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Abrupt change in tropical African climate linked to the bipolar seesaw over the past 55,000 years

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[1] The tropics play a major role in global climate dynamics, and are vulnerable to future climate change. We present a record of East African climate since 55 ka, preserved in Lake Malawi sediments, that indicates rapid shifts between discrete climate modes related to abrupt warming (D-O) events observed in Greenland. Although the timing of the Malawi events cannot be determined exactly, our age model implies that they occur prior to their Greenland counterparts, consistent with southward excursions of the Intertropical Convergence Zone during Greenland stadials. The magnitude of each of the events recorded in Malawi sediments corresponds to the scale of the subsequent Greenland warming. This suggests that a tropical component of climate sets a template for abrupt high northern latitude climate fluctuations associated with the bipolar seesaw. **Citation:** Brown, E. T., T. C. Johnson, C. A. Scholz, A. S. Cohen, and J. W. King (2007), Abrupt change in tropical African climate linked to the bipolar seesaw over the past 55,000 years, *Geophys. Res. Lett.*, *34*, L20702, doi:10.1029/2007GL031240.

1. Introduction

[2] The African Continent is highly vulnerable to climate change, and is likely to be the site of its greatest human toll [*Intergovernmental Panel on Climate Change*, 2007]. Although an understanding of the history of African climate variability would provide insights into the continent's response to future climate forcing, we have little information concerning high frequency climate variability in the African tropics during the last glacial period when much of the planet was subject to massive and rapid climate fluctuations.

[3] Abrupt and substantial millennial- to decadal-scale changes in regional climate linked to the Dansgaard-Oeschger (D-O) warming events of Greenland [*Dansgaard et al.*, 1993; *Langway et al.*, 1985] have been reported with varying levels of confidence in paleoclimate proxy records from worldwide locations [*Voelker et al.*, 2002]. In tropical and subtropical South America and Asia these are generally manifested as northward shifts of the ITCZ and related monsoonal circulation patterns during Northern Hemisphere interstadials [*Burns et al.*, 2003; *Peterson et al.*, 2000; *Wang et al.*, 2004; *Wang et al.*, 2001]. Such behavior has recently been noted in records of the West African monsoon during the broad (2–5 kyr) climate shifts of marine isotope stage (MIS) 4 [*Weldeab et al.*, 2007]. However, the higher frequency D-O type events of MIS 3 have not been previously noted in Africa, possibly due to the paucity of appropriate proxy records.

2. Methods

[4] To obtain a continuous record extending well into the last glacial period the Lake Malawi Drilling Project recovered a core, MAL05-2A, from 10° 01.1′S, 34° 11.2’E in 345 m water depth in the lake's north basin in March 2005 (Figure 1). Lake Malawi, the southernmost of the large rift lakes of East Africa (9–14° S, 35°E), lies near the southern extent of the annual migration of the Intertropical Convergence Zone (ITCZ) and near a climatic boundary between tropical East and Southern Africa (Figure 1). The drilling operation recovered a complete sequence of sediment from the lake floor to a prominent seismic reflector at 38 m below lake floor (mblf), which is a nearshore sand overlying an erosional unconformity. It marks the termination of a series of major droughts around 70 ka that are attributed to eccentricity-enhanced precessional forcing [*Scholz et al.*, 2007]. This core consists primarily of laminated or homogeneous diatomaceous silty clay, with calcareous silty clay in two intervals (28 – 31 mblf and 33 – 35 mblf) overlying the nearshore sand at 37 mblf (Figure 1).

[5] An age model was constructed for MAL05-2A using 24 radiocarbon dates in the upper 22 m of the core (calibrated using the "Fairbanks 0107" calibration curve [*Fairbanks et al.*, 2005]; see auxiliary material)[1] and stratigraphic correlation of the two carbonate-rich intervals with equivalent intervals in core MAL05-1C in the central basin of the lake [*Scholz et al.*, 2007] (Figure 1). The model establishes an age of about 75 ka for the nearshore sand and 62 ka for the top of the upper calcareous horizon in MAL05-2A. The sedimentation rate at the site has varied between 0.3 and 0.6 m/kyr, faster during the Holocene and during the rise in lake level prior to 50 ka, and slower throughout most of the intervening period.

[6] The bulk elemental composition of MAL05-2A was evaluated at the University of Minnesota Duluth using the Large Lakes Observatory's ITRAX X-ray Fluorescence Core Scanner (Cox Analytical Instruments). The scanner was operated at 1-cm resolution (corresponding to ~20 years) with 60 sec scan times using a Mo x-ray source set to 30 kV

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl031240. Other auxiliary material files are in the HTML.

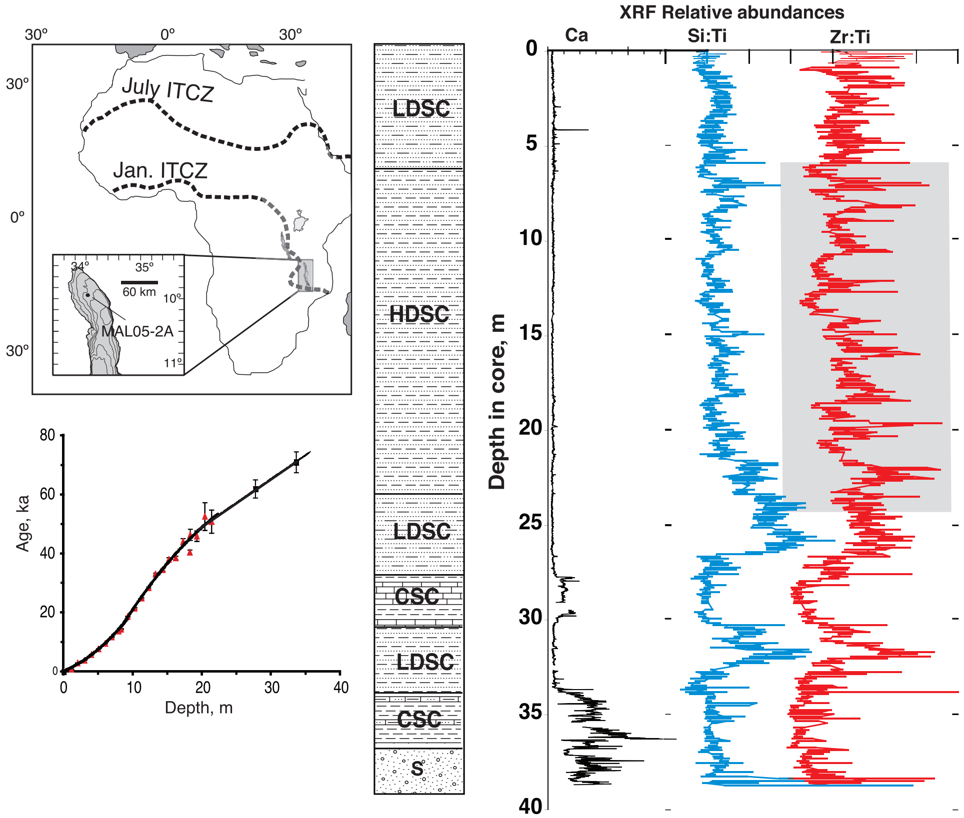

Figure 1. Stratigraphy and elemental data from drill site MAL05-2A. Map displays core site location and the seasonal boundaries of the ITCZ (dashed lines). Lithology abbreviations: LDSC, laminated diatomaceous silty clay; HDSC, homogeneous diatomaceous silty clay; CSC, calcareous silty clay; S, sand. The shaded portion of the Zr:Ti profile is presented as a function of age in Figure 2. The age model is built on the basis of 24 (out of 25) radiocarbon dates (red triangles; see auxiliary material). Black squares are age estimates for terminations of periods of carbonate deposition. These have been correlated to Ca peaks in drill site MAL05-1C in the central basin of the lake, which have been dated by luminescence and paleomagnetic/^{10}Be correlations [*Scholz et al.*, 2007]. A date of 80 ± 10 years BP (1870 CE) was determined for the core top through stratigraphic relations with a nearby multi-core [*Barry*, 2001]. Error bars on the radiocarbon dates are ±1 standard deviation on the dates (see auxiliary material), and are assumed to be ±5% for the dates based on stratigraphic correlation.

and 15 mA. This work focuses on Si:Ti, an indicator of abundance of biogenic opal, and on Zr:Ti, which reflects input of weathered volcanogenic sediment [*Bonjour and Dabard*, 1991; *Brown and Johnson*, 2005; *Johnson et al.*, 2002]. XRF results for these elements compare well with results from conventional techniques for the range of sedimentary facies found in this core (see auxiliary material).

3. Results and Discussion

[7] In previous studies of piston cores and multi-cores, we concluded that biogenic silica production and input of weathered volcanogenic material are elevated when the northern basin of the lake is subjected to northerly winds [*Brown and Johnson*, 2005; *Johnson et al.*, 2002]. These conditions promote upwelling and high diatom productivity, as well as aeolian transport of volcaniclastic material from the only nearby source of volcanic material, the Rungwe volcanoes to the north of Lake Malawi. Northerly winds are funneled down the lake axis when the region is exposed to the northeast trade winds and the ITCZ is positioned just south of the lake during austral summer.

[8] Such conditions, attributed to southward displacement of ITCZ relative to present conditions, were more prevalent when the Northern Hemisphere was relatively cold during the Little Ice Age, the Younger Dryas (YD), and Heinrich Events 1 and 2 [*Brown and Johnson*, 2005; *Johnson et al.*, 2002]. Recent work indicates that the YD was a time of elevated abundance of C4 grass in the Malawi basin, indicating relatively arid conditions [*Castaneda et al.*, 2007]. Evaluation of these results in light of modern vegetation surveys [*Tieszen et al.*, 1979], suggests a 5–10% drop in available soil moisture during the YD. We thus interpret peaks in Zr:Ti and Si:Ti to result from northerly winds and relative aridity. This interpretation is not consistent with a study suggesting wetter conditions during the YD and LGM in Lake Masoko, a small maar lake 30 km north of Lake Malawi [*Garcin et al.*, 2006] but Masoko may be responding to local rather than regional processes; it appears out of step with other lake records in East Africa. Our interpretation of aridity during times of elevated diatom productivity is

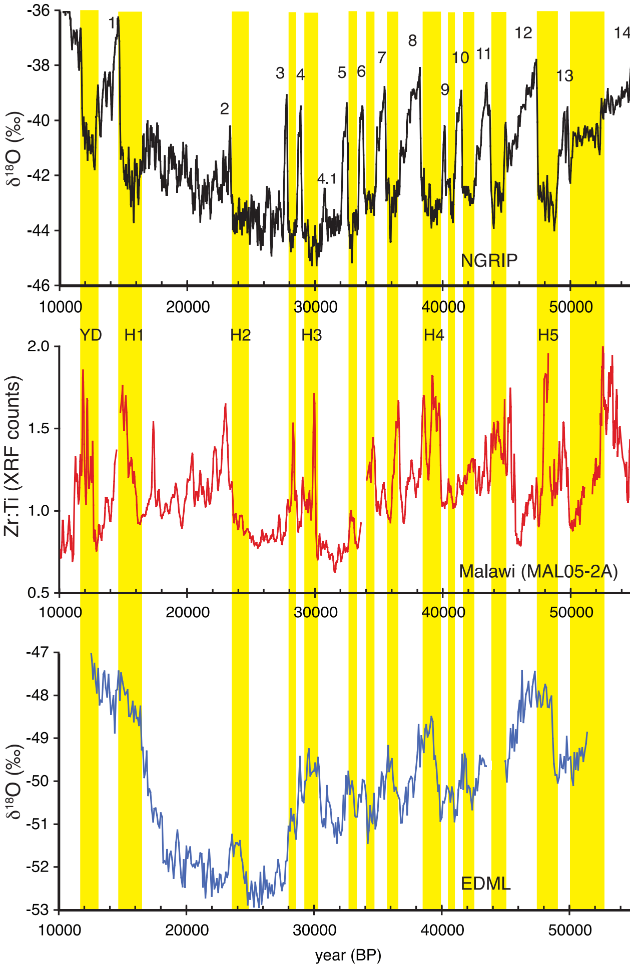

Figure 2. High latitude and tropical expression of millennial scale climate variability recorded in Greenland δ^{18}O (NGRIP; black) [*North Greenland Ice Core Project Members*, 2004], Lake Malawi Zr:Ti (red) and Antarctic δ^{18}O (EDML; blue) [*EPICA*, 2006] between 10 and 55 ka. Values represent ~100-year running means in each record. Greenland stadials and corresponding Antarctic warming are highlighted in yellow. To minimize the influence of individual volcanic events, we do not include Zr:Ti data associated with discrete ashes, which have been identified visually, in smear slides, and by anomalous K concentrations. Our record thus reflects input of soils developed from weathered volcanic ash. The general form of the millennial scale events in Malawi strongly resembles, but appears to precede, corresponding DO events in Greenland.

further supported by high resolution (0.2 mm) XRF scans of a varved multi-core recovered from near drill site MAL05-2A, that clearly reveal the seasonality of the Zr and Si signals, out of phase with Fe and Ti input during the rainy season (see auxiliary material).

[9] Profiles of Si:Ti and Zr:Ti show considerable variability with depth in MAL05-2A, and display parallel trends (Figure 1). The Zr:Ti profile shows greater variability than the Si:Ti profile, except near the bottom of the core, where there are two broad peaks in Si:Ti, lying just over the carbonate-rich intervals of sediment. The nearshore sand at the base of MAL05-2A, approximately 380 m below present lake level, and the two calcareous intervals in the core indicate conditions much drier than today. We attribute the abrupt and substantial rise in Si:Ti immediately above both calcareous intervals (Figure 1) to elevated nutrient input to the lake with the onset of more rainfall, as well as to the much reduced size of the north basin of the lake compared to today, resulting in focused deposition of biogenic silica.

[10] A plot of Zr:Ti versus age for the interval between 10 and 55 ka in MAL05-2A resembles the δ^{18}O profile of D-O events in the Greenland NGRIP ice core (Figure 2). Variability in Zr:Ti is characterized by abrupt rise and either abrupt or gradual fall, often leading to a saw-tooth-shaped profile. Peak values can persist for decades, and relatively elevated values for millennia. The number, magnitude and overall shape of prominent Zr:Ti peaks match the overall pattern of D-O events in the NGRIP record (Figures 2 and 3). We hypothesize that the sediments of the northern basin of Lake Malawi record the presence of decadal to millennial variability in climate related to the D-O events of Greenland, and to similar events observed in records of the northwestern Indian Ocean [*Burns et al.*, 2003; *Shakun et al.*, 2007], China [*Wang et al.*, 2001], the Cariaco Basin [*Peterson et al.*, 2000], Brazil [*Wang et al.*,

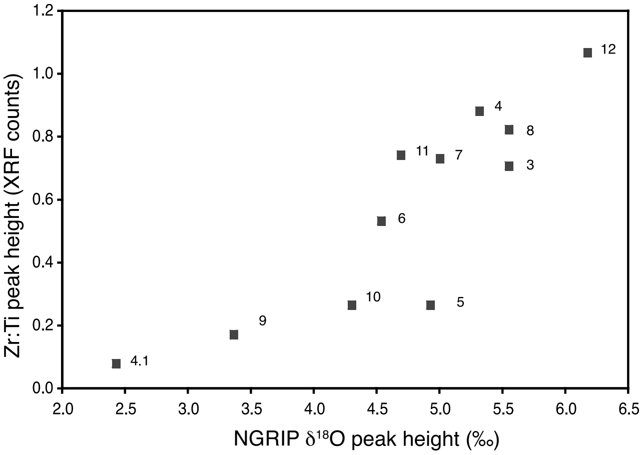

Figure 3. Heights of Zr:Ti peaks in the Malawi record as a function of heights of subsequent NGRIP D-O δ^{18}O peaks (r^2 = 0.72). Values were taken from ~100-year running means of datasets (see Figure 2) and estimated relative to the nearby low frequency baseline. Data labels correspond to the numbering of DO events. If our age model is accurate, this provides evidence that tropical processes modulate the magnitude of high latitude climate fluctuation.

2004], and Antarctica [*European Project for Ice Coring in Antarctica Community Members* (*EPICA*), 2006].

[11] Our age-depth model for MAL05-2A (which is untuned and assumes a constant 450-year "old carbon effect" – see auxiliary material) suggests that peaks in Zr:Ti align with stadials and precede the corresponding D-O warming events in the Greenland record. We recognize that uncertainties in both chronologies do not allow establishment of rigorous phase relationships of Malawi Zr:Ti events with D-O events, but association of the Malawi episodes with Greenland stadials is mechanistically consistent with our prior observations of increased deposition of biogenic silica and volcaniclastic material during the YD and H1 [*Brown and Johnson*, 2005; *Johnson et al.*, 2002]. On the basis of our understanding of these more recent records, we interpret the peaks in Zr:Ti and in Si:Ti to reflect abrupt shifts to more prolonged or intense northerly winds, indicating a southward displacement of the ITCZ, and relatively arid conditions in the Malawi basin. This response is out of phase with the records of northern ITCZ movement associated with D-O events noted above.

[12] Although uncertainties in age models do not allow us to preclude the possibility that Malawi Zr:Ti events were coeval with Greenland D-O events, we do not believe this to be the case. First, major peaks in Si:Ti and Zr:Ti are clearly associated with the YD (equivalent to peaks in biogenic silica and Nb:Ti noted for the YD in earlier work in Malawi's north basin [*Johnson et al.*, 2002]). Radiocarbon dates for these events would have to be corrected by negative 500 years (i.e. contamination by modern carbon) in order to align the peaks with the B/A, which is highly unlikely given the multiple dates included in the chronologies. Second, tuning the age-depth model so that the Zr:Ti peaks align with D-O interstadials would require invocation of variable admixtures of 0 to 25% dead carbon to obtain age adjustments of 0 to 2500 years. There is no evidence of such high old carbon/reservoir effects in either Lake Malawi or Lake Tanganyika [*Barry et al.*, 2002; *Felton et al.*, 2007]. Finally, under this interpretation, the Zr:Ti and biogenic silica peaks would result from dry windy conditions during times of northward ITCZ excursions. However, southeasterly winds associated with northward ITCZ excursion are unlikely to induce spikes of diatom productivity in the lake's north basin, or to deliver weathered Rungwe volcanic ash from the north.

[13] Our age model also suggests that Zr:Ti peaks in the Malawi record align with relatively warm episodes in Antarctica, as recorded in the EDML ice core (Figure 2), that are concurrent with Greenland stadials between D-O events [*EPICA*, 2006]. Under such conditions of polar temperatures, climate models display southward ITCZ displacement [*Broccoli et al.*, 2006], consistent with our record. The magnitude of warm events in Antarctica has been shown to reflect the duration of the corresponding stadials in the Greenland ice core record [*EPICA*, 2006], supporting the hypothesis of a thermal bipolar seesaw linking decadal-to-millennial climate variability between Antarctica and Greenland [*Stocker and Johnsen*, 2003]. We conclude that abrupt climate change observed in the Malawi basin is integrally linked to this thermal bipolar seesaw.

[14] The cause of such abrupt climate shifts remains elusive. Initially these were attributed to ice sheet instability and/or the dynamics of North Atlantic thermohaline circulation; other mechanisms, particularly of tropical origin, were proposed when sites of well documented D-O events were recognized in areas far from the direct influence of the North Atlantic Ocean (e.g., Socatra Island off Somalia [*Burns et al.*, 2003]; Hulu Cave, China [*Wang et al.*, 2001]; Santa Barbara Basin off California [*Hendy and Kennett*, 2000]). Proponents of North Atlantic driven D-O events invoke a well-defined mechanism (shutdown of the thermohaline circulation) with the potential to last for centuries [*Broecker*, 2003], whereas proponents of a tropical source [*Clement et al.*, 2001; *Sirocko*, 2003] more easily explain the apparent global extent of D-O events, although the mechanism and reason for its duration are not well defined [*Ivanochko et al.*, 2005].

[15] Results from Lake Malawi are relevant to this controversy. The abrupt shift to drier conditions and more northerly winds in the Malawi record is consistent with model results [*Dahl et al.*, 2005] for tropical East Africa when the Atlantic Meridional Overturn Circulation (AMOC) is shut down due to a large fresh water influx to the North Atlantic Ocean. However, our results also suggest that Zr:Ti peaks (abrupt shifts to windy/arid conditions) in Malawi precede the corresponding D-O events in Greenland, and that a tropical component of the bipolar seesaw may play a major role in setting the abruptness, amplitude and duration of D-O events in Greenland. Such a tropical link would provide a more effective mechanism than mere reduction of AMOC for development of global responses to decadal - millennial scale climate variability during the last ice age [*Clement et al.*, 2001; *Seager and Battisti*, 2007].

[16] Regardless of the exact timing or trigger mechanism, sudden shifts in climate conditions in tropical East Africa appear to be an essential part of the bipolar seesaw and the

abrupt temperature shifts at high latitudes during the last ice age. Understanding the dynamics of such climate variability will advance our critical evaluation of the African response to continuing change in global climate, improve our understanding of the role of tropical Africa in modulating global atmospheric methane concentrations as recorded in polar ice [*Blunier and Brook*, 2001], and allow examination of the impact of climate on the distribution of African flora and fauna, including our human ancestors during their migrations within and from the African Continent [*Mellars*, 2006].

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