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Sunspots, El Niño, and the levels of Lake Victoria, East Africa

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[1] An association of high sunspot numbers with rises in the level of Lake Victoria, East Africa, has been the focus of many investigations and vigorous debate during the last century. In this paper, we show that peaks in the ~11-year sunspot cycle were accompanied by Victoria level maxima throughout the 20th century, due to the occurrence of positive rainfall anomalies ~1 year before solar maxima. Similar patterns also occurred in at least five other East African lakes, which indicates that these sunspot-rainfall relationships were broadly regional in scale. Although irradiance fluctuations associated with the sunspot cycle are weak, their effects on tropical rainfall could be amplified through interactions with sea surface temperatures and atmospheric circulation systems, including ENSO. If this Sun-rainfall relationship persists in the future, then sunspot cycles can be used for long-term prediction of precipitation anomalies and associated outbreaks of insect-borne disease in much of East Africa. In that case, unusually wet rainy seasons and Rift Valley Fever epidemics should occur a year or so before the next solar maximum, which is expected to occur in 2011–2012 AD.

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1. Introduction

[2] Paleoclimate records offer abundant evidence that variability in the amount of energy emitted by the Sun has significantly affected climates in and around East Africa during much of the late Quaternary. Sediment cores suggest a solar origin for the desiccation of Lake Victoria ~15,000 years ago [*Stager et al.*, 2002], speleothem records from Oman show that rainfall there increased with solar activity between 9600 and 2700 years ago [*Neff et al.*, 2001; *Fleitmann et al.*, 2003], solar signals appear in Arabian Sea monsoonal records [*Jung et al.*, 2002; *Staubwasser et al.*, 2002; *Gupta et al.*, 2005], and Holocene rhythmites from lakes Magadi and Tanganyika display periodicities similar to those of the ~11-year sunspot cycle [*Damnati and Taieb*, 1995; *Cohen et al.*, 2006]. During the last millennium, the levels of lakes Naivasha and Victoria fluctuated in concert with changes in atmospheric radiocarbon concentrations that were probably driven by solar variability [*Verschuren et al.*, 2000; *Stager et al.*, 2005]. Coral records of recent Indian Ocean sea surface temperatures display significant ~11-year periodicities [*Cole et al.*, 2000; *Charles et al.*, 1997], as do Nile flood heights [*Hameed*, 1984], Oman speleothem records [*Fleitmann et al.*, 2003], and both Ethiopian and Indian rainfall series [*Wood and Lovett*, 1974; *Bhattacharyya and Narasimha*, 2005]. Solar cycles of ~88 and 200-year duration are also present in the Nile flood record [*Ruzmaikin et al.*, 2006].

[3] Paleoclimatic evidence for solar influences on climates is also common in regions outside of Africa. A comprehensive survey is beyond the scope of this paper but we list several examples here: irradiance disruptions have been linked to droughts in Central America [*Hodell et al.*, 2001], lake level changes in Switzerland [*Magny*, 1993], ice rafting in the North Atlantic [*Bond et al.*, 2001], and various climatic changes over Scandinavia [*Karlén and Kuylenstierna*, 1996], Greenland [*Mayewski et al.*, 1997], Chile [*van Geel et al.*, 2000], North America [*Anderson*, 1992], and China [*Wang et al.*, 2005].

[4] In light of these findings, one might also expect to find solar variability influencing East African weather today. However, suggestions that sunspot-climate links occur in modern times have often been met with skepticism [*Hurst*, 1952; *Pittock*, 1978; *Hoyt and Schatten*, 1997; *Foukal et al.*, 2006]. These reactions generally stem from the temporal intermittency of Sun-climate relationships, a lack of understanding about causal mechanisms, politicized skeptics who attribute current global warming to solar forcing alone, and the seemingly overwhelming influence of El Niño on East African precipitation [e.g., *Nicholson*, 2000]. However, recent studies clearly show that the solar cycle influences stratospheric and tropospheric weather systems, thereby providing a new conceptual framework within which to reconsider the evidence for solar influences

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on climate [*Labitzke and van Loon*, 1997; *Svensmark and Friis-Christensen*, 1997; *Raspopov et al.*, 1998; *Shindell et al.*, 1999; *Haigh*, 2001; *Kodera and Kuroda*, 2002; *Rind*, 2002; *Ruzmaikin and Feynman*, 2002; *Gleisner and Thejll*, 2003; *Coughlin and Tung*, 2004; *Higginson et al.*, 2004; *van Loon et al.*, 2004].

[5] In this paper, we present strong evidence that decadal solar variability does indeed influence modern East African rainfall, by examining historical records of sunspot numbers, precipitation, and the levels of East African lakes during the 20th century. We focus primarily on the following questions: (1) What is the relationship between rainfall and the levels of Lake Victoria? (2) What sunspot-lake and sunspot-rainfall associations existed in East Africa during the 20th century? (3) How might solar variability influence East African rainfall?

2. Historical Background

[6] Relationships between sunspot numbers and the levels of Lake Victoria have been presented as examples of both the reality and the nonexistence of Sun-climate connections. Because that conflicted legacy continues to complicate discussion of the topic, we summarize major features of it here.

[7] *Brooks* [1923] was among the first to describe an association between the levels of Lake Victoria and the abundance of sunspots associated with the ~11-year solar cycle. Strong positive correlations (~0.9) between lake surface levels and sunspot numbers spanned the period from 1896 to 1922 AD at Lake Victoria, and a similar but weaker relationship was also found for Lake Albert (Figure 1). For a time, the case of Lake Victoria was considered to be a classic example of solar influences on lake level fluctuations.

[8] After circa 1927 AD, however, these Sun-lake correlations weakened and reversed sign because additional lake level rises developed during intervening sunspot minima. As a result, later papers purported to show, albeit with some exceptions [*Cochrane*, 1964], that the presumed Sun-lake connection was simply a misleading statistical artifact [*Walker*, 1936; *Hurst*, 1952; *Hoyt and Schatten*, 1997].

[9] Published spectral analyses have offered little or no evidence of decadal signals in East African rainfall patterns, and shorter periodicities associated with El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole events [*Saji et al.*, 1999] explain much of the region's high-frequency rainfall variability during the 20th century. These events tend to warm western Indian Ocean sea surface temperatures and contribute to positive rainfall anomalies in East Africa [*Rodhe and Virji*, 1979; *Nicholson*, 2000; *Mistry and Conway*, 2003; *Behera et al.*, 2005]. In this context, the possibility of significant solar forcing has been virtually ignored in many, though not all [*Mason*, 1993, 1998, 2006], of the recent climatological studies in this region.

[10] Newer observational data from Lake Victoria [*Sutcliffe and Parks*, 1999] now show that a striking correspondence between peaks in sunspot numbers and lake level pulses recommenced circa 1968 AD (Figure 2). Visual examination of the record reveals a close association of solar maxima with lake level pulses throughout the century. Even between circa 1927 and 1968 AD, when additional lake pulses between solar maxima canceled the Sun-lake correlations, every sunspot peak coincided with a rise in the level of Lake Victoria (Figure 2).

[11] The same Sun-lake relationship probably existed before the 20th century, as well; reconstructions of Victoria levels derived from anecdotal reports and from Nile discharge records [*Tate et al.*, 2001] suggest that moderate to large lake level pulses also coincided with the solar maxima of 1883–1884 and 1893–1894 AD.

[12] This relationship is complicated by a lack of correspondence between the relative magnitudes of sunspot and lake level maxima, and by the sporadic development of additional lake level rises that were not clearly related to solar variability. As a result, simple linear correlations between sunspot numbers and lake levels during the 20th century as a whole are low. Only when broken down into shorter time periods, such as individual sunspot pulses (Table 1) or the first and last 30-year subsets of the detrended lake level series (r-squared 0.60 and 0.27, respectively), do linear correlations seem to support the visually obvious connection.

3. Rainfall and Lake Levels

[13] We now describe Lake Victoria's physical and climatic setting in order to show how its surface levels respond to regional rainfall patterns.

[14] The lake is located astride the equator (Figure 1) and is enormous but relatively shallow (SA = ~68,000 km^2, max. depth ~80 m [*Crul*, 1995]). The largest tributary is the Kagera River, which drains 60,000 km^2 of the Ruanda-Burundi highlands, and the only major outflow exits through the Nile outlet at Jinja, Uganda. Most of Lake Victoria's water enters and leaves via the atmosphere [*Piper et al.*, 1986]. The Owen Falls (Nalubaale) dam was built in the mid-1950s AD on the Nile outlet, and was managed so as to have negligible effects on 20th century lake levels [*Kite*, 1981], though that practice was discontinued recently [*Mugabe and Kisambira*, 2006].

[15] Most precipitation in the region is associated with the seasonal passage of the Intertropical Convergence Zone (ITCZ) during the so-called "long rains," in March–May, and the "short rains of October–December. NCEP-NCAR reanalysis [*Kalnay et al.*, 1996] suggests that precipitation in the Victoria watershed derives primarily from the southern Indian Ocean, but Atlantic Ocean moisture also enters from the Congo basin [*Latif et al.*, 1999; *Nicholson*, 2000]. In addition, a thermally driven nocturnal convection cell over the lake recycles an important but as yet unquantified fraction of the annual precipitation inputs [*Flohn and Burkhardt*, 1985].

[16] Hydrological modeling shows that the levels of Lake Victoria are determined primarily by the amount of rain falling within the catchment [*Nicholson et al.*, 2000; *Nicholson and Yin*, 2001; *Tate et al.*, 2004]. For example, a major lake level rise after 1961 AD (Figure 3) was initiated by unusually heavy and prolonged, continent-wide precipitation [*Grove*, 1998]. The sustained high levels that followed were probably due to rainfall increases associated with increased Indian Ocean Dipole activity and reduced evaporation related to global insolation declines [*Conway*, 2002; *Wild et al.*, 2005].

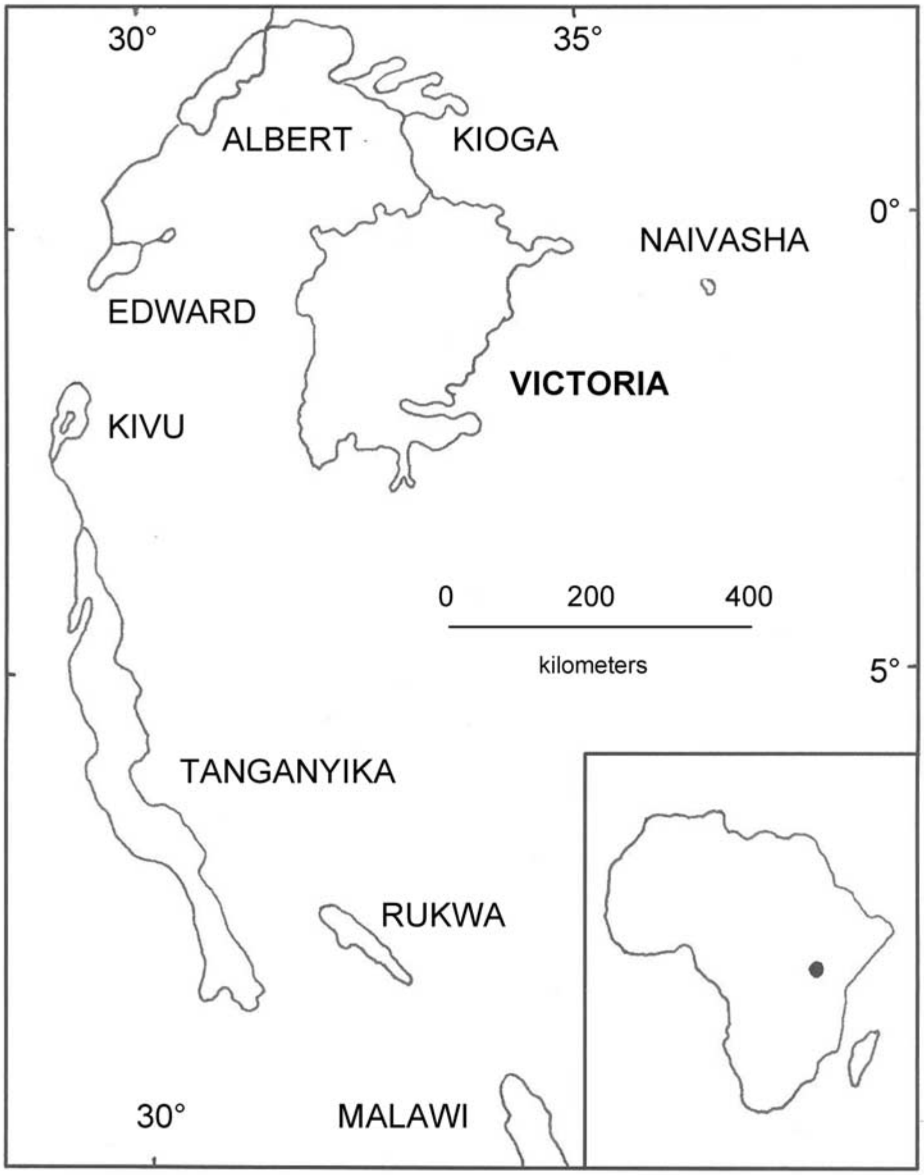

Figure 1. Map of East Africa showing lakes mentioned in this study. Inset shows Africa, with location of Lake Victoria indicated.

[17] The relationship between rainfall and lake levels, however, is complex, and their correlation for the entire 20th century was only 0.4 [*Mistry and Conway*, 2003]. Because solar influences are transmitted to lake levels through rainfall, this might help to explain why sunspot-lake level correlations are not stronger. Much of this complexity stems from the sheer size of the watershed, as a short subset of the monthly rainfall series illustrates (Figure 4) [*Conway*, 2005]. Between 1910 and 1920 AD, the lake tended to rise immediately in response to precipitation on its surface but more slowly and significantly, with lags on the order of 1–2 years, to delayed runoff from the watershed. Such delays, during which evaporation could significantly influence water budgets, also contributed to differences in the relative magnitudes of rainfall and lake level fluctuations. In addition, the two annual rainy seasons affected the lake differently, with the long rains (March–May) producing larger lake pulses, on average, than the short rains did (October–December).

[18] Although decade-scale oscillations in the levels of Lake Victoria primarily reflect localized rainfall inputs (Figure 3), they are also indicative of precipitation patterns over a much wider area. During the last 50 years, for example, all of Kenya's major outbreaks of Rift Valley Fever, which are triggered by heavy rains that increase mosquito breeding habitats, coincided with pulses in the level of Lake Victoria (Figure 5, asterisks) [*Linthicum et al.*, 1999]. Concurrent multiyear pulses also occurred in the levels of Lakes Tanganyika and Naivasha (Figure 5), as well as in Lakes Turkana, Albert, and Malawi [*Brooks*, 1923; *Verschuren*, 2003], despite markedly disparate long-term trends, and rainfall in the Ethiopian highlands increased

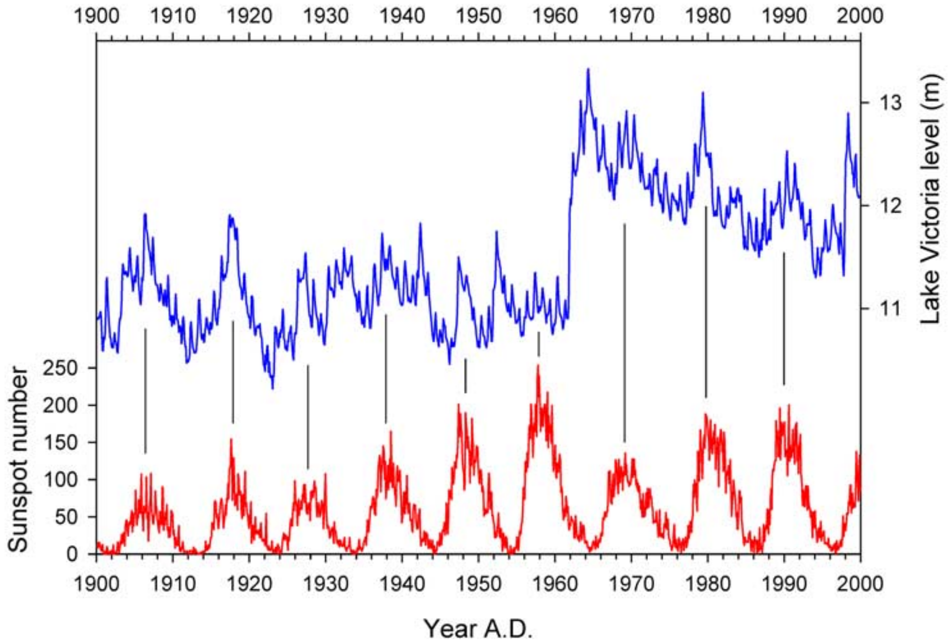

Figure 2. Monthly levels of Lake Victoria measured at Jinja, Uganda [*Sutcliffe and Parks*, 1999], and monthly sunspot numbers during the 20th century.

during sunspot peaks between 1900 and 1970 AD [*Wood and Lovett*, 1974].

[19] In summary, because changes in the levels of Lake Victoria generally reflect rainfall patterns within the catchment, and because most lakes in the region display similar short-term lake level changes, we conclude that the Victoria lake level series accurately records the pace, if not necessarily the exact magnitudes, of decade-scale precipitation fluctuations over most of East Africa during the 20th century.

4. Solar-Type Signals at Lake Victoria

[20] To better discuss the relative timing of maxima in rainfall, lake levels, and sunspot numbers, the most prominent decade-scale pulses in the Victoria lake level series are numbered sequentially in Figure 6. Their approximate dates are also listed in Table 2, along with those of rainfall and sunspot peaks and of potentially relevant El Niño and Indian Ocean Dipole events.

[21] All nine of the 20th century's sunspot maxima coincided with multiannual lake level pulses, a visually prominent pattern upon which most debate over Sun-lake associations centers (Figures 2 and 6). Pulses 4, 6, 8, 10, 13, and 15 occurred outside of the sunspot maximum envelopes (Figure 6 and Table 2) and are attributable to known El Niño and/or Indian Ocean Dipole events. Lake pulses 4, 6, 8 and 10 were most directly responsible for the decay of Sun-lake correlations in midcentury.

[22] Figure 7 shows that the co-occurrence of lake level pulses with all nine sunspot peaks of the 20th century (numbered bold in Table 2) resulted from a variably lagged relationship between sunspot numbers and rainfall in which the precipitation maxima that caused major lake pulses usually preceded sunspot peaks by about a year. A similar tendency for positive rainfall anomalies to slightly precede sunspot peaks existed in Ethiopia during the 20th century, as well [*Wood and Lovett*, 1974].

[23] Figure 7 also illustrates the relatively loose relationships between the magnitudes, and sometimes even the timing, of El Niño fluctuations and their associated rainfall disruptions in East Africa, which weakens linear correlations between them (the NINO4 index is used here to represent ENSO activity because it is more strongly correlated with climatic parameters in much of East Africa than other indices are [*Plisnier et al.*, 2000]). We mention this complexity in the widely accepted ENSO teleconnection because, in our experience, similar inherent nonlinearities in sunspot-lake level relationships are sometimes believed to negate the existence of Sun-climate linkages.

[24] Fourier-based spectral analyses of rainfall series from the Victoria watershed, including our own (not shown), do not reveal highly significant power in the 11-year band [*Rodhe and Virji*, 1979; *Vincent et al.*, 1979]. However, Figure 7 shows that sunspot cycles consistently overlaid multiannual rainfall maxima with a 1–2 year phase lag. This demonstrates that decadal patterns are indeed present within precipitation time series in the Victoria watershed.

Table 1. Correlations for Lake Victoria Levels Versus Sunspot Numbers During the First and Last Three Solar Cycles of the 20th Century

Solar Cycle Number	Period (AD)	Correlation R^2	Correlation P Value
14	1902–1913	0.72	0.0005
15	1913–1923	0.86	<0.0001
16 (partial)	1923–1927	0.75	0.008
20 (partial)	1969–1976	0.91	<0.0001
21	1976–1986	0.46	0.0003
22	1986–1996	0.60	0.0001

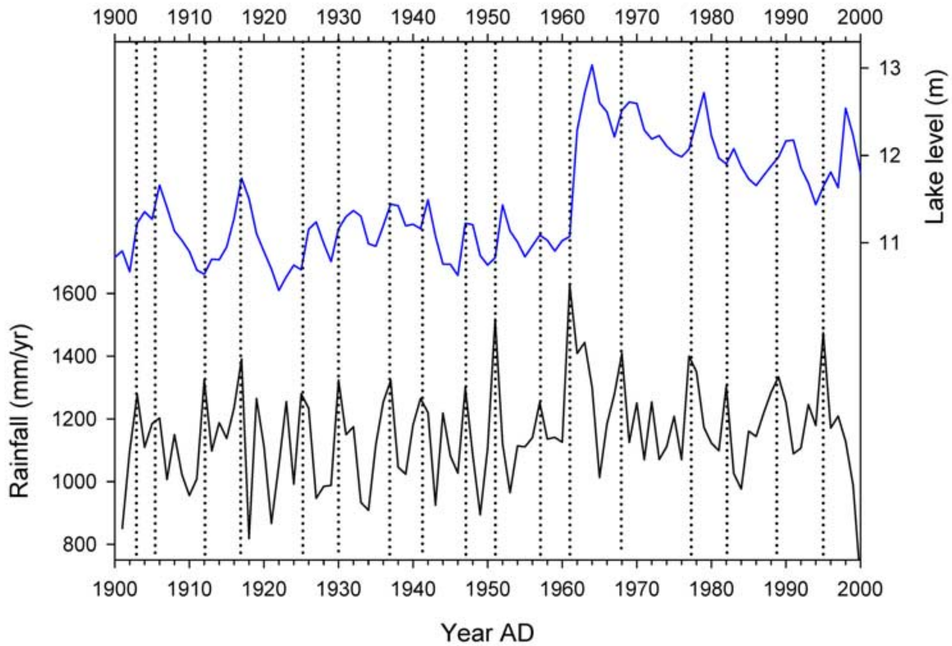

Figure 3. Mean annual Victoria lake levels and rainfall with 3-year smoothing. Dotted lines indicate the peaks of high-rainfall episodes that were responsible for the major lake level pulses.

The difficulty in detecting them with linear correlations or Fourier-based spectral analyses can be attributed to instability in the strength and timing of solar influences on climates as well as to the confounding effects of higher-frequency signals, chaotic "noise," and the anomalously wet 1961–1964 AD period.

[25] To help bypass the tendency of high-frequency and nonstationary oscillations to reduce the power of decadal periodicities, and to reveal the time dependence of the spectral content, we subjected the monthly rainfall, NINO4 index, and lake level records of the 20th century to wavelet analysis, which better captures the time-varying nature of periodicities (Figure 8; wavelet software courtesy of C. Torrence and G. Compo, http://paos.colorado.edu/research/wavelets/).

[26] Our results show that the precipitation series is dominated by the overwhelming influence of annual rainy season cycles (Figure 8). The NINO4 index displays

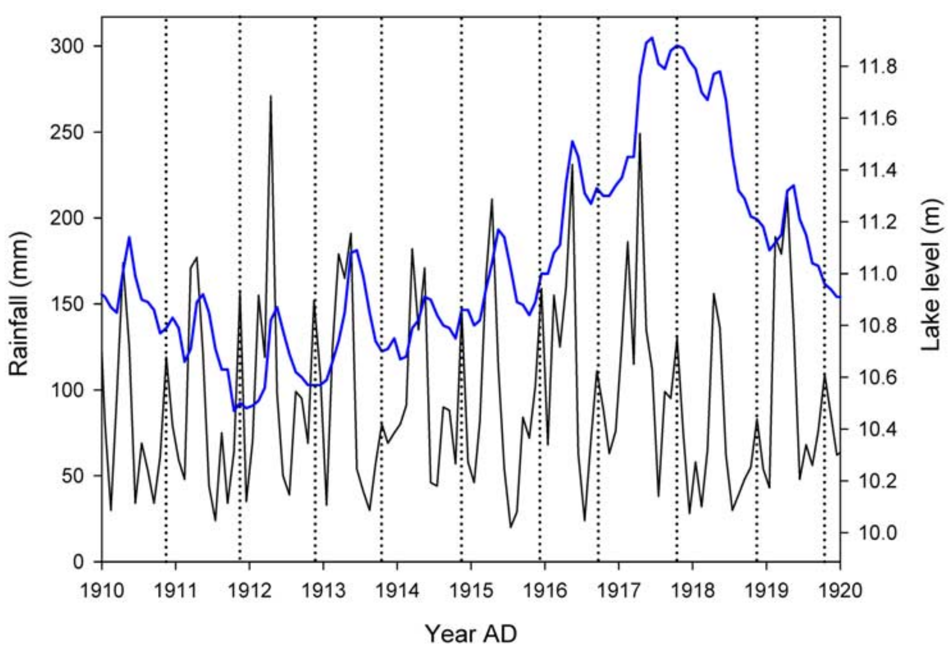

Figure 4. Monthly levels of Lake Victoria (blue) and rainfall in the watershed (black) between 1910 and 1920 AD. Dotted vertical lines indicate October–December "short rains," which appear to have had less immediate effects on lake levels than the March–May "long rains" (not marked).

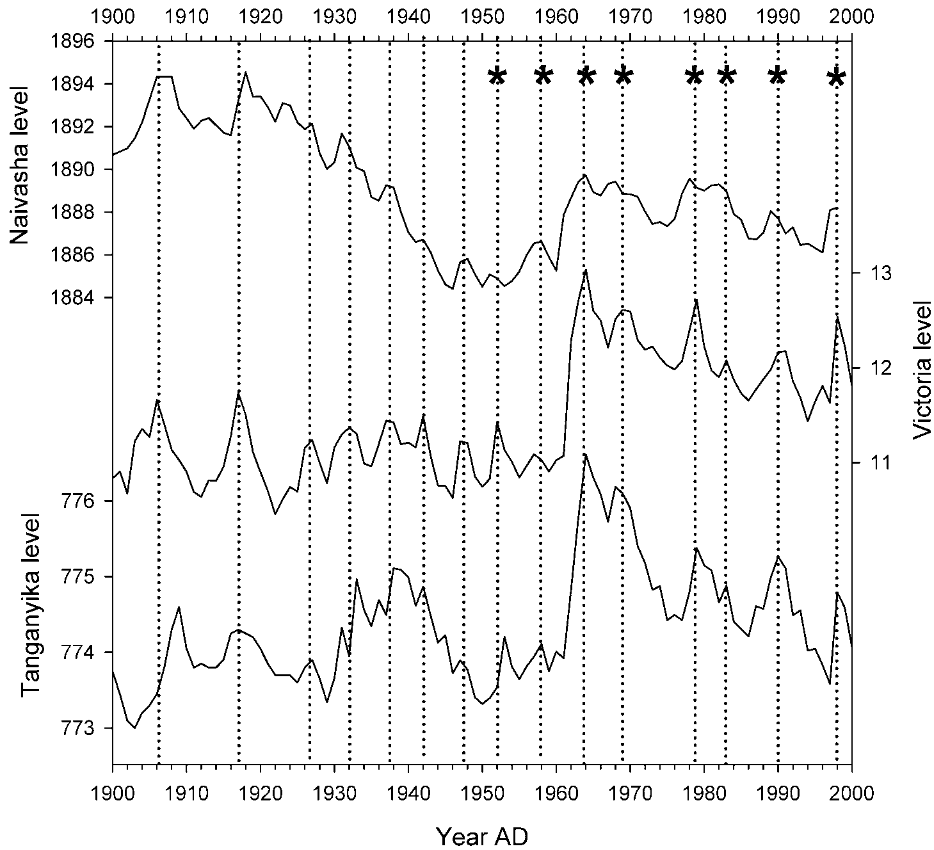

Figure 5. Mean annual levels of Lakes Naivasha, Victoria, and Tanganyika during the 20th century. Dotted lines show the synchrony of multiannual lake level pulses among the three lakes despite notable differences in longer-term trends. Asterisks indicate major outbreaks of Rift Valley Fever, which lagged rainfall peaks much as lake levels did [*Linthicum et al.*, 1999]. Victoria and Naivasha data courtesy of J. Sutcliffe and R. Becht, respectively.

significant power in the classic ENSO frequency range and also in the decadal, sunspot-type range. The monthly lake level series displays significant power in the decadal sunspot band as well as at lower frequencies. We therefore conclude that the visually obvious association of lake level pulses with sunspot cycles reflects a statistically significant relationship, as well.

5. Seasonality of Rainfall Anomalies

[27] Comparison of monthly values in the Victoria rainfall series that represent different phases of the solar cycle shows that precipitation varied significantly with solar irradiance only during rainy season months. Mean October rainfall ("short rains") in the full 20th century time series was heavier in 5-year windows centered on solar maxima (92 versus 78 mm) than in windows centered on solar minima; no other statistically significant differences were found using 5-year windows. With shorter, 3-year windows, mean November rainfall ("short rains") was higher immediately following solar maxima (138 versus 112 mm), and mean March rainfall ("long rains") was higher immediately preceding solar maxima than at other times (154 versus 132).

[28] The rainfall anomalies that were responsible for Victoria's decadal Sun-lake association often began with an enhancement of the duration and intensity of the October–December rains, which is consistent with earlier observations that much of the region's precipitation variability is due to fluctuations in the duration or intensity of the short rains [*Nicholson*, 2000]. In addition, these analyses suggest that solar variability influences East African precipitation through changes in the ITCZ, which only comes to the region during the two annual rainy seasons.

[29] NCEP-NCAR rainfall reconstructions show that rainy season precipitation over East Africa was heavier than usual during 2-year time blocks positioned on, and 1 year before, the peaks of solar cycles 19–22, and that positive rainfall anomalies during March–May were more widespread and pronounced than those during October–December (Figure 9). Positive March–May rainfall anomalies also occurred in the vicinities of lakes Turkana, Albert, Naivasha, Tanganyika, and Malawi, all of which displayed short-term level fluctuations similar to those of Victoria during the 20th century.

[30] From these findings, we conclude that (1) the Victoria lake level series displayed oscillations with periods, timing, and signs similar to those of the sunspot cycle during the

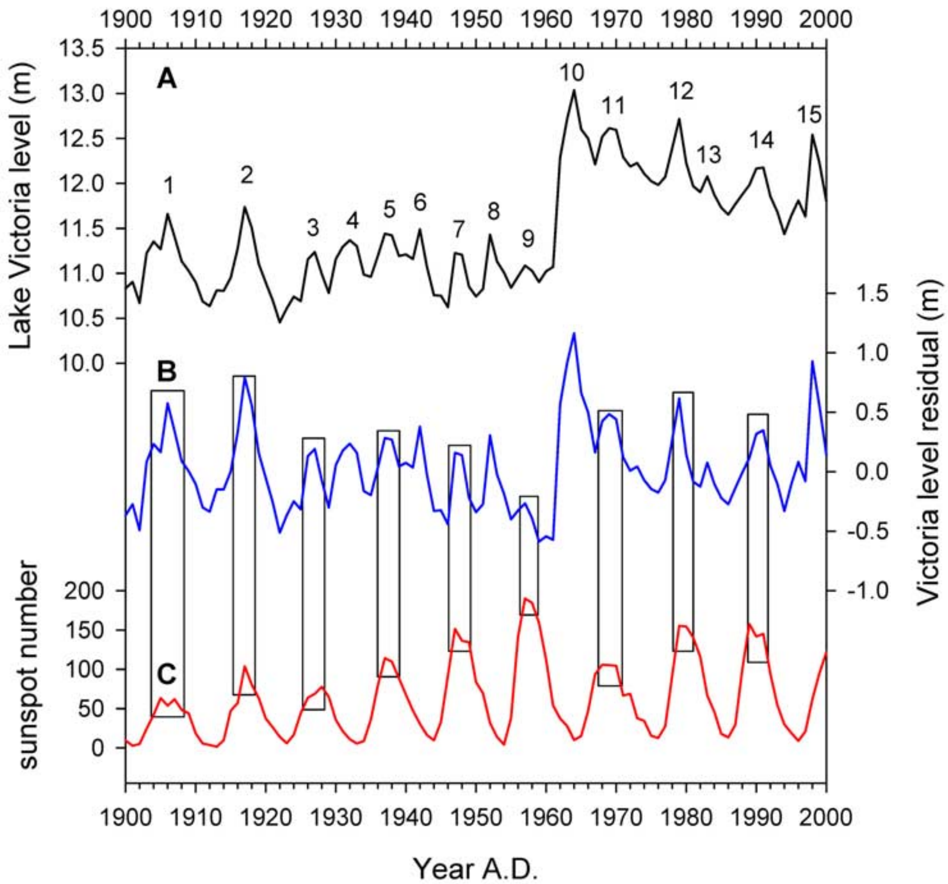

Figure 6. (a) Mean annual levels of Lake Victoria with pulses 1–15 labeled. (b) Victoria lake level residuals with long-term trend removed. (c) Annual sunspot number (SSN).

20th century; (2) the rainfall increases that triggered the Sun-coincident lake level pulses occurred during or shortly before sunspot peaks; and (3) rainfall anomalies were usually most pronounced during the March–May long rains.

6. Possible Causal Mechanisms

[31] It is beyond the scope of this paper to conclusively identify causal mechanisms behind the sunspot-rainfall associations in and around the Lake Victoria basin. However, we will now outline several ways in which weak decadal solar irradiance changes [*Lean and Rind*, 1998] could, in theory, trigger significant tropical rainfall anomalies.

[32] Perhaps the simplest mechanism would be the additive amplification of small thermal effects. Solar warming of land or water surfaces could enhance local convection and precipitation over the Victoria catchment. In addition, solar maxima slightly warm the troposphere over most of the planet [*Coughlin and Tung*, 2004]; by increasing marine evaporation and the moisture retention capacity of the air, this could raise the water vapor content of onshore winds that blow over East Africa. Higher humidity, in turn, could increase rainfall within the ITCZ and simultaneously reduce evaporation, thereby raising lake levels. Solar maxima can also intensify Hadley circulation within the ITCZ and deepen the landward penetration of African monsoons [*van Loon et al.*, 2004]. Because solar maxima reduce cosmic ray fluxes, they might also reduce cloud cover, thus increasing insolation on land and sea surfaces [*Svensmark and Friis-Christensen*, 1997; *Carslaw et al.*, 2002].

[33] Higher sea surface temperatures (SST) in the western Indian Ocean tend to increase rainfall over equatorial East Africa, particularly during El Niño and Indian Ocean dipole events that disrupt zonal SST gradients in the tropical oceans [*Nicholson and Kim*, 1997; *Nicholson*, 2000; *Black et al.*, 2003; *Mistry and Conway*, 2003]. Solar variability might likewise affect tropical SSTs through direct ocean heating and/or disruptions of atmospheric circulation systems. For example, *White et al.* [1997] have shown that warm SST anomalies occur in the tropical Indian and Atlantic Oceans shortly after solar maxima, causing SST oscillations as high as 0.15–0.30°K through direct heating alone. In addition, ∼11 year periodicities in Indian Ocean coral records [*Cole et al.*, 2000; *Charles et al.*, 1997] provide additional evidence that solar cycle influences on tropical SSTs could have contributed to decadal rainfall variability in East Africa during the 20th century.

[34] We have already shown that most of the decadal rainfall maxima in the Victoria watershed and elsewhere in East Africa preceded sunspot peaks by a year or so. Therefore, if direct, cyclic solar heating of tropical oceans was their primary cause, then it seems that each rainfall

Table 2. Dates of Victoria Lake Level Peaks, With Potentially Related Rainfall Pulses, Sunspot Maxima, and ENSO (NINO4) and Indian Ocean Dipole (IOD) Excursions

Lake Peak	Lake	Rainfall	Sunspots	NINO4	IOD
1	1906–1907	1905–1906	1905–1907	1904–1905	1905–1906
2	1917–1918	1916–1917	1917–1919	1912–1914	1913–1915
3	1926–1927	1925–1926	1927–1929	1925	1923–1925
4	1931–1933	1930–1932	no sunspot peak	1929–1930	no IOD peak
5	1937–1938	1935–1937	1937–1939	1935–1936	1934–1935
6	1942	1941–1942	no sunspot peak	1939–1941	1939, 1941
7	1947–1948	1947	1947–1949	1946	1946
8	1952	1951	no sunspot peak	1951	1949, 1951
9	1957–1958	1957	1957–1959	1957–1958	no IOD peak
10	1962–1966	1961–1964	no sunspot peak	1960, 1963	1961–1963
11	1968–1970	1967–1968	1968–1970	1968–1969	1966–1967
12	1978–1980	1977–1978	1979–1981	1976–1977	1976–1977
13	1983	1982	no sunspot peak	1982–1983	1982
14	1990–1991	1987–1990	1989–1991	1986–1987	1985–1988
15	1998–1999	1997	no sunspot peak	1997	1997

[a]Bold numbers indicate sunspot peaks of the 20th century.

peak might have to have been caused by insolation maxima that occurred nearly a decade earlier (see above). However, we are doubtful that solar SST anomalies could persist that long in the Indian Ocean. Alternatively, marine warming might somehow have increased East African rainfall 2–3 years before peak SSTs were reached.

[35] Recent studies of solar influences on atmospheric circulation show that solar variability affects high-altitude winds through the absorption of ultraviolet (UV) radiation by ozone, and that stratospheric disturbances can be transmitted to ground levels [*Baldwin and Dunkerton*, 1998; *Coughlin and Tung*, 2004]. *Hameed and Lee* [2005] found that stratospheric perturbations are more likely to reach the Earth's surface during solar maxima than during solar minima. *Ruzmaikin et al.* [2006] suggested that meridional SST gradients in the Indian Ocean are influenced by the North Atlantic Oscillation (NAO), particularly during periods of high solar activity when the NAO's effects are felt on a more hemispheric scale and persist for longer periods [*Kodera*, 2003]. Variations in UV flux modulate fluctuations in stratospheric ozone and temperature gradients which influence interactions between zonal winds and planetary waves. These, in turn, affect the Northern Annular Mode and the associated NAO [*Limpasuvan and Hartmann*, 2000]. During negative phases of the NAO, an anomalous ascending airflow in the upper troposphere prevails over equatorial East Africa, which leads to wetter conditions there. This mechanism may have contributed to unusually high water levels at lakes Naivasha and Victoria during the Maunder Minimum [*Verschuren et al.*, 2000; *Stager et al.*, 2005], when the NAO was primarily negative [*Ruzmaikin et al.*, 2004].

[36] Solar activity might further influence tropical SST and climates by altering oceanic high-pressure cells. The

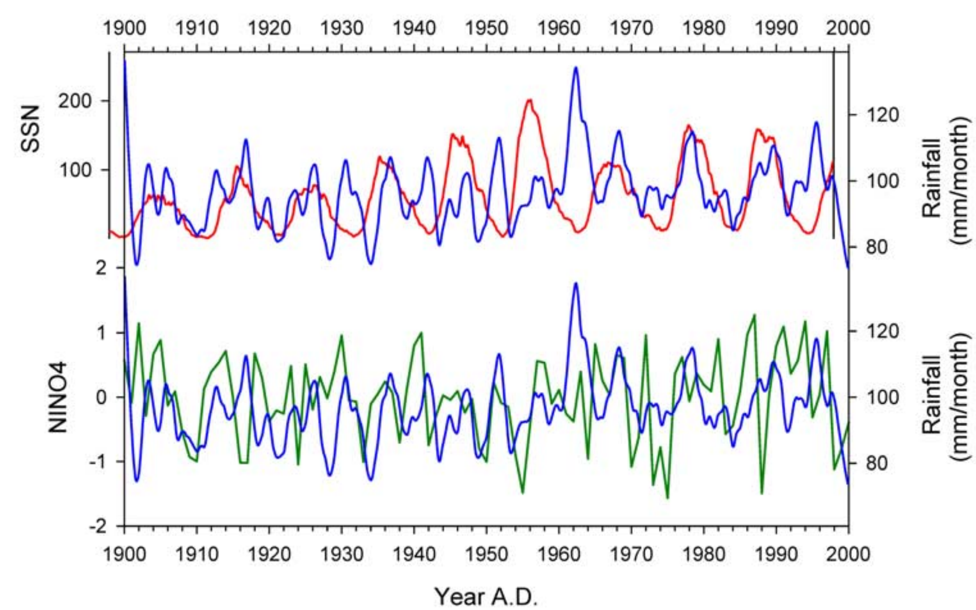

Figure 7. Sunspot numbers (red; SSN) and NINO4 index (green) with 2 year smoothing, versus monthly rainfall (blue). In the top plot, SSN series is shifted 2 years earlier in time relative to rainfall.

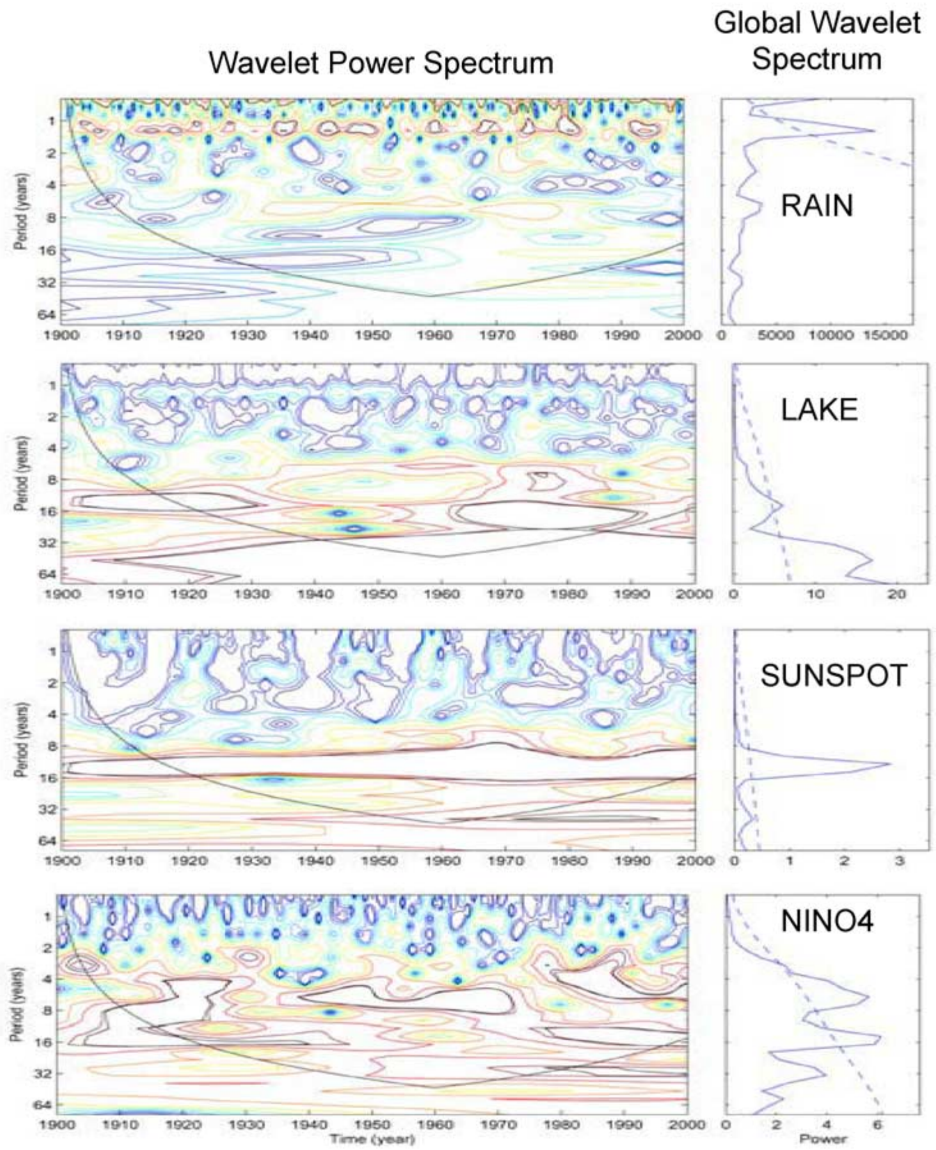

Figure 8. Wavelet power diagrams of monthly rainfall, lake levels, sunspot numbers, and October–December NINO4 index. The complex Morlet wavelet is used here, and data were normalized by their variance. Red contours correspond to higher levels and blue contours to lower levels. Solid curves on the right plots show the integral wavelet power; dashed curves show the 95% significance level over red noise background. For more detail on methods, see *Torrence and Compo* [1998].

southwestern Indian Ocean High and South Atlantic High produce trade winds that bring marine moisture to the ITCZ over Africa. Strengthened highs are associated with clearer skies (more insolation) over moisture source regions of the southern oceans, which could increase evaporation into onshore winds. Winds spinning off a strengthened Indian Ocean High could hasten the delivery of warm tropical waters into the southern Indian Ocean, thus raising SSTs there, and winds from the South Atlantic High can work against westward flow of the warm Agulhas Current around the tip of southern Africa. Finally, stronger highs can contribute to more vigorous circulation within the ITCZ which, in turn, can increase convective rainfall during the tropical rainy seasons.

[37] The latitudinal positions and strengths of the Indian Ocean and South Atlantic Highs in June–August were significantly correlated with solar activity between 1967 and 1995 AD (Table 3) [*Hameed and Piontkovski*, 2004]. Although the positions of the highs showed no obvious relationship to rainfall over Lake Victoria, their strengths in June–August did. Atmospheric pressure within the Indian Ocean High was positively correlated with precipitation during subsequent October–December rainy seasons ($r = 0.31$, $P = 0.090$), and pressure within the South Atlantic High was correlated with precipitation during the preceding March–May rainy seasons ($r = 0.44$, $P = 0.012$).

[38] Finally, we consider possible interactions between solar variability and the ENSO system itself. The mean

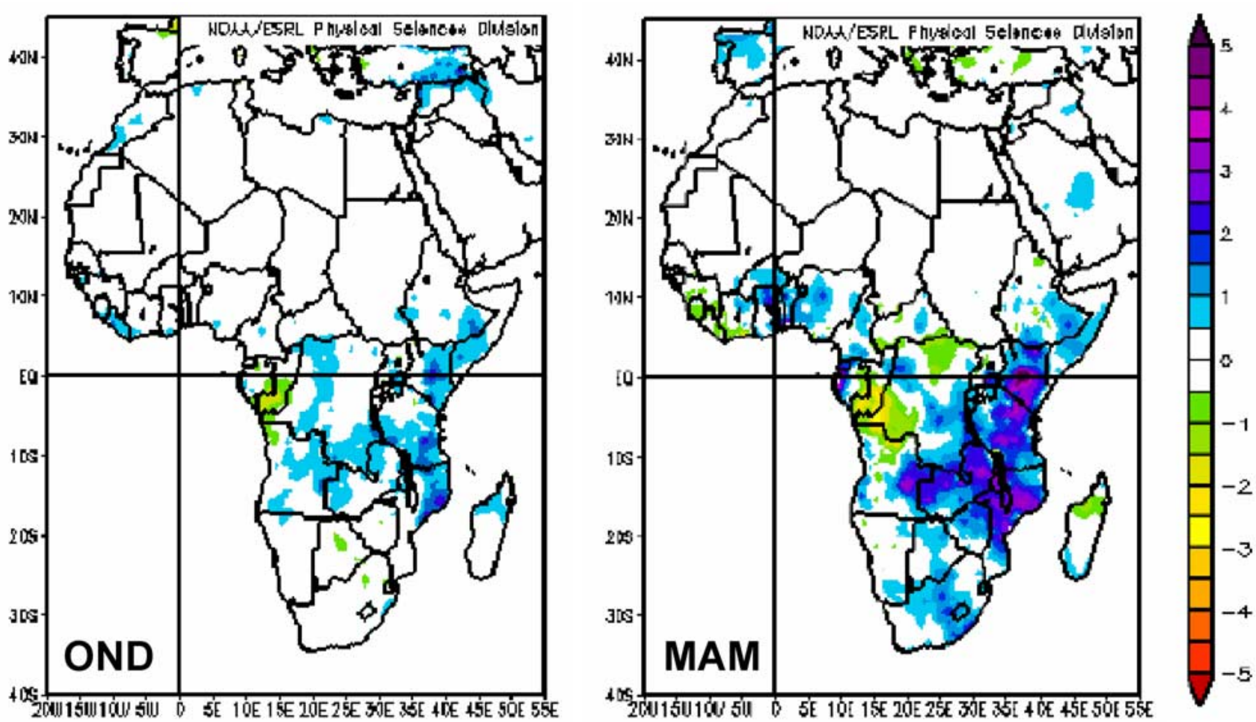

Figure 9. University of Delaware data [*Legates and Willmott*, 1990] showing that (left) October–December and (right) March–May rainfall in East Africa was heavier than average 0–1 years before solar maxima between 1950 and 1996 AD. Dark blue to purple colors indicate strong positive anomalies. Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado Web site (http://www.cdc.noaa.gov/).

frequency of El Niño occurrences (~5.5 years) is roughly twice that of the solar cycle, and ~11-year periodicities also exist within the ENSO system (Figure 8) [*Cole et al.*, 2000]. Others have, in fact, already suggested the existence of significant teleconnections between ENSO, solar variability, and the Afro-Asian monsoon system [*Higginson et al.*, 2004; *Fink*, 2005].

[39] We cannot rule out the possibility that interactions among solar variability, El Niño, and Indian Ocean Dipole disturbances caused decadal patterns in East African lake level variability. For example, *Higginson et al.* [2004] showed that El Niño events tend to occur ~2–3 years before and after sunspot peaks, producing a mean periodicity with roughly half the wavelength of the solar cycle. Presumably, while El Niños and associated IOD episodes act as the primary mechanisms for the delivery of SST-linked rainfall anomalies to East Africa, the solar cycle might modulate the frequency of their occurrence through stochastic resonance between the 5.5 and 11-year variations [*Ruzmaikin*, 1999], possibly by warming SSTs in the tropical oceans and/or by altering atmospheric circulation systems (Table 3) [*Higginson et al.*, 2004]. By revealing the presence of significant decadal periodicities within the NINO4 index, as well as in the lake level series, our wavelet analysis lends further support to this hypothesis (Figure 8).

[40] It still remains to be explained why the ~11-year periodicity is so readily apparent in the first and last portions of the East African lake level series, standing out prominently amid the higher-frequency, purely ENSO-driven pulses, and why the maximal rainfall anomalies usually preceded sunspot maxima by ~1 year instead of coinciding with or following them. We encourage further investigation into these issues.

7. Sun-Rainfall-Connection Stability and Predictions

[41] The intermittency of sunspot-lake and sunspot-rainfall correlations during the 20th century is often advanced as evidence that such relationships are fortuitous. However,

Table 3. Correlations Between Sunspot Numbers (SSN) and the OND NINO4 Index and the Strength and Positions of the Indian Ocean High (IOH) and South Atlantic High (SAH), for 1967–1995 AD [*Hameed and Piontkovski*, 2004][a]

	IOH-Pressure (JJA)	IOH-Latitude (SON)	SAH-Pressure (JJA)	SAH-Latitude (JJA)
SSN	0.32 (0.078)	0.31 (0.096)	0.49 (0.006)	−0.35 (0.055)
NINO4 (OND)	0.36 (0.044)	0.08 (0.653)	0.23 (0.223)	0.03 (0.891)

[a]P-values in parentheses.

temporal stability is a poor measure of the reality of climatic patterns, as the most cursory examination of 20th century climate teleconnection histories quickly reveals. Even the widely accepted relationship between El Niño and East African rainfall is itself both nonlinear and temporally unstable, as is the relationship between El Niño and the Indian monsoon [*Kumar et al.*, 1999; *Nicholson and Selato*, 2000; *Richard et al.*, 2000; *Conway*, 2002; *Black et al.*, 2003].

[42] We believe that the instability of Sun-rainfall relationships in East Africa simply reflects wavering sensitivity of complex climate systems to solar influences, most likely due to changing boundary conditions. The shifting correlations between sunspot numbers and lake levels during the 20th century were also accompanied by shifts in the nature of rainfall variability in the Victoria watershed, with precipitation becoming less seasonally restricted in midcentury. During the periods 1901–1927 AD and 1968–2000 AD, for instance, the short rains tended to begin in October, but during the intervening interval they were twice as likely to begin in September. Heavy rainfall excursions during the July–August "dry season" were also more numerous during the midcentury interval than during the earlier and later intervals. Climatic systems elsewhere changed during the mid-20th century, as well [*Hoyt and Schatten*, 1997]. Indian rainfall was unusually high then [*Kumar et al.*, 1999], Atlantic trade winds weakened [*Black et al.*, 1999], the Icelandic Low moved southward [*Kelly*, 1977], the North Atlantic Oscillation index decreased [*Jones et al.*, 2001], and ENSO variability was unusually muted [*Torrence and Compo*, 1998].

[43] Sun-climate relationships also display instability on longer timescales. The occurrence of lake level maxima at Victoria and Naivasha during the prolonged sunspot minima of the Little Ice Age [*Verschuren et al.*, 2000; *Stager et al.*, 2005] implies that century-scale Sun-rainfall relationships then were reversed relative to those that we have described for the 20th century, and longer diatom records from Lake Victoria [*Stager et al.*, 2003] show little correspondence to the atmospheric delta-14C record prior to the last millennium. Again, we suggest that changing terrestrial boundary conditions are the most likely causes of such instability in Sun-climate relationships.

[44] Recently developed models have successfully employed monitoring of ENSO indices and SSTs for predicting future rainfall anomalies in East Africa several months in advance [*Linthicum et al.*, 1999]. Our analyses show that unusually heavy rainy seasons could also have been consistently predicted, several years in advance, by monitoring the sunspot cycle.

[45] The predictive value of the lake-Sun relationships discussed here might be limited to forecasting positive rainfall anomalies that are associated with solar maxima. Rainfall peaks of the 20th century also occurred in response to other causes, and the solar cycle seems unable to yield reliable predictions of drought in this region. The ENSO system displays a similar asymmetry of influence; La Niña events are not consistently associated with drought in East Africa despite the stronger association of El Niño with heavier rainfall [*Nicholson and Selato*, 2000].

[46] Nonetheless, the pronounced effects of heavy rain on African ecosystems and societies make this a potentially valuable predictive tool, particularly considering the long lead times involved. We expect East Africa to experience a major intensification of rainy season precipitation, along with widespread Rift Valley Fever epidemics, a year or so before the solar maximum of 2011–2012 AD [*Kerr*, 2006].

8. Conclusions

[47] There is no doubt that solar irradiance plays a central role in establishing the rhythm of diurnal, seasonal, and orbital-scale climate cycles, and that it drives convection and migrations of the ITCZ. In studying past influences of solar variability on paleoclimates, investigators rely upon records that tend to smooth much of the noise out of rainfall patterns, and Sun-paleoclimate relationships are typically identified by simple visual comparison between solar and climate proxy time series.

[48] In contrast, analyses of modern climate systems usually involve larger, noisier data sets and more mathematically based testing that greatly raises the bar to acceptance of Sun-climate relationships today. We acknowledge the need for caution in attributing causality to apparent sunspot-weather relationships, considering some of the poorly substantiated cases that have appeared in the past. However, in the case of Lake Victoria, many of the statistical tools that have been applied to this question have been ill suited to the analysis of complex, nonlinear systems. Our study shows that more time-sensitive techniques such as wavelet analysis, in addition to thoughtful visual inspection of relevant time series, more clearly reveal underlying patterns of change that are otherwise easily missed or discounted.

[49] We have shown that significant relationships between the solar cycle and rainfall existed in East Africa during the 20th century, discussed mechanisms that might help to explain those relationships, and shown how sunspot cycles could be used to predict positive regional rainfall anomalies several years in advance. When one considers that heavy rains in East Africa have serious consequences for soil erosion, hydropower generation, flooding, and insect-borne disease, and that they can also affect regions farther north that respond to the ebb and flow of the Nile, the importance of pursuing the subject further becomes clear. We hope that this paper serves as a stimulus for that endeavor.

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