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Solar variability and the levels of Lake Victoria, East Africa, during the last millenium

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Abstract

A new diatom series with 1–6 year resolution from Lake Victoria, East Africa, shows that lake level minima occurred ca. 820–760, 680–660, 640–620, 370–340, and 220–150 calendar years BP. Inferred lake levels were exceptionally high during most of the 'Little Ice Age' (ca. 600–200 calendar years BP). Synchrony between East African high lake levels and prolonged sunspot minima during much of the last millenium may reflect solar variability's effects on tropical rainfall, but those relationships reversed sign ca. 200 years ago. Historical records also show that Victoria lake levels rose during every peak of the ca. 11-year sunspot cycle since the late 19th century. These findings suggest that, if these apparent tropical sun–climate associations during the last millenium were real, then they were subject to abrupt sign reversals.

Introduction

Modeling and predicting tropical rainfall patterns is complicated by a relative scarcity of high-resolution paleo records that are directly linked to modern climates. The erratic but significant effects of short-term disturbances such as El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events on tropical African rainfall are well known (Linthicum et al. 1999; Nicholson 2000; Richard et al. 2000; Conway 2002), but few records of solar variability's effects on tropical paleoclimates cover recent centuries, leading most investigators of modern African climate dynamics to disregard it. Evidence from Lake Naivasha, Kenya (Figure 1; Verschuren et al. 2000), has suggested that prolonged sunspot minima caused lake levels to rise there during the Little Ice Age (LIA), but it conflicted with previously published, incomplete microfossil records from the adjacent Victoria basin (Stager et al. 1997) which is orders of magnitude larger. In this paper we present a fine-interval diatom series from Lake Victoria's Pilkington Bay (Figure 1) which displays hydrological fluctuations very similar to those registered at Lake Naivasha, thus resolving the earlier

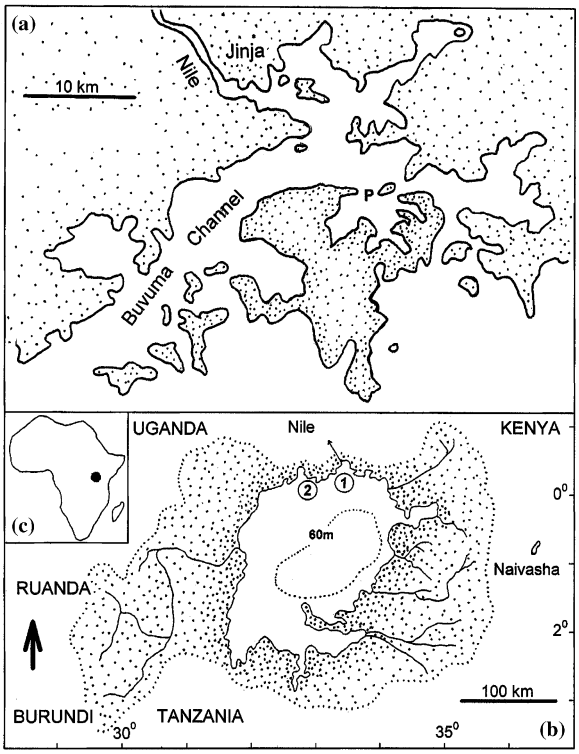

Figure 1. Location maps. (a) Pilkington Bay and vicinity. 'P' marks P2K-1 coring site. (b) Lake Victoria watershed. 1 = Pilkington Bay, 2 = Damba Channel. (c) Africa, with Lake Victoria watershed dotted.

conflict. In addition, we suggest that sun–climate relationships, if they existed in this region, were more variable than is often assumed.

Study site

Lake Victoria drains into the Nile River, but >90% of its water enters and leaves via the atmosphere with most rain falling ca. April–May and November–December with the arrival of the Intertropical Convergence Zone (ITCZ). Its enormous size (Figure 1; area 68,800 km^2; watershed ~200,000 km^2) and sensitivity to rainfall (Nicholson and Yin 2001) make reconstructions of its former levels representative of climate variability over much of equatorial East Africa. Pilkington Bay occupies 40 km^2 of the north end of Buvuma Island, Uganda (Figure 1); 0°17′95″ N, 33°19′83″ E). The bay floor dips northwards to a maximum depth of 12 m, and *Papyrus* swamps rim the shoreline.

Methodology

We inferred relative paleolake levels and conductivities from the diatom record of 1.74 m long core P2K-1 (Figure 2), which was collected from 8 m depth in Pilkington Bay with a hand-held micro-Kullenberg piston corer and extruded vertically in the field in 1 cm increments.

Between 350 and 650 diatom valves were identified per subsample at 1000X. Taxa indicating shallow water habitats were grouped as 'shallow-water diatoms' (SWD; Figure 2) and belonged to the genera *Achnanthes*, *Amphora*, *Cocconeis*, *Cymbella*, *Epithemia*, *Eunotia*, *Fragilaria*, *Gomphonema*, *Navicula*, *Pinnularia*, and *Rhopalodia*. SWD percentages increased in surface sediments from five progressively shallower sites in Pilkington Bay (Figure 2), supporting their use as a proxy for littoral zone encroachment during lake level declines as has been done in other studies (Stager et al. 1997; Gasse et al. 2002; Stager et al. 2003). Conductivity (μS cm^{-1}) was inferred from 32 taxa in the P2K-1 diatom assemblages using weighted-average transfer functions developed from the European Diatom Database (Battarbee et al. 2000) which also incorporates diatom training sets from Africa. The most recent inferred conductivities were slightly higher than measurements made at Lake Victoria during the early AD 1960's (111–134 vs. 91–97 μS cm^{-1}, respectively; Talling and Talling 1965) but they consistently rose with %SWD in P2K-1 (r^2 = 0.85), reflecting evaporative concentration and reduced outflow during low stands and thus lending support to our use of SWD as a lake level proxy (Figure 2).

Chronology

Accelerator mass spectrometry (AMS) dates were obtained for six 1 cm^3 organic sediment subsamples in core P2K-1 (Table 1). AMS dating of isolated terrestrial botanical fractions was deemed unsuitable in the present study because of the strong possibility of reworking of peats from fringing *Papyrus* mats in the bay (cf. Mensing and Southon 1999). Such conditions were also apparent in a core from Nabugabo, a marsh-rimmed lake near Lake Victoria, in which a grass fragment yielded an AMS date 700 ^{14}C year older than that

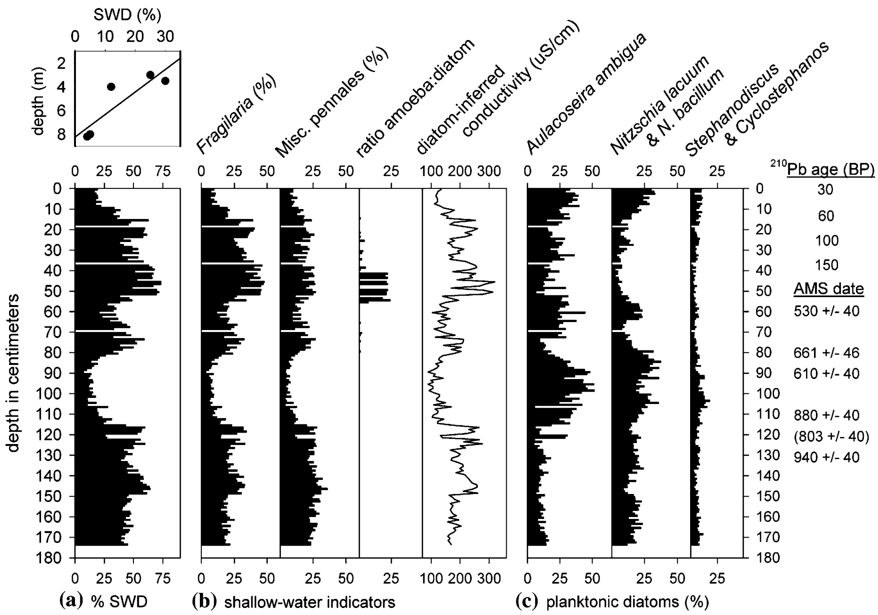

Figure 2. Major diatom taxa in core P2K-1. (a) percentages of shallow-water taxa (SWD) in fossil diatom assemblages vs. depth in 5 grab samples collected from Pilkington Bay (upper panel) and vs. depth in core P2K-1 (lower panel). (b) Shallow-water indicators, including diatoms comprising SWD, ratios of testate amoeba plates vs. diatom valves (X100), and diatom-inferred conductivity. (c) Planktonic diatoms indicating greater lake depths and reduced conductivity. Uncorrected AMS dates to the right. The selected ^{210}Pb ages shown here were based on matching of SWD peaks in core P2K-1 with those in P2K-4, which was dated by ^{210}Pb, ^{137}Cs, and AMS methods.

of the surrounding organic gyttja (unpublished data).

We chose instead to date whole sediments and then to estimate possible ancient carbon age offsets by aligning the AMS age–depth regression with ^{210}Pb- and ^{137}Cs-based regressions obtained for neighboring gravity cores that preserved the mud-water interface (Figure 3); and see below). Our chronological model for P2K-1 uses a linear age–depth relationship below the 18th century level (ca. 60 cm) constrained within 1-sigma calendar age brackets (Figure 3), which is supported by linear age–depth regressions of similar slope (6–10 years cm^{-1}) in heavily dated Holocene records from Pilkington Bay (Kendall 1969; Stager et al. 2003) and other Victoria cores (Stager et al. 1997;

Table 1. AMS dates from cores P2K-1 and P2K-4.

Depth (cm)	AMS date (1-σ)	Max–min calyr BP	Date chosen calyr BP	Sample number
P2K-1				
60–61	530 ± 40	53–344	290	Beta-153238
80–81	661 ± 46	364–506	415	AA-38997
90–91	610 ± 40	340–479	455	Beta-146902
110–111	880 ± 40	573–674	590	Beta-146903
120–121	803 ± 40	551–587	omitted	AA-38998
130–131	940 ± 40	604–697	697	Beta-146904
P2K-4				
44–45	388 ± 35	0–301	77	AA-38996

Calendar year ages relative to AD 2000 were determined with CALIB 4.4.2 (Stuiver et al. 1998) after subtraction of 330 years from the AMS ages to compensate for ancient carbon contamination (see text). Maximum–minimum calendar age intervals are based upon the 1-sigma calibrated age ranges of the adjusted AMS dates. Subsample ages below 60 cm were obtained by interpolation between AMS dates, using a 6.2 year cm^{-1} regression model. The date for the 120–121 cm subsample was omitted due to inconsistency with the linear age–depth model.

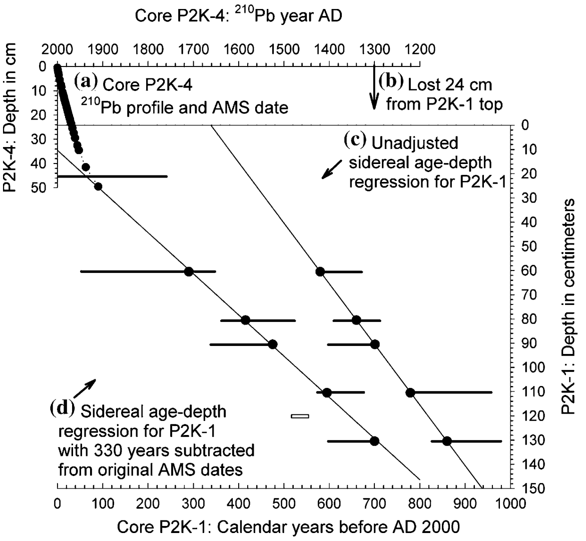

Figure 3. Basis for a 330-year ^{14}C age correction in core P2K-1. (a) Upper panel shows ^{210}Pb- and ^{137}Cs-based age–depth curve and single AMS date (horizontal bar) for gravity core P2K-4. The P2K-4 profile is steeper than that of P2K-1, primarily reflecting compression with depth but also possibly indicating increased sediment accumulation due to recent anthropogenic eutrophication and sediment inputs. (b) Comparison of diatom records among cores indicated that 24 cm were lost from the top of P2K-1; the P2K-1 age–depth chart was therefore dropped 24 cm relative to the depth scale of the P2K-4 chart. Main panel shows calendar year age–depth relationships for P2K-1 before (c) and after (d) 330 years were subtracted from the AMS dates. Linearity was assumed because heavily dated Pilkington Bay records displayed linear profiles throughout the mid- to late-Holocene (Kendall 1969; Stager et al. 2003). The unadjusted dates (c) caused the age–depth regression to meet the upper x-axis to the right of the origin, indicating loss of top sediments as well as contamination with ancient carbon. When both the lost sediment and age adjustments were applied to P2K-1, the P2K-4 age–depth profile (a) curved downwards to meet the final P2K-1 regression (d) in the ca. AD 1900 interval. Horizontal bars represent 1-sigma calendar age ranges for AMS dates. Open bar = AMS date omitted from final age–depth profile (d).

Stager and Johnson 2000), and is the most parsimonious age model in this relatively flat-bottomed site.

A slight temporal offset between the P2K-1 diatom record and those of nearby gravity cores suggested both the loss of the mud-water interface in P2K-1 during piston coring and the effect of ancient carbon on bulk radiocarbon dates. To test for surface sediment loss and radiocarbon age offsets in P2K-1, the youngest portions of its principal diatom series were compared to those of 50 cm long gravity core P2K-4, which was dated by ^{210}Pb, ^{137}Cs, and AMS methods. The diatom stratigraphy of an additional, 30 cm long gravity core (P2K-2) was similar to that of P2K-4 but was too short to include the full ^{210}Pb decay sequence and was therefore used only for general stratigraphic comparisons in this study.

Results

Chronology

Disturbance of the top of gravity core P2K-4 was indicated by low ^{210}Pb and high ^{137}Cs concentrations, but the lower sections displayed relatively smooth ^{210}Pb reductions with depth. The ^{137}Cs curve in P2K-4 was more irregular, but the lowest major peak was taken to represent AD 1963 (27–28 cm), which matched the ^{210}Pb age for that depth interval. An AMS date obtained for the basal (44–45 cm) subsample in P2K-4 (Table 1; Figure 3a) was consistent with its ^{210}Pb-inferred age. However, the wide calendar age brackets for that date were also consistent with the hypothesized radiocarbon age offset discussed below.

When aligned visually, the diatom series in gravity cores P2K-4 and P2K-2 indicated the loss of 24 cm (ca. 30 years) from the top of P2K-1. This amount is consistent with the absence of a transition to *Nitzschia*-dominated diatom assemblages in the core top that occurred in Pilkington Bay (unpublished data) and offshore during the late AD 1970's to early 1980's (Verschuren et al. 1998). The P2K-1 age–depth chart was lowered accordingly in Figure 3b to account for the 24 cm sediment loss.

Despite our correction for missing surface sediments, the regression line still met the upper x-axis far to the right of the origin (Figure 3c), as expected when radiocarbon dated organic materials are contaminated with ancient carbon. The age–depth regressions of P2K-1 and gravity core P2K-4 were brought into alignment by subtracting 330 years from the AMS dates in P2K-1 before conversion to calendar years (Figure 3d). The causes of this ancient carbon contamination are unknown, but we also obtained the same correction factor using similar methods for cores from neighboring Buvuma Channel, so it is apparently not unique to Pilkington Bay. Possible

contamination sources could include volcanic carbonatites in the watershed as well as reworked lake and swamp deposits. Applying our 330-year ^{14}C age correction to the chronology of the diatom record of Damba Channel as well (Figure 1; Stager et al. 1997, 2003) shifts low stands that were previously inferred from the channel diatom series earlier in time and brings them into conformity with those in the P2K-1 and Naivasha records. A linear, AMS age–depth relationship of 6.2 calendar years cm^{-1} was assumed in our final age model for the lowest meter of P2K-1 (Figure 3d). An apparent ^{14}C age conflict between the 80–81 and 90–91 cm samples became a temporal overlap when the dates were converted to calendar years, leaving only the 120–121 cm sample off the age–depth regression (Table 1; Figure 3d).

Paleolake level reconstruction

Inferred levels of Lake Victoria were low (conductivities high) ca. 820–760, 680–660, 640–620, 370–340 calendar years BP, and lowest of all ca. 220–150 BP (Figure 4d). Numerous testate amoeba plates, reflecting marginal wetland habitats, in combination with high %SWD and conductivities further suggest that the early 19th century was the driest period of the millennium (Figure 2b). Inferred lake levels were highest during the LIA interval, ca. 600–400 and 300–250 BP.

The SWD series in cores P2K-1, P2K-2, and P2K-4 displayed generally decreasing values after the early 20th century, reflecting a rise in planktonic diatom productivity caused by cultural eutrophication which complicated lake level inferences for the last century (Figure 4d). However, the lowest SWD values of these most recent records occurred in samples deposited during the early AD 1960's, when Lake Victoria experienced its highest levels of the century (Sutcliffe and Parks 1999; Tate et al. 2001), and a subsequent return to somewhat higher SWD percentages in the gravity cores reflected a fall in lake levels after the AD 1960's high stand (the P2K-1 series lacked this youngest time interval). Despite the limitations of this youngest part of the sediment record, the general similarities among the recent proxy and historical lake level series, the decrease of SWD concentrations with depth in Pilkington Bay surface sediments (Figure 2a), and strong internal consistency among the SWD, testate amoeba, and inferred conductivity profiles in P2K-1 (Figure 2a and b) together support our interpretation of the P2K-1 SWD series as a general indicator of decade- to century-scale rises and falls in the level of Lake Victoria during the last millenium.

Discussion

Possible sun–climate relationships

The atmospheric ^{14}C residual series (Stuiver and Brauzanias 1989) suggests that lake levels (rainfall?) increased at Lakes Victoria and Naivasha as $\delta{-}^{14}C$ rose during the LIA's Wolf, Spörer, and Maunder sunspot minima (Figure 4c–e). The indirectly dated Kilimanjaro F^{-} series, which was tuned to the Naivasha record, indicates widespread deflation of exposed soda lake deposits related to regional aridity during solar maxima (Thompson et al. 2002) that also coincided with droughts in Mexico (Hodell et al. 2001). Opposing patterns occurred in the Cariaco Basin (Haug et al. 2001), the Oman Margin (Anderson et al. 2002), and South Africa (Tyson and Lindesay 1992).

Apparent sun–rainfall linkages reversed sign, however, as severe drought developed over much of tropical Africa during the Dalton sunspot minimum, ca. AD 1800–1820 (Figure 4). Positive associations between rainfall and solar activity (sunspot numbers) also typified the late 19th and 20th centuries in the Victoria basin. Strong positive correlations between sunspot numbers and detrended Victoria levels persisted between AD 1890 and AD 1927 (0.85, $p < 0.001$; Figure 4a and b; Sutcliffe and Parks 1999; Tate et al. 2001). Reduced amplitudes and doubled frequencies of lake level fluctuations after AD 1927 caused a much-cited sign reversal and reduction in sun–lake correlations (-0.35, $p < 0.1$; Hoyt and Schatten 1997), but every second lake level pulse still coincided with a sunpot peak. We show here for the first time that positive sun–lake correlations resumed in the Victoria basin ca. AD 1968 and continued through AD 2000 (0.43, $p < 0.05$).

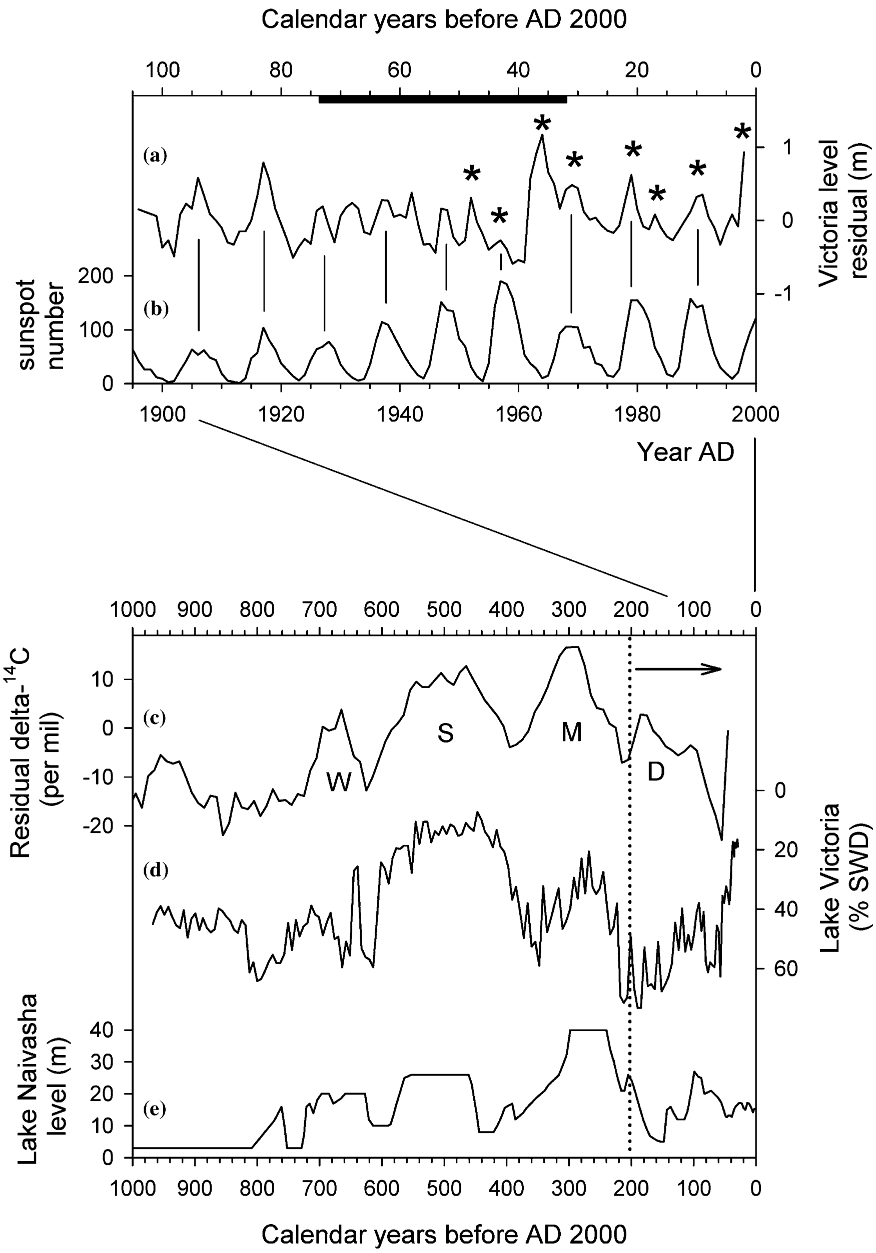

Figure 4. Upper panel: Sun–lake level relationships during the 20th century in the Victoria basin. (a) Detrended Lake Victoria levels. A strong non-linear trend and long period structure in the original lake level series (Sutcliffe and Parks 1999; Tate et al. 2001) obscure the shorter Victoria lake level oscillations that are the focus of this study. They were removed for this figure and for correlation analysis by a high-tension robust spline method that is commonly used in ice core analyses (Meeker et al. 1995). Vertical solid lines show co-occurrence of lake level rises with sunspot peaks. Black bar indicates period of reversed lake–sunspot correlations due to interspersed ENSO- and IOD-related rainfall events (see text). (b) Zürich sunspot numbers (Hoyt and Schatten 1997). Asterisks indicate Rift Valley Fever outbreaks during wet periods (Linthicum et al. 1999). Lower panel: East African sun–climate relationships since AD 1000. (c) Atmospheric ^{14}C residual series (Stuiver and Brauzanias 1989), with Wolf, Spörer, Maunder, and Dalton sunspot minima (W, S, M, and D, respectively). (d) Inverted SWD series from core P2K-1. (e) Lake Naivasha levels (Verschuren et al. 2000). Dotted vertical line and arrow mark an apparent sun–climate reversal during the Dalton sunspot minimum.

Possible causal mechanisms

The inconsistency of sun–rainfall associations in the Victoria basin and its surroundings during the last millenium calls into question the strength of assumed causal relationships, unless tropical sun–climate relationships themselves are subject to abrupt variability. Most of the rainfall variability exhibited in equatorial East African records is related to conditions within the ITCZ (Nicholson 2000). Prolonged solar irradiance increases, possibly amplified by vegetational changes, should strengthen summer low pressure systems over northern and southern Africa, thus perhaps reducing equatorial rainfall by increasing the amplitude and/or duration of the ITCZ's poleward migrations. Increased rainfall near the latitudinal limits of today's ITCZ during the equatorial droughts supports this hypothesis (Tyson and Lindesay 1992; Anderson et al. 2002).

Solar irradiance fluctuated by $<1\%$ during the last millenium (Crowley 2000), so temperature changes directly related to radiation decreases were probably small. However, weakening solar activity also increases the flux of cosmic radiation striking the upper atmosphere, potentially increasing cloud nucleation and altering storm tracks (Hoyt and Schatten 1997; van Geel et al. 2000). Solar maxima might therefore increase insolation by reducing cloudiness, as would reduced ITCZ time at the equator, thus amplifying equatorial droughts by increasing evaporation.

During the Dalton Minimum, on the other hand, severe droughts occurred in equatorial East Africa, as indicated by both paleo and cultural records (Figure 4d and e; Verschuren et al. 2000; Nicholson and Yin 2001; Thompson et al. 2002). Similarly, orbitally induced insolation decreases during the late Quaternary also generally caused drier conditions in the tropics (Kutzbach and Street-Perrott 1995), making presumed linkages between reduced insolation and East African lake high stands during much of the last millenium atypical. Evidence for long-term solar variability is widespread (Denton and Karlén 1973; Magny 1993; Hoyt and Schatten 1997; Shindell et al. 1999; van Geel et al. 2000; Hodell et al. 2001), and some have proposed that the LIA was caused by the latest pulse in a ~1,500-year solar cycle (Mayewski et al. 1997; Bond et al. 2001). One could therefore speculate that the Dalton reversal marks the end of the last pulse of the ~1,500-year cycle, or that sensitivity to solar forcing was modified by a restructuring of African climate systems around the close of the 18th century.

The decay of formerly strong, positive sunspot–lake level correlations in Lake Victoria between AD 1927 and AD 1968 (Figure 4a and b), which has led many to discount their existence (Hoyt and Schatten 1997), was due primarily to the confounding effects of intervening lake level rises during strong ENSO and IOD events, whose effects on tropical climates were themselves inconsistent throughout the 20th century (Kumar et al. 1999; Richard et al. 2000; Nicholson and Yin 2001; Conway 2002). Climate systems beyond East Africa also experienced major disruptions ca. AD 1927–1968 as well (Hoyt and Schatten 1997), suggesting that sensitivity to influences other than solar forcing may have changed then. For example, Indian rainfall was unusually high (Kumar et al. 1999), Atlantic trade winds weakened (Black et al. 1999), the Icelandic Low moved southwards (Kelly 1977), and the North Atlantic Oscillation index decreased (Jones et al. 2001).

If these apparent sunspot–rainfall linkages in this region are real, then their effects may be societally important: Lake Victoria's surface level rises during the late 20th century coincided with widespread flooding and epidemics triggered by the associated expansion of mosquito breeding habitats (Figure 4a, Linthicum et al. 1999). Further investigation of this possibility is therefore warranted.

Conclusions

The P2K-1 record shows that century-scale lake level rises in the Victoria basin during the last millenium coincided with similar changes in the Naivasha record, thus resolving previous temporal conflicts between the two sites. Several of the largest rises also coincided with solar activity reductions. However, these apparent sun–rainfall relationships reversed sign during the Dalton Minimum, and recent positive sunspot–lake level correlations suggest that the post-Dalton pattern remained typical of hydrological variability in the Victoria basin through the end of the 20th century. If such variable linkages between lake levels and

solar activity are not merely fortuitous, then they suggest that sun–climate linkages in this region have been subject to abrupt sign reversals.

Acknowledgements

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Supplementary information available

Supplementary information to this article can be found in the journal contents on http://www.kluweronline.com/issn/0921-2728/.

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