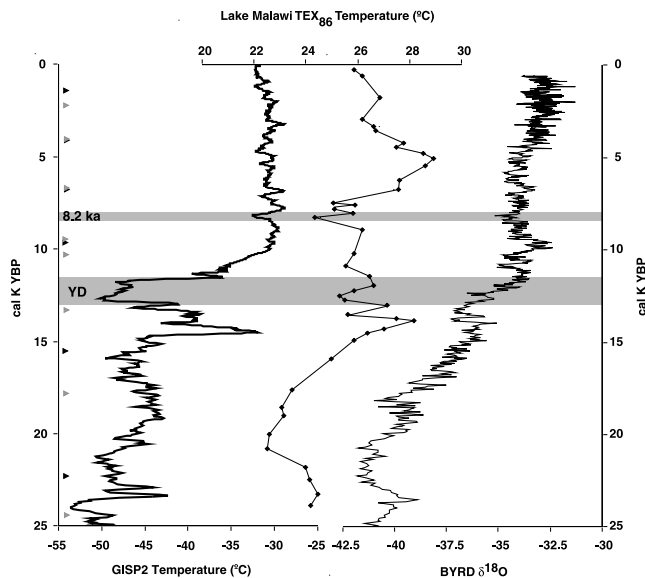
[7] LST and air surface temperature should be fairly well coupled because the same elements of the heat budget (insolation, cloud cover, evaporation and precipitation, etc.) affect both lake surface waters and the overlying air mass. There are of course complicating factors such as water depth, the range of seasonal temperature variability, and the localized effects of lake circulation. Nevertheless there is a strong linear relationship between mean annual LST and mean annual surface air temperature (SAT) based on published values for all nine of the lakes included in the  $TEX_{86}$  calibration ( $LST = 1.09 \cdot SAT + 0.70$ ,  $R^2 = 0.95$ ).

### 3. Results and Discussion

[8] The  $TEX_{86}$  temperature record from Lake Malawi shows a range from  $\sim 22$  to  $29^{\circ}C$ . Interestingly,  $TEX_{86}$  analysis of sediments younger than 600 years suggest temperatures of  $\sim 26^{\circ}C$ , well within the modern range of mean annual LST in Lake Malawi, confirming that the  $TEX_{86}$  records LST. The LST in Lake Malawi during the LGM was  $\sim 23^{\circ}C$  (from 18–21 ka BP) which is an average  $\sim 3.5^{\circ}C$  cooler compared to late Holocene ( $< 3.5$  ka BP) LST of  $\sim 26.5^{\circ}C$ , (Figure 2). This is well within the range of previous estimates from 2 to  $8^{\circ}C$  in continental Africa [Chalie, 1995; Coetsee, 1967; Holmgren *et al.*, 2003; Talma *et al.*, 1974]. Furthermore, a cooling of  $3.5^{\circ}C$  is comparable with a number of studies that have suggested tropical sea surface temperatures were 2 to  $5^{\circ}C$  cooler during the LGM [Lea *et al.*, 2003; Rosell-Melé *et al.*, 2004; Visser *et al.*, 2003]. The most proximal (off Madagascar) SST estimates from the LGM are  $\sim 2^{\circ}C$  cooler than modern [Rosell-Melé *et al.*, 2004]. We would expect the LST to be cooler than this SST estimate as this site lies in the warm Agulhas Current.

[9] We have compared the Lake Malawi  $TEX_{86}$  temperature record to both the GISP2 temperature record [Alley, 2004] and the Byrd oxygen isotope record [Johnsen *et al.*, 1972], which has been used to infer temperature changes from the polar regions of Greenland and Antarctica, respectively (Figure 2). There is a striking similarity in the timing of the warming in the Lake Malawi  $TEX_{86}$  record and the Byrd oxygen isotope record during the late Pleistocene. Both records indicate minimum temperatures at 21 ka BP, concurrent with the time of maximum Northern Hemisphere ice extent. The warming trend at the end of the LGM in Lake Malawi precedes warming in Greenland by  $\sim 5000$  years, yet appears to be coincident with warming in Antarctica (Figure 2).

[10] The late Pleistocene in the Lake Malawi record is characterized by steady warming of  $\sim 1^{\circ}C/kyr$  until  $\sim 13.8$  ka BP, when temperature decreases by more than  $2^{\circ}C$ , before the onset of the Younger Dryas. This brief cold excursion may be related to the Antarctic Cold Reversal (ACR) evident in the Byrd record (Figure 2). The temperature increases again briefly, followed by cooling at 12.7 ka BP, when temperatures decreased by  $\sim 2^{\circ}C$ , coin-



**Figure 2.** Lake Malawi  $\text{TEX}_{86}$  temperature curve plotted with GISP2 temperature curve [Alley, 2004] and Byrd oxygen isotope record (on the GISP2 timescale) [Blunier and Brook, 2001a; Johnsen et al., 1972] and supplemental Holocene data provided by Dr. Sigfus Johnsen. Radiocarbon dates from core M98-1P (black triangles) and M98-2P (gray triangles) are shown on the left. Two major events are highlighted, the Younger Dryas (YD), and the cooling at 8.2 ka. The uppermost 40 samples are from core M98-1P and the last 3 samples are from core M98-2P. Standard deviations of at least duplicate analyses for all samples are  $\leq \pm 1^\circ\text{C}$ .

cident with the Younger Dryas. The Younger Dryas has been previously characterized as a period of arid conditions in the equatorial region of Africa, with widespread low lake levels [Gasse, 2000]. Here we have direct evidence of substantial cooling during this period as well, although temperatures did not return to full glacial conditions as they did in several global records such as in Greenland [Blunier and Brook, 2001b] or the tropical Atlantic [Lea et al., 2003], nor did the Younger Dryas of Lake Malawi appear to last as long as it did in Greenland.

[11] The Holocene is characterized by substantial temperature variability in the Lake Malawi record. Emerging from the Younger Dryas event, the Byrd oxygen isotope values exhibit relative stability, whereas the Lake Malawi temperature shows a cooling of about  $\sim 2^\circ\text{C}$  to  $\sim 24^\circ\text{C}$  at around 8.2 ka BP. This was a time of relatively low summer insolation in the Southern Hemisphere [Berger, 1978] and represents the coldest period during the Holocene in Lake Malawi. The 8.2 ka BP climatic event, clearly evident in the GISP2 temperature record and characterized in the Northern Hemisphere by massive ice sheet collapse [Barber et al., 1999], may have exacerbated the early Holocene cooling in the Lake Malawi record. Although the 8.2 ka event has been seen in other tropical African records [Stager et al., 1997] as an arid period, the thermal magnitude of this signal appears to be notable.

[12] The transition from the cool early Holocene into the mid-Holocene represents a significant temperature reversal. We note a maximum Holocene temperature of  $\sim 29^\circ\text{C}$  at

5 ka BP, a warming of  $\sim 1.5^\circ\text{C}$  per thousand years since 7.5 ka. This period of extremely warm temperature precedes a period of widespread drought in equatorial and north Africa [Gasse, 2000]. The occurrence of the warmest Holocene temperatures at about 5 ka BP is unexpected as global models of Holocene climate [Liu et al., 2003] do not generate such conditions in the tropics at this time. Following this period of maximum warmth, a return to cooler temperatures occurred rapidly, after which the temperature varied within  $25$  to  $27^\circ\text{C}$  over the past 3000 years, comparable to modern temperatures [Patterson and Kachinjika, 1995].

[13] It is unlikely that the temperature signal is a result of changes in upwelling through time. When we compare the  $\text{TEX}_{86}$  temperature record from Lake Malawi to an independent record of upwelling intensity, biogenic silica mass accumulation (BSi MAR) [Johnson et al., 2002] from the same core, we don't see a consistent relationship that would suggest that upwelling is related to the temperature trends we see in the Lake Malawi  $\text{TEX}_{86}$  record.

[14] The degree of coupling between temperature and hydrologic changes is still relatively poorly known for the tropics over millennial and longer time scales. This is primarily due to the lack of an independent continental paleotemperature proxy that can provide a temperature record against which to compare hydrologically influenced proxies. The hydrologic response of the African tropics to temperature change is complex. For example, several lacustrine records from both northern and southern equatorial Africa, including Lake Malawi [Barker and Gasse, 2003; Johnson et al., 2002], have provided evidence for significantly drier conditions during the LGM [Gasse, 2000, 2002; Kulongoski et al., 2004]. While it is not yet possible to create an accurate hydrological (lake level) history for Lake Malawi, we know that it regressed briefly during the Younger Dryas cold interval [Barker and Gasse, 2003], which is described as a period of widespread aridity in tropical Africa [Gasse, 2000]. During the early Holocene, when much of tropical and North Africa were characterized by humid conditions, Lake Malawi experienced a low stand [Ricketts and Johnson, 1996], again coincidental with the observed cooling in the  $\text{TEX}_{86}$  record. This consistent hydrologic response to cooling in East Africa is in agreement with some model predictions of tropical climate behavior [Ganopolski et al., 1998; Jolly et al., 1998], and allows exploration of the connections between temperature change and hydrologic response in the tropics.

#### 4. Conclusions

[15] This Lake Malawi temperature record illustrates important ties between the tropics and high latitudes. The onset of warming at Lake Malawi coincidental with the timing of the BYRD warming after the LGM suggests a strong tie to Antarctica in the Late Pleistocene. However, this relationship becomes weaker during the Holocene when we see much stronger ties to Northern Hemisphere climate signals such as the Younger Dryas and possibly the 8.2 ka BP event, suggesting a thermal response to shutdown of the North Atlantic thermohaline circulation. Surface temperature in this part of tropical Africa thus may be far more sensitive to shutdown of the thermohaline circulation than



has been predicted by global climate models [Vellinga and Wood, 2002]. The Lake Malawi temperature record illustrates how global climate events have a substantial impact on the intensity and timing of continental climate at this important Southern Hemisphere site in the African tropics. Further, the TEX<sub>86</sub> paleothermometer provides an excellent means for independent continental paleotemperature reconstructions.

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