Decadal record of climate variability spanning the past 700 yr in the Southern Tropics of East Africa

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ABSTRACT

Biogenic silica profiles in varved sediments from northern Lake Malawi (Nyasa), East Africa, span the past 700 yr and reflect past primary productivity in the overlying waters. On a centennial scale this has been influenced by lake level and a consequent shift in the location of high diatom productivity within the lake basin. Primary production was higher during the Little Ice Age, an arid period from about A.D. 1570 to 1850, when lake level was about 120 m lower than during the previous three centuries or the past 150 yr.

Keywords: Africa, paleoclimate, Little Ice Age, lake sediments, tropical climate.

INTRODUCTION

Knowledge of past climate variability in tropical Africa lags substantially behind that of the temperate and polar regions of Earth. There are only two annual- to decadal-scale proxy records of past climate variability encompassing the past few centuries that have been published for all of tropical Africa. A coral record from Malindi, Kenya, spanning the past 200 yr has revealed decadal variability in coastal sea surface temperature (SST) (Cole et al., 2000). A sediment record from Lake Naivasha, Kenya, provides a history of lake level for the past 1100 yr, and indicates a relatively dry Medieval Warm Period from about A.D. 1000 to 1270 and a relatively wet Little Ice Age from A.D. 1270 to 1850 (Verschuren et al., 2000). More such high-resolution proxy records of African paleoclimate need to be generated in order to unveil teleconnections within the global weather system that may lead to forecasting trends one or more years in advance with some accuracy.

Here we add a third high-resolution record of past climate variability in tropical Africa, based on profiles of biogenic silica abundance in varved sediments of northern Lake Malawi. The varved nature of the sediments allows for sufficient control on the geochronology to resolve aspects of the climate record on a time scale of decades to centuries spanning the past seven centuries.

SEDIMENTS OF LAKE MALAWI (NYASA)

Lake Malawi, the second largest lake in Africa, is about 650 km long, 40 km wide, and 700 m deep. The waters of Lake Malawi are very dilute (salinity of <0.2 ppt) and they are anoxic below a depth of 200 m. Although the surface waters are near saturation with respect to calcite, most of the water column is undersaturated (Ricketts and Johnson, 1996). In the absence of calcareous sediments, the sedimentary record of biogenic silica abundance is one of the most useful proxy indicators of past climate change in the Malawi basin. These profiles reflect past primary productivity of diatoms in the euphotic zone of the lake. Diatoms dominate the phytoplankton during periods of high productivity, when the supply of nutrients from the metalimnion is elevated by upwelling (Bootsma et al., 1996; Patterson and Kachinjika, 1995). Upwelling is most intense during the windy, cool, dry season, usually between June and November, when the Southeast Trade Winds are funneled up the Malawi portion of the East African Rift Valley (Patterson and Kachinjika, 1995).

The pattern of sedimentation in Lake Malawi is complex. Sands interbedded with mud dominate the nearshore facies to a depth of ~100 m in most regions of the lake, and diatomaceous mud or turbidites prevail farther offshore (Johnson and Ng'ang'a, 1990). Laminated sediments are found in many regions of the lake. The laminations are about 0.7 mm thick and consist of light and dark couplets of diatom ooze interbedded with dark layers of more terrigenous material, including clay, silt, and microscopic plant debris (Pilskaln and Johnson, 1991). The light layers result from diatom deposition during the high productivity season, and the dark layers ensue from high terrigenous input from rivers during the warm rainy season in December–March.

Although laminated sediments are commonly observed in the deeper portions of many cores recovered from the lake, they are not ubiquitous throughout the anoxic part of the basin. Modern sediments are laminated only in the northern basin of the lake, where

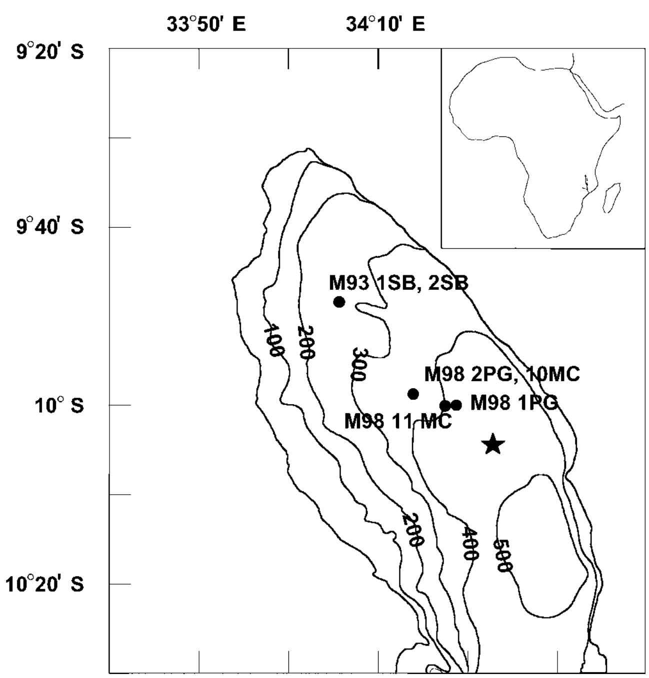

Figure 1. Northern basin of Lake Malawi, showing locations of six cores (circles) analyzed for this study, and of sediment trap (star) of C. Pilskaln that provided biogenic silica flux data for period 1987–1990 (Francois et al., 1996). Depth contours are in meters. Inset map shows location of Lake Malawi on African continent.

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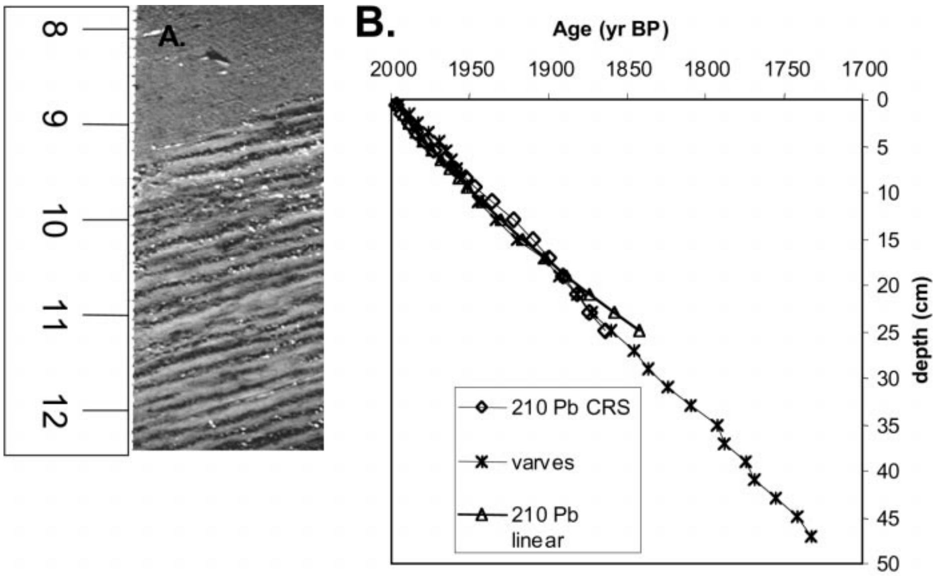

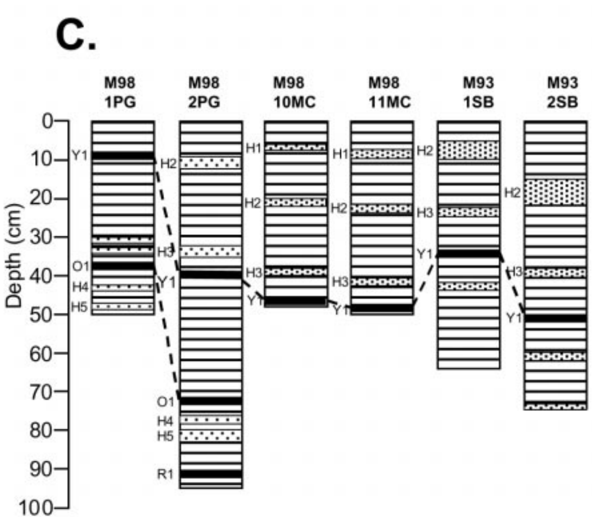

Figure 2. A: Homogenite layer H1 overlying varves in core M98 11MC (depth scale is in cm). B: Comparison of chronology in core M98-11MC based on lamination counts and ^{210}Pb activity. CRS refers to constant rate of supply and linear refers to linear model of age assignment. C: Stratigraphic summary of six cores analyzed in this study. Locations of marker beds Y1, O1, and R1, and of homogenites, H1–H5, are indicated by labeled black and stippled bands, respectively. Intervening sediments are varved.

seasonal input from the major rivers during the rainy season is substantial and contrasts with the biogenic sediment flux during the dry, windy season.

METHODS AND RESULTS

We measured profiles of biogenic silica abundance in multicores and box cores collected from several sites in northern Lake Malawi (Nyasa) near lat 10°S, long 34°E (Fig. 1). The short cores were stored upright and uncapped, and allowed to dewater for a few days in Malawi to make them less fluid for transport. They were then capped and air freighted back to Minnesota, where they were split, visually described, and sampled immediately for water content. A consistent stratigraphy was established for the basin spanning the past 20 k.y., based on a succession of varved and nonvarved intervals, radiocarbon dates, and a few prominent marker beds, mainly of volcanic ash.

The six cores used for this study are laminated throughout most of their 50–100 cm lengths. The laminations are interrupted by a few thin (1–2 cm thick) muddy homogenites (nonlaminated beds) with erosional lower boundaries (Fig. 2). These homogenites and three visually distinct, thin marker layers (designated Y1 [tephra], O1 [diatomite], and R1 [tephra]) can be correlated among the cores, providing a master stratigraphy for the deposits (Fig. 2C). The cores were sampled at 1 cm intervals for microscopic biogenic silica and ^{210}Pb analyses. Microscopic examination of smear slides revealed that the only significant source of biogenic silica was diatom tests, primarily of the genera *Aulacoseira, Stephanodiscus,* and *Cyclostephanos.* The naturally occurring isotope ^{210}Pb has a half-life of 22.26 yr. The ^{210}Pb activity was determined by alpha counting its isotopic granddaughter, ^{210}Po (Robbins and Edgington, 1975). Age assignments based on ^{210}Pb are illustrated in Figure 2 by both the constant rate of supply model and the linear model.

Varves were counted and labeled using computer imaging software (Photoshop) to establish the chronology in each core. The number of varves counted in intervals between correlatable homogenites among the cores varied because of erosion by the turbidity currents that formed the homogenites. The maximum number counted in any core was taken as the correct estimate of age between marker horizons. There were fewer than 10 missing varves in any sequence when compared to the maximum count.

The ^{210}Pb age assignments down cores M93–2SB, M98–10MC, and M98–11MC agree well with sediment age based on couplet counts, confirming the interpretation of the laminations as varves (Fig. 2B). We estimate the uncertainty in absolute ages for the past century to be ~5 yr based on the comparison of varve counts with ^{210}Pb activity, and ~20 yr in the older sediments.

Biogenic silica analyses were by the time-series chemical digestion technique (DeMaster, 1979; Krause et al., 1983), using 0.5 *M* NaOH solution at 80 °C. Concentrations of biogenic silica in the six cores range between about 5 and 35 wt% SiO_2. Due to the sample thickness of 1 cm, each data point represents an average value for about a 7 yr period. The profiles of the cores match well, especially from about A.D. 1670 to the present (Fig. 3). Prior to 1670 the major trend in all cores is toward lower biogenic silica concentrations with age, but some discrepancies exist, in part due to uncertainties in age assignment that cannot be resolved independently.

CLIMATIC SIGNIFICANCE OF THE BIOGENIC SILICA PROFILES

Biogenic silica versus age data for all of the cores were combined and averaged decadally to provide a master curve for the north basin of the lake. The curve is plotted as decadal deviations from the mean value of 17.1 wt%; positive deviations are plotted to the left of the zero axis (Fig. 4). High concentrations are sustained from about A.D. 1570 to 1820. Low concentrations of biogenic silica characterize the late nineteenth and twentieth centuries, as well as most of the period between A.D. 1300 and 1520. The period of high diatom productivity (A.D. 1570–1820) corresponds roughly to the Little Ice Age.

High burial rates of biogenic silica in marine sediments are normally attributed to intensified upwelling leading to enhanced productivity in the photic zone. This is also the case on short time scales (<10 yr) in rift lakes. Time-series sediment trap data collected in northern Lake Malawi between 1987 and 1990 by C. Pilskaln show strong seasonal pulses in the biogenic silica flux to the lake floor, occurring in September–October of 1987 and 1988, and in April–May of 1989 (Francois et al., 1996). The biogenic silica peak flux in 1989 was more than double the seasonal peaks of 1987 or 1988. While 1989 was not an unusual year in terms of either extreme winter cold or wind intensity, the previous summer's (late 1988) maximum air temperatures were the coolest recorded in the period from 1980 to 1994 (Patterson and Kachinjika, 1995). Thus the high diatom production in 1989 was caused by relatively weak stratification in the water column preceding the windy season, allowing for earlier and more intense overturn and nutrient replenishment to the photic zone.

The reservoir of dissolved silica in the water column of Lake Malawi is finite, however. A model of the silica dynamics has demonstrated that intensified upwelling can sustain higher diatom productivity for only a decade, after which the concentration of dissolved silica in the entire water column becomes sufficiently depleted to restore diatom productivity to its previous level (Bootsma and Hecky, 2000). A prolonged escalation of diatom productivity in the northern basin of the lake can be sustained only if there is an equally prolonged increase in the supply of dissolved silica to the lake from inflowing rivers, or if the locus of high diatom productivity shifts from another part of the lake to the north basin. The former mechanism would suggest that the Little Ice Age was a time of enhanced chemical weathering in the drainage basin of the lake, and would require wetter conditions than today. This, however, conflicts with sediment core data from the southeast and southwest arms of the lake, as well as archeological data, that provide compelling evidence for lake level having been about 120 m lower than present at some time (not well defined) between about A.D. 1500 and 1850 (Owen et al., 1990). A lowstand of this magnitude would have dried up the most productive region of the modern lake (Patterson and Kachinjika, 1995), the southeast and southwest arms, where the most diatomaceous sediments ($>$50% biogenic silica) currently accumulate. Not only would this drop in lake level have forced a shift in the primary site of diatom accumulation in the lake basin, but it would have exposed the silica-rich diatomites of the southeast and southwest arms to subaerial weathering, thereby increasing the input of dissolved silica to the lake. We conclude that our biogenic silica profile accurately delineates the timing of this lowstand, when diatom productivity in the northern, deep basin of the lake benefited from the collapse of diatom production in the desiccated southwest and southeast arms.

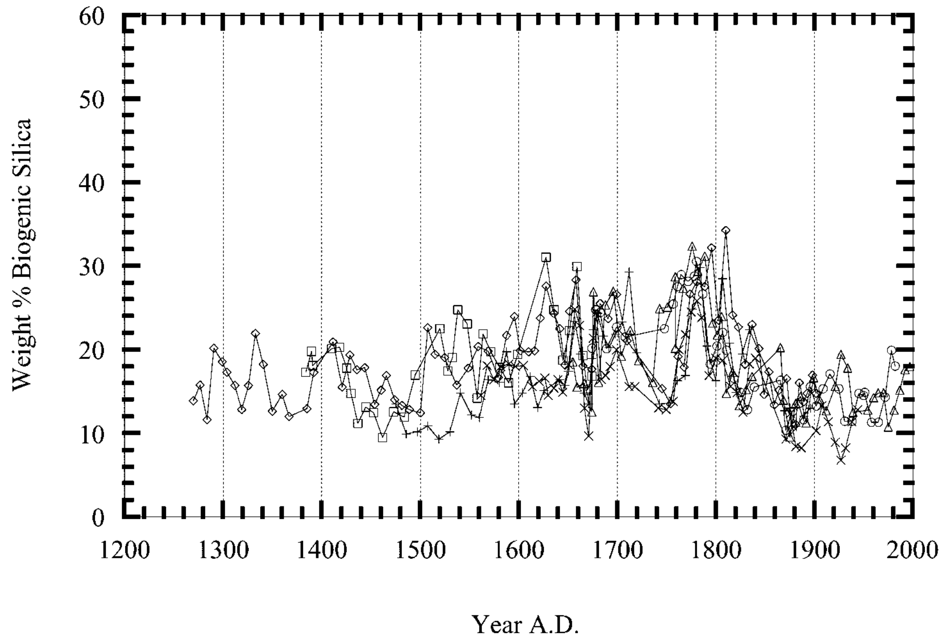

Figure 3. Weight percent biogenic silica (BSi) versus age for six cores. Squares—M98-1PG; diamonds—M98-2PG; circles—M98-10MC; triangles—M98-11MC; plus signs—M93-1SB; and X—M93-2SB.

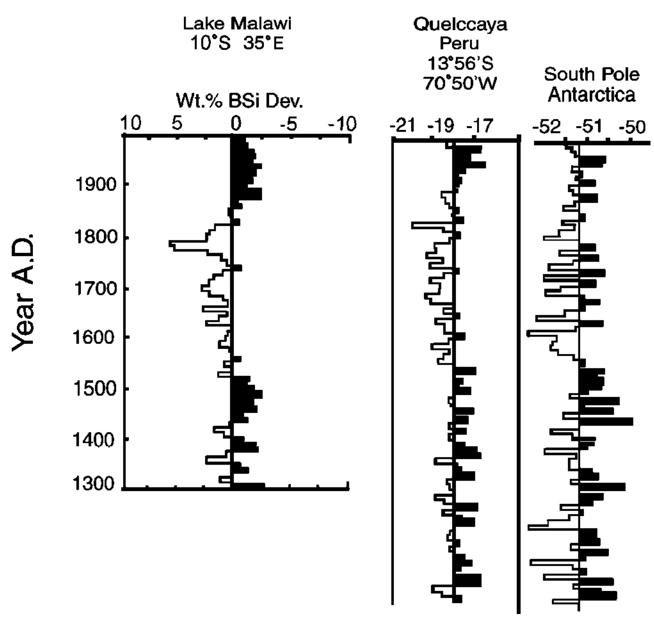

Figure 4. Left: Decadal mean percent biogenic silica (Bsi) for northern basin of Lake Malawi from A.D. 1300 to present, expressed as deviations from mean value of 17.1%. Center and right: Decadal average profiles of oxygen isotopic composition (expressed as $\delta^{18}O$) of ice on Quelccaya ice cap, Peru, and at South Pole, Antarctica, plotted on same time scale.

GLOBAL TELECONNECTIONS

The overall shape of the decadal average biogenic silica curve resembles decadal average $\delta^{18}O$ curves from Quelccaya, Peru, and South Pole, Antarctica (Thompson, 1995), the relatively high concentrations of biogenic silica in the Malawi cores corresponding to relatively light $\delta^{18}O$ in the ice cores (Fig. 4). The $\delta^{18}O$ profiles are usually interpreted as a reflection of temperature, the lighter isotopic values corresponding to relatively cooler conditions (Thompson, 1995; Thompson et al., 1986). The lighter isotopic values in Andean ice cores have also been interpreted to reflect wetter mean conditions (Baker et al., 1999). Thompson et al. (1986) attributed the cold (or wet?) conditions at Quelccaya, Peru, from A.D. 1550 to 1900 to the Little Ice Age, claiming the ice-core record to be well-dated evidence for the global extent of this climate phenomenon. Our biogenic silica profiles further support, and extend, the global expanse of the Little Ice Age.

The biogenic silica profiles indicate that Lake Malawi underwent a pronounced lowstand during much of the Little Ice Age, when the Northern Hemisphere was relatively cool and so, perhaps, were the Peruvian Andes and the South Pole. The periods of Malawi lowstands coincide roughly with periods of low Nile outflow (Said, 1993; Nicholson, 1998), but also overlap with the highest stand of Lake Naivasha, Kenya, during the past millennium (Verschuren et al., 2000). This illustrates the complexity of climate variability in tropical Africa on this time scale.

The Little Ice Age may be the most recent manifestation of a millennial-scale cycle in climate variability associated with southward excursions of cold, ice-bearing surface waters in the North Atlantic Ocean (Bond et al., 1997). These excursions occur roughly every 1500 yr in the North Atlantic (Bond cycles), and include the Younger Dryas event, the 8.2 ka event, and Dansgaard-Oeschger cycles in the late Pleistocene. In the North Atlantic region of Greenland and Iceland, all of these millennial-scale cycles mimic cold (ice age) conditions.

Lake Malawi shifted out of Little Ice Age conditions around 1850, ~50 yr earlier than warming began at Quelccaya or than tree-ring records indicate warming of the Northern Hemisphere (Mann et al., 1998). This suggests that tropical Africa is not responding to changes in North Atlantic circulation, but perhaps is responding earlier to the force that results in the Bond cycles of the North Atlantic. This also is seen in the 8.2 ka event of tropical Africa, a prolonged dry period in Ethiopia and elsewhere in North Africa, but not in Malawi, which appears to have started earlier than in Greenland, lasted longer, and had greater impact on local conditions (Johnson, 1999).

Human welfare in the African tropics is intimately tied to climate variability. Our ability to predict forthcoming weather on an annual scale in this region is in its infancy, but will improve through the acquisition of more high-resolution records of floods and droughts over time scales relevant to the socioeconomic challenges of the region.

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