Little Ice Age drought in equatorial Africa: Intertropical Convergence Zone migrations and El Niño–Southern Oscillation variability

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ABSTRACT

High-resolution analyses of the Mg concentration in authigenic calcite in five cores from Lake Edward provide a water balance history of central equatorial Africa spanning the past 1400 yr. A high ratio of Mg to Ca (%Mg) indicates strong droughts in central Africa during the Little Ice Age (A.D. 1400–1750), in contrast to records from Lake Naivasha, Kenya, which suggest a wet Little Ice Age. This spatial pattern in Africa likely arose due to coupled changes in the high latitudes, the position of the Intertropical Convergence Zone, and the El Niño–Southern Oscillation (ENSO) system. Our results further suggest that the patterns and variability of twentieth-century rainfall in central Africa have been unusually conducive to human welfare in the context of the past 1400 yr.

Keywords: Lake Edward, Africa, paleoclimate, carbonate, Little Ice Age, Medieval Warm Period.

INTRODUCTION

On orbital to millennial time scales, tropical regions experience broad, zonal changes in precipitation and temperature driven by shifts in the mean position of the Intertropical Convergence Zone (Haug et al., 2001; Johnson et al., 2002; Wang et al., 2004). Yet we know little of the climate history of equatorial regions on time scales of decades to centuries during the late Holocene, which is critical to evaluating current, anthropogenically driven global climate change. What is the regional phasing of high-frequency tropical climate change, and what does this phasing imply for its cause? How does the climate of the past century compare with previous intervals in terms of rainfall amount and temporal stability? Recent studies have addressed some of these questions in tropical Africa (Brown and Johnson, 2005; Verschuren et al., 2000), but we remain far from understanding the timing, phasing, and causes of tropical climate variability.

METHODS AND INTERPRETATIONS

Lake Edward occupies a half-graben in central equatorial Africa (Fig. 1). Climate in the region is subhumid, with average annual rainfall of ~0.9 m/yr and evaporation rates of ~2 m/yr (Russell and Johnson, 2006). Rain falls from October to December and March to May during the twice-annual passage of the Intertropical Convergence Zone through the region, when moisture is derived from the Indian and Atlantic Oceans (Nicholson, 1996).

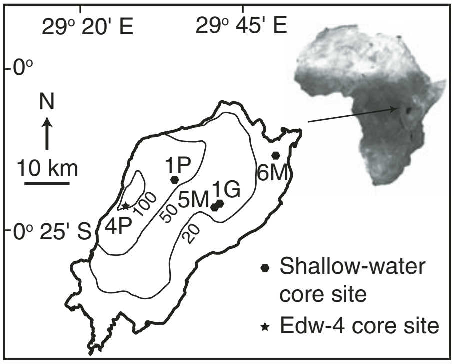

Figure 1. Bathymetric map of Lake Edward showing core sites (depth contours in m). Letter codes refer to core sites. Arrow marks location of Lake Edward on eastern edge of Congo Basin.

The ratio of Mg to Ca in authigenic calcite (%Mg) in Lake Edward's sediments has been shown to be a robust and sensitive indicator of the moisture balance of Lake Edward through cross-proxy validation, including correlation of shifts in %Mg to lowstands in the Lake Edward basin (Russell et al., 2003; Russell and Johnson, 2005), and measured declines in dissolved Mg/Ca during recent periods of high rainfall (Lehman, 2002). Temperature effects on the %Mg in calcite in Lake Edward are weak: Strong, positive correlation between the $\delta^{18}O$ and %Mg of calcite in Lake Edward shows that hydrological changes, not temperature, dominate trends in %Mg (Russell et al., 2003). During periods of drought, rising salinity concentrates the more conservative ion Mg^{2+} relative to the more reactive ion Ca^{2+} in lake water, while during wet periods, Ca^{2+} is recharged relative to Mg^{2+}. These climate-driven changes in dissolved Mg/Ca are recorded by shifts in the %Mg of inorganic, authigenic calcite. Intervals of rising and high %Mg represent periods of drought, while falling or low values of %Mg indicate wetter conditions (Müller et al., 1972).

We increased the resolution of previous analyses of the %Mg from Lake Edward (Russell et al., 2003) to centimeter-scale in four cores from relatively shallow water using X-ray diffraction (Goldsmith et al., 1961; Fig. 1). We also conducted centimeter-scale %Mg analyses in core Edw-4P, which was recovered just south of the deepest part of Lake Edward and is archived at the Wood's Hole Oceanographic Institution (Hecky and Degens, 1973). Core Edw-4P is composed of laminated clays and biogenic oozes, indicating undisturbed sedimentation, and lacks the frequent turbidites found in the deepest part of the lake, providing the highest-resolution record obtained thus far from Lake Edward.

We combined fifteen accelerator mass spectrometry (AMS) ^{14}C ages obtained on terrestrial macrofossils from Edw-4P with AMS ^{14}C- and ^{210}Pb-dated features in the %Mg data from other cores visually matched to Edw-4P to provide an age model for Edw-4P anchored by 20 ages, excluding outliers (Fig. 2). Inclusion of ^{14}C ages from the shallow-water cores corroborates the age model based on the dates from Edw-4P alone (Fig. 2). The ^{14}C ages were calibrated using Calib 4.3 (Stuiver and Reimer, 1993). This chronology shows that Edw-4P has an average sedimentation rate of ~3.5 mm/yr, providing an average sampling interval of ~3 yr

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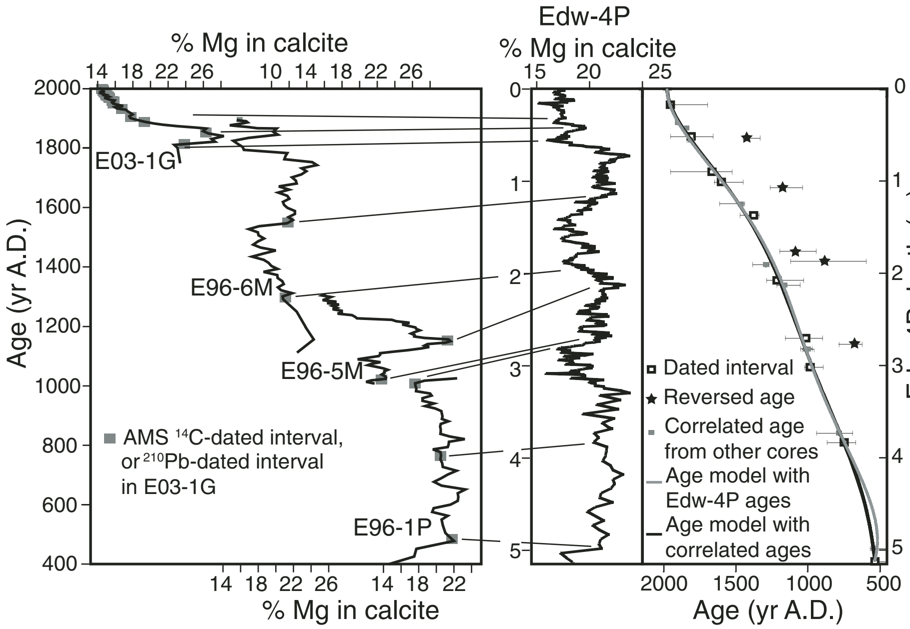

Figure 2. Left panel: Ratio of Mg to Ca (%Mg) in calcite for cores E96-6M, E03-1G, E96-5M, and E96-1P, recovered from 10 to 60 m water depth. Note *x*-axis shift to right with each core. Accelerator mass spectrometry (AMS) ^{14}C-based models for these cores have been published previously (Russell et al., 2003), except for E03-1G, which was collected and extruded in 1 cm intervals in 2003 for ^{210}Pb dating. %Mg data for Edw-4P is plotted against depth in central panel; lines show visual tie points for transferring dates (gray squares) from shallow-water cores. Right panel: Black line: polynomial age model for Edw-4P using ages from other cores and AMS ^{14}C dates on Edw-4P (open squares). Five AMS ^{14}C ages from Edw-4P appear reworked (closed stars). Gray line is a polynomial age model based upon Edw-4P dates only. Gray line indicates a negative sedimentation rate near base of core, so we use model with direct and transferred ages.

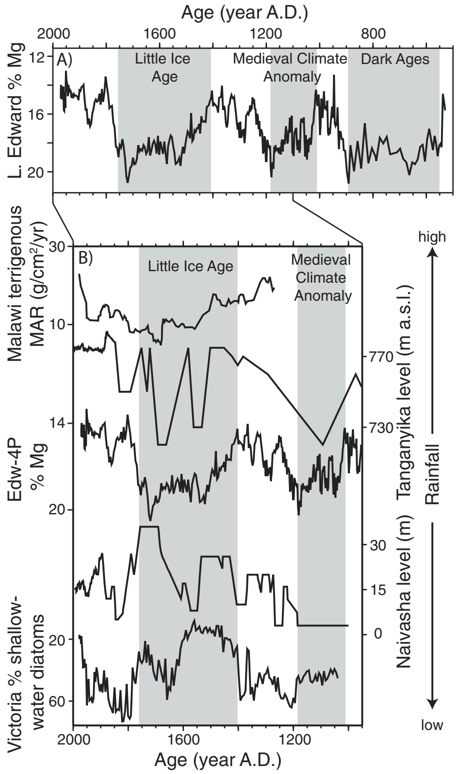

Figure 3. A: Ratio of Mg to Ca (%Mg) in Lake Edward calcite spanning the past 1400 cal yr B.P. Higher %Mg indicates drier conditions. Note reverse scale on *y*-axis. B: Paleoclimate records from Lakes Malawi, Tanganyika, Naivasha, Victoria, and Lake Edward. Decadal-scale differences in timing of onset and termination of events in these records cannot be resolved with existing age models, yet out-of-phase behavior between Lakes Malawi, Tanganyika, and Edward versus Naivasha and Victoria during Little Ice Age is clear (a.s.l.—above sea level). Malawi terrigenous MAR—Malawi terrigenous mass accumulation rate.

for centimeter-scale analyses. See the GSA Data Repository[1] for additional ^{14}C and ^{210}Pb data.

RESULTS AND DISCUSSION

The %Mg profiles from the five Lake Edward cores correlate well (Fig. 2), and vary between 14% and 28%. These high values result from high dissolved Mg/Ca values characteristic of East African lakes of elevated salinity (Talling and Talling, 1965). There are small differences in %Mg values between cores that likely reflect chemical gradients within the lake, with slightly higher values in the shallow, eastern half of the lake where calcite precipitation may be enhanced, driving dissolved Mg/Ca to higher values. Nevertheless, multidecadal- to centennial-scale changes in the five cores are strongly covariant and indicate large variations in central African water balance at decade to centennial time scales

Rising or high %Mg marks three major intervals of drought from A.D. 540–890, 1000–1200, and 1400–1750, each of which was followed by a period of wetter conditions documented by falling or low %Mg (Fig. 3A). The timing of these three arid phases is similar to the timing of cool intervals in the northern high latitudes known as the Dark Ages and the Little Ice Age, as well as the period of warm conditions known as the Medieval Warm Period or Medieval Climate Anomaly (MCA) (Lamb, 1985), although the MCA and Dark Ages are marked by substantial short-term regional variability that makes definitive global correlation difficult (Bradley et al., 2003). Drought during the MCA is evident across much of eastern Africa (Russell and Johnson, 2005), but our finding of drought from A.D. 1400 to 1750 stands in contrast to previous studies documenting wet conditions in East Africa during the Little Ice Age.

The most widely cited record of East African rainfall history during the past millennium is the water-level record of Lake Naivasha (Verschuren et al., 2000), which shows that severe drought during the MCA was followed by increasingly wet conditions in the equatorial eastern rift valley until ca. A.D. 1750 (Fig. 3B), in contrast to Little Ice Age drought at Lake Edward. Other records as far west as Lake Victoria also indicate moist conditions during the Little Ice Age (Stager et al., 2005; Thompson et al., 2002). In contrast, to the south of Lake Edward, Lake Malawi became progressively drier from A.D. 1400 to 1780 (Brown and Johnson, 2005), and Lake Tanganyika was generally low between A.D. 1550 and 1800 (Alin and Cohen, 2003; Cohen et al., 2005). To the west, Lake Bosumtwi experienced some of the most dramatic lowstands of the Holocene during the Little Ice Age (Overpeck et al., 2002). Thus, wet Little Ice Age conditions in eastern equatorial Africa coincided with dry conditions over western and central Africa (Fig. 3B). How might this spatial pattern have been produced?

Zonal shifts in the position of the ITCZ are often invoked to explain tropical African climate variability (e.g., Brown and Johnson, 2005), and evidence for southward shifts of the ITCZ in association with high-latitude cooling during the Little Ice Age appears robust (Baker et al., 2001; Brown and Johnson, 2005; Haug et al., 2001). However, shifts in the position

[1]GSA Data Repository item 2007014, ^{14}C and ^{210}Pb data for cores E72-4P and E03-1G, Lake Edward, Uganda, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

of the ITCZ alone should not result in strong meridional gradients across Africa. Today, moist, unstable flow from the Atlantic converges with drier air from the Indian Ocean near the longitude of Lake Edward along a north-south–trending convergence zone known as the Congo Air Boundary (Nicholson, 1996). It seems plausible that shifts in the position of the Congo Air Boundary in the past, driven by large-scale changes in the Atlantic and Indian monsoons, may have caused large meridional moisture gradients across equatorial Africa.

What might cause the Congo Air Boundary to migrate? We argue that the key factor linking high-latitude cooling, the ITCZ, and moisture gradients within Africa is the El Niño–Southern Oscillation (ENSO). Numerical models and proxy data indicate that increased Southern Hemisphere insolation during the late Holocene and southward ITCZ migration are associated with more frequent and/or more intense El Niño events (Clement et al., 2000; Haug et al., 2001; Moy et al., 2002). Simulations using fully coupled general circulation models suggest a shift toward an El Niño–like sea-surface temperature (SST) gradient in the Pacific during periods of northern high-latitude cooling and reductions in thermohaline convection (Zhang and Delworth, 2005). El Niño events are positively correlated with East African rainfall through changes in the Walker circulation and ENSO's effects on western Indian Ocean SSTs (Goddard and Graham, 1999; Nicholson, 1996). Positive rainfall anomalies in tropical Africa during El Niño events are strongest in easternmost Africa, but El Niño is often associated with above-average rainfall as far west as Lake Edward (Nicholson, 1996). However, southward migration of the ITCZ and reduced meridional heat transport in the Atlantic Ocean during northern high-latitude cooling are predicted to cause strong, positive SST anomalies in the equatorial and southern tropical Atlantic basin (Vellinga and Wood, 2002), which weakens the African monsoon within the Congo Basin and decreases Atlantic moisture transport to inland sites such as Lakes Edward, Tanganyika, and Malawi. It is thus possible that interactions between the ITCZ and the ENSO system during the Little Ice Age could have triggered a shift toward El Niño–like conditions and increased rainfall in easternmost Africa, while southward ITCZ migration triggered drought in the west.

Support for the ENSO system as the key linking variable in regional Little Ice Age variability comes from proxy data and modeling studies of western Pacific and other paleoclimate records spread across the tropics. Coral records suggest stronger zonal SST gradients across the equatorial Pacific during the twelfth century than during the seventeenth century, suggesting a shift toward El Niño–like conditions during the Little Ice Age (Cobb et al., 2003). Paleolimnological data from Eastern Java indicate drought and El Niño–like conditions from A.D. 1450–1650 and 1700–1750 (Crausbay et al., 2006). ENSO models suggest that El Niño–like conditions in the western Pacific during much of the Little Ice Age occurred due to solar and volcanic forcing (Mann et al., 2005). Elsewhere in the tropics, trends in the Ti content of sediments in the Cariaco Basin off the Venezuelan coast indicate decreased rainfall from A.D. 1350 to 1740 (Haug et al., 2001), and conditions were also dry across much of southern Asia, from the Arabian peninsula (Fleitmann et al., 2004) to tropical China (Wang et al., 2005). Each of these climate anomalies can be explained by southward ITCZ migration, increased El Niño events, or both (Diaz and Kiladis, 1992; Vellinga and Wood, 2002). In contrast, our observation of strong meridional gradients across the equator within Africa provides a unique observatory to investigate gradients across the tropics and interactions between the high latitudes, the ITCZ, and ENSO, and, together with the records presented already, these factors suggest a shift toward El Niño–like conditions during the Little Ice Age.

Was the dipole structure that emerged in Africa during the Little Ice Age unique? Lakes Naivasha, Edward, Tanganyika, and Victoria all experienced drought during the MCA. This could indicate that interactions between the high latitudes, the ITCZ, and ENSO do not produce meridional gradients in Africa during high-latitude warming, perhaps due to differences in the behavior of the Congo Air Boundary over Africa during high-latitude warming and northward ITCZ migration. However, it should be noted that warming during the MCA was regionally and temporally variable (Bradley et al., 2003), and perhaps had a lesser impact on the ENSO system than large-scale Northern Hemisphere cooling during the Little Ice Age. Additional data are needed to better constrain interactions between the ITCZ, ENSO, and African climate under multiple climate states. Yet negative shifts in the oxygen isotopic composition of glacial ice from Mount Kilimanjaro could indicate wetter conditions between ca. 3200 and 2700 cal yr B.P. (Thompson et al., 2002), when Lake Edward (Russell and Johnson, 2005) and northern South America (Haug et al., 2001) experienced drought and the high latitudes were cool (Bond et al., 2001), similar to the pattern observed during the Little Ice Age. This could suggest persistent ENSO modulation of global climate anomalies during late Holocene intervals of high-latitude cooling, as predicted by Zhang and Delworth (2005).

Numerous shorter-term shifts in %Mg indicate substantial decadal-scale climate variability in central Africa during the past millennium. These include recent drought from A.D. 1800 to 1850, wet conditions from A.D. 1850 to 1880, and falling lake levels near the turn of the century. This history matches well with the timing of rainfall and lake-level changes observed elsewhere in equatorial Africa, and shows striking similarities to coral-based SST reconstructions in the equatorial Indian Ocean (Cole et al., 2000), confirming an important role for the Indian Ocean in decadal African rainfall anomalies (Russell and Johnson, 2005). We also see evidence for at least three discrete decadal-scale drought events within the MCA; this is a new finding for Africa that supports previous suggestions for significant short-term, regional variability within this time period (Bradley et al., 2003).

The relatively low %Mg values in Lake Edward during the twentieth century indicate that the region is experiencing an unusually prolonged period of stable, wet conditions in comparison to previous centuries of the past millennium. This pattern is similar to Lakes Tanganyika (Cohen et al., 2005) and Malawi (Brown and Johnson, 2005). Unless global warming is a mitigating factor (e.g., Treydte et al., 2006), central Africa is overdue for a return to decades-long drought that exceeds anything observed in the past century. In light of sub-Saharan Africa's burgeoning population and the demands placed on water resources by that population, future management practices must be fundamentally reorganized to account for the dynamic nature of African climate at decadal to centennial time scales.

ACKNOWLEDGMENTS

We thank the Ugandan National Council for Science and Technology and the Ugandan Wildlife Authority for permission to work on Lake Edward. Dan Engstrom and the Science Museum of Minnesota are acknowledged for assistance with ^{210}Pb dating. We thank Andy Cohen, Michael Talbot, and an anonymous reviewer for comments on a previous version of this paper. This research was supported by National Science Foundation grant ATM-0314832.

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Manuscript received 23 June 2006
Revised manuscript received 3 August 2006
Manuscript accepted 8 August 2006

Printed in USA