

RAINFALL CONDITIONS IN EQUATORIAL EAST AFRICA DURING THE NINETEENTH CENTURY AS INFERRED FROM THE RECORD OF LAKE VICTORIA

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Abstract. The East African lakes have exhibited dramatic fluctuations on both historical and paleo-climatic time scales. Levels of these lakes, and other historical indicators in Africa, suggested that environmental conditions in the nineteenth century were much more extreme than anything evident in the modern record. In this study, a water balance model is used to estimate the rainfall associated with these conditions, based on the Lake Victoria record. The results suggest that the conditions were not unlike anomalous periods found during the twentieth century, but they may have persisted for somewhat longer periods of time. The paper also demonstrates a generic tool that can be applied to interpreting historical and paleo-lake levels in quantitative terms of rainfall.

The lakes of East Africa are important indicators of environmental and climatic change on long time scales. The lakes register the pulse of rainfall variability in the equatorial tropics, hence historical records of their fluctuations can potentially provide a spatially and temporally detailed picture of this variability prior to the availability of actual rainfall measurements. Dramatic fluctuations occurred during the nineteenth century (Nicholson, 1995, 1998a,b, 1999, 2000), suggesting a period of continent-wide desiccation in the first decades and markedly wet conditions in the last few decades. The stands of the lakes and other historical indicators suggested that these environmental conditions were more extreme than anything evident in the twentieth-century record. In this article, a water balance model is used to interpret the record of one lake, Lake Victoria, in terms of rainfall over the lake and catchment. Through use of this model, we produce the first quantitative estimate of the rainfall associated with these major environmental changes.

Figure 1 shows reconstructions of lake levels since 1800 for ten lakes spanning latitude 15° N to 22° S. These suggest that two starkly contrasting climatic episodes occurred during the nineteenth century (Nicholson, 1995, 1998a,b, 1999, 2000). The first, which spanned the first few decades of the century, was one of drought and desiccation throughout Africa. The second occurred in the latter half of the century and was marked by extremely high stands of the lakes and remarkably favorable environmental conditions in arid and semi-arid regions of West Africa. A wealth of historical and geographical indicators evidence the character of these



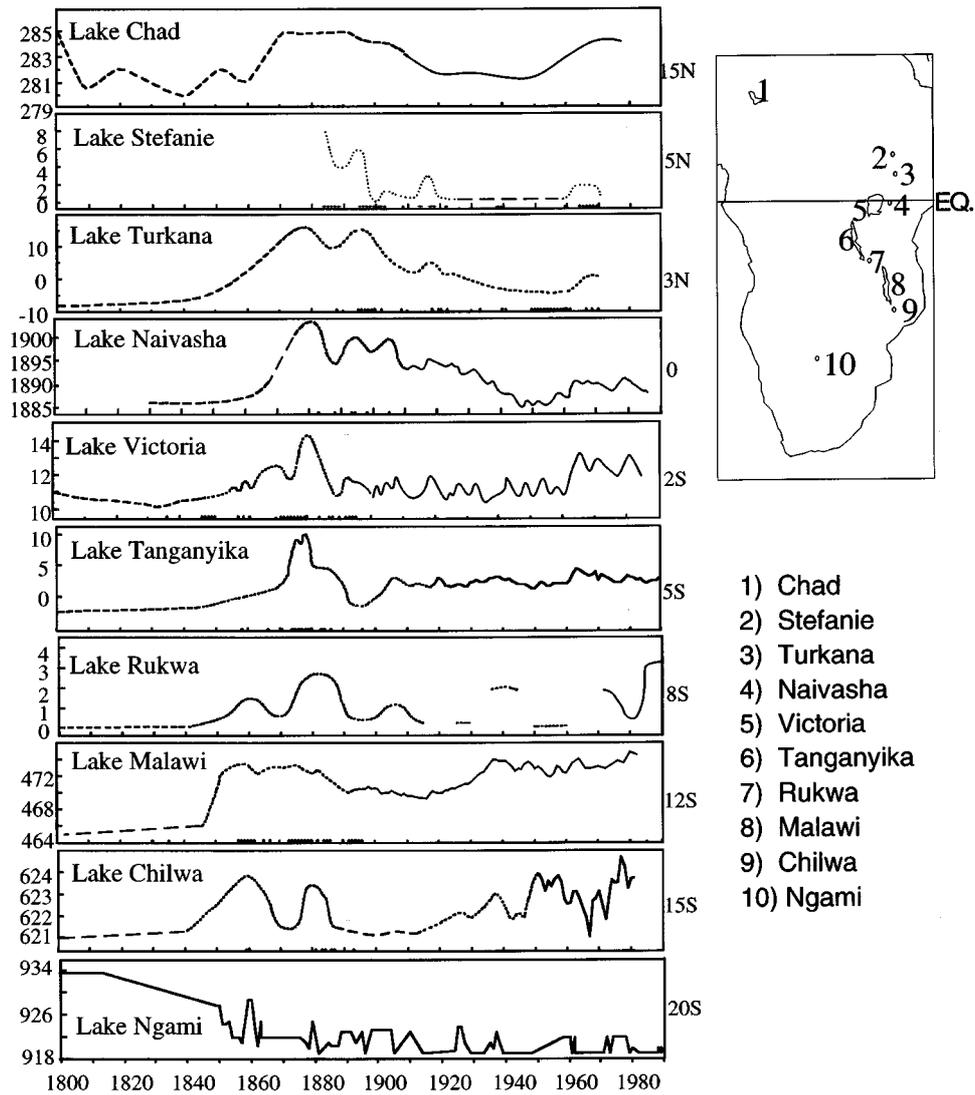


Figure 1. Historical fluctuations of African lakes (2). Except for Lake Ngami, solid lines indicate modern measurements, short dashed lines indicate historical information, and long dashed lines indicate general trends. Where indicated, the dots on the x-axis represent years with actual historical references. In the location map, numbers 1 to 10, respectively, represent Lakes Chad, Stefanie, Turkana, Naivasha, Victoria, Tanganyika, Rukwa, Malawi, Chilwa and Ngami. The horizontal line represents the equator.

periods and suggest that conditions were more extreme than at any time within the twentieth century (Nicholson, 1978, 1980, 1981, 1995).

The arid episode commenced in the late eighteenth century and was probably most extreme during the 1820s and 1830s. Lake Tanganyika was some 9 m lower than during the 1870s (Nicholson, 1999), Lake Turkana sank to a very low level, and Lake Naivasha was reduced to a puddle (Nicholson, 1998a; Verschuren, 1999; Stager et al., 1999). The Nile floods were extremely low in the early 1800s and Lake Chad was desiccated (Nicholson, 1995). Lake Malawi was so low that local inhabitants traversed dry land where a deep lake now resides. Both Lake Rukwa and the Ruhuru River, a major tributary to Lake Malawi, were completely desiccated at some time early in the century. Lake Chilwa, at its southern end, was very low and nearby Lake Chiuta almost dried up (Nicholson, 1998b). At this same time, intense droughts were ubiquitous (Nicholson, 1980, 1981, 1995, 1998a,b, 1999; Owen et al., 1990). Evidence of these droughts and accompanying famines is recorded in the historical chronicles of residents throughout the Sahelian region of West Africa; in some cases, direct witness to nearly two decades of drought is indicated. The droughts throughout East and southern Africa were long and severe enough to force the migration of peoples and create warfare among various tribes.

By mid-century, many of the lakes were rising or had returned to high stands. Lake Malawi had risen about 6 m and maintained this level throughout the next few decades. By the 1870s, high stands were noted in all lakes except Ngami and these persisted into the 1880s or 1890s. Lakes Chad, Tanganyika, Victoria, Naivasha and others rose 3 to 10 m above their early nineteenth-century stands, attaining levels higher than any achieved during the current century. Wetter conditions also prevailed in West Africa from the 1870s to the early 1890s (Nicholson, 1978, 1980, 1981, 1995, 2000). Semi-arid regions of Mauritania and Mali experienced agricultural prosperity and abundant harvests; floods of the Niger and Senegal Rivers were continually high; and wheat was grown in and exported from the Niger Bend region. Maps and geographical reports described 'forests' across the east-west extent of the northern Sahel and numerous wells and wadis in now hyperarid areas of the southern Sahara.

The interpretation of the past history of the lakes in climatic terms is a complex problem. The lakes integrate conditions over large and diverse regions and, together with the surrounding topography, they produce regional-scale climates that are superimposed upon and interact with the large-scale patterns (Flohn and Burkhardt, 1995). Also, the conversion of lake level changes to rainfall depends on the relative magnitude of water balance terms, as well as on lake geometry and basin characteristics. Thus, the climatic interpretation of the lakes' histories requires a rigorous understanding of the water balance of each lake.

TABLE I

Annual water balance of Lake Victoria 1956–1978, as calculated by this study (unit: mm)

Over lake rainfall	Tributary flow	Evaporation from lake	Discharge from Jinja	Lake level change
1780	338	1537	524	73

In this paper we use a water balance model to infer the changes in mean rainfall conditions that accompanied the arid and wet episodes described above. The basic water balance equation is:

$$\Delta H = P_w + I - (E + D), \quad (1)$$

where ΔH is a change in end-of-year lake level from the preceding year, input is precipitation over the lake (P_w) plus tributary inflow (I) and output is evaporation over the lake E plus discharge D . In this equation the terms are in units of mm over the lake. Details of the model and a demonstration of the feasibility of using it to infer rainfall are presented elsewhere (Yin and Nicholson, 1998; Nicholson et al., 2000).

The first version of the model utilized evaporation calculated from surface energy balance considerations, plus measured tributary flow and discharge. Satellite data were used to estimate rainfall over the lake and to derive a relationship between rainfall over the lake and in the surrounding catchment (Ba and Nicholson, 1998). This analysis showed that the nocturnal lake breeze effect enhances rainfall over the lake by about 30% compared to rainfall over the surrounding land area of the catchment, leading to the mean water balance indicated in Table I for the period 1956–1978.

A second version of the model was adapted so that it could simulate the lake's water balance during periods prior to the availability of tributary inflow and discharge measurements. Regression equations were derived to estimate these parameters from two variables, catchment rainfall and height of the lake (Nicholson et al., 2000). These two variables were selected, so that the model could be inverted to predict rainfall from the better established lake level fluctuations. The regressions yielded the following model equations:

$$I_i = 0.33395H_i - 0.24311H_{i-1} - 0.266P_{l(i)} + 0.2356P_{l(i-1)} - 726 \quad (2)$$

$$D_i = 0.15913H_{i-1} + 0.07054H_i - 2223 \quad (3)$$

$$P_{w(i)} = 1.3533P_{l(i)} - 87, \quad (4)$$

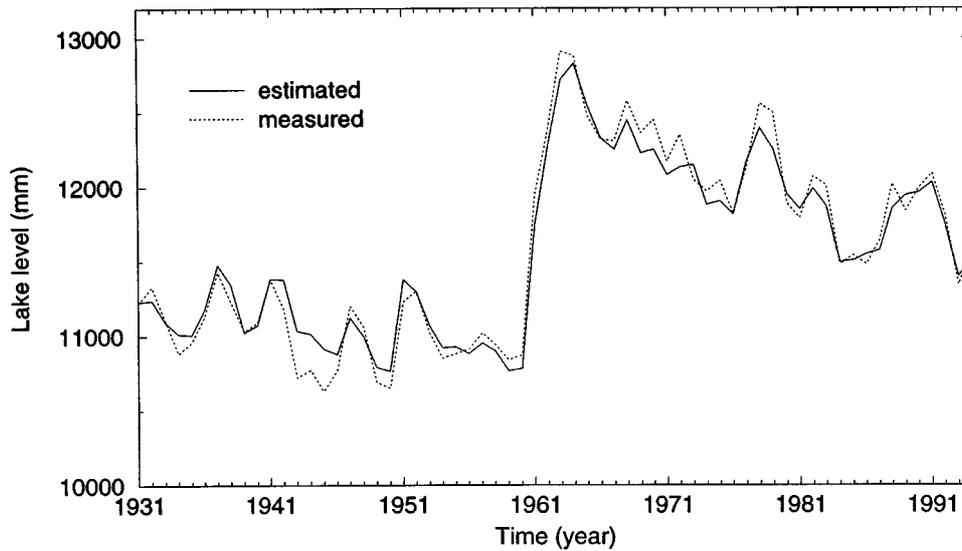


Figure 2. Predicted year-to-year changes in lake level, 1931 to 1994.

where I_i is inflow in year i , $P_{l(i)}$ and $P_{l(i-1)}$ are catchment rainfall during years i and $i - 1$, D_i is discharge in year i , $P_{w(i)}$ is the annual rainfall over the lake in year i , and H_i and H_{i-1} are the lake levels at the end of the current and previous year, respectively. A cross-validation determined that the standard error of the estimates is 71, 24 and 46 mm/year for catchment rainfall, discharge and tributary flow, respectively.

Equation (1) can be rearranged to solve for the change in lake level from year to year. Figure 2 shows the comparison between model-estimated and measured lake-level change year by year during the period 1931–1994. There is excellent agreement between estimated and measured changes until the early 1970s. Since that time there is some systematic underestimation, which an error analysis indicated was likely due to variations in cloud cover, which the model assumes to be constant (Nicholson et al., 2000). The standard error in the estimates is 79 mm, which is equivalent to roughly 5% of the mean rainfall over the lake.

We have inverted the model to calculate mean rainfall from fluctuations in lake level. By combining Equations (1–4), rearranging terms and summing over N years, it can be shown that:

$$\begin{aligned}
 0.18847 \sum_{i=1}^N H_i + 0.81153 \sum_{i=1}^N (H_i - H_{i-1}) &= 1.0905 \sum_{i=1}^N P_{w(i)} + \\
 + 0.2364 \sum_{i=1}^N P_{w(i-1)} - \sum_{i=1}^N 58. & \quad (5)
 \end{aligned}$$

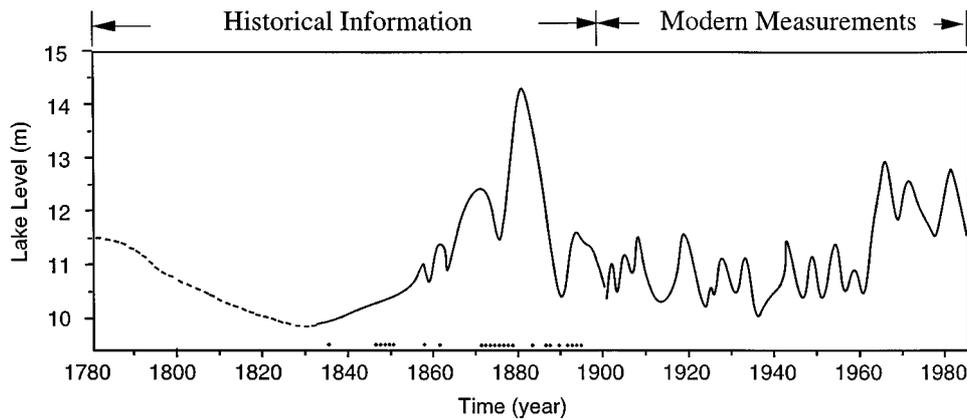


Figure 3. Fluctuations of Lake Victoria since 1780. Years for which specific references are available are indicated at the bottom with dots. Levels since 1896 are based on modern measurements and earlier years are reconstructed from historical references. Dashed line indicates period for which only general trends, not specific years, can be ascertained.

For a relatively long period, the following approximation can be made:

$$\frac{1}{N} \sum_{i=1}^N P_{w(i-1)} \approx \frac{1}{N} \sum_{i=1}^N P_{w(i)} \equiv \overline{P_w}, \quad (6)$$

where, $\overline{P_w}$ is the long-term mean of over-lake rainfall. Since in Equation (5) the coefficient of the term $P_{w(i-1)}$ is much smaller than the coefficient of the term $P_{w(i)}$, the approximation in Equation (6) is reasonable. Dividing the two sides of Equation (6) by N and rearranging the terms, we have:

$$\overline{P_w} = 0.14204\overline{H} + 0.61161 \left(\frac{H_N - H_0}{N} \right) + 43, \quad (7)$$

where \overline{H} is the mean lake level in the period. If the lake levels at the beginning H_0 and end of a period H_N are known and the mean lake level in the same period can be derived, then mean rainfall over the lake in this period can be estimated by Equation (7).

The above equation was validated (Nicholson et al., 2000) using two twentieth-century periods during which adequate rainfall data were available. Mean rainfall over the lake for the period 1956–1978 is 1780 mm. The model estimates a mean of 1794 for the same period, or an error on the order of 1%. For the period 1961–1968, when the lake rose rapidly, the model estimate is 1946 mm/year, compared to 1939 mm/year from the satellite data, or an error on the order of 1%. Here it is used for the first time to assess rainfall variability during historical times.

Figure 3 shows a detailed reconstruction of the levels of Lake Victoria. This graph is based on extensive historical witness to the lake and miscellaneous reports of meteorological conditions near the lake (Nicholson, 1998a). The heights

indicated are fairly accurate since approximately the 1850s, but with some margin of error. The possible degree of error is illustrated by the diverse sources that discuss the maximum stand of 1878. Catholic missionaries at Buganda reported around 1876 that the average water level of Victoria was 8 feet (2.4 m) higher than during that of 1898, when actual measurements were available (Ravenstein, 1901). This suggests, according to Lamb (1966), that the level around 1876 to 1880 was slightly (about 0.5 to 0.7 m) above the 1964 peak of 13.36 m. Possibly based on this information, Beadle (1974) estimated that its peak was roughly 14.0 m at the Jinja gauge, but he placed the maximum in 1876. All other sources agree that the maximum was in 1878, consistent with the reports of continually high rainfall between 1876 and 1878 (Nicholson 1998a). Also in 1878 Lado, on the Bahr el Jebel, was flooded, Lake Albert reached an unusually high level, and the flow of the White Nile was also quite high, producing tremendous floods (Howell et al., 1988). Similarly, Johnson (1992) suggests that the flood of 1878 was somewhat in excess of those in 1916–1919 and 1961–1964 in the southern Sudan. On the other hand, Bishop (1969) concluded from dated beach gravel in a cave near Entebbe that Lake Victoria had at no time within the past 3720 years reached the cave. This would place the historical limit (Sutcliffe, personal communication) as between 13.85 and 14.46 m. Based on these various sources, we have placed the 1878 maximum at roughly 14.3 m.

Prior to the 1850s, the levels of the lake in Figure 3 are quite approximate, as there is no quantitative information about lake level. However, the trends can be considered reliable (Nicholson, 1995, 1998b, 1999, 2000; Owen et al., 1990). Here we approximate the pre-1850 levels from the summer Nile flow (Toussoun, 1925), a rough proxy for the levels of Lake Victoria (Flohn and Burkhardt, 1995). The 1780s are selected as a starting point for the graph because there is a peak in the Nile flow around 1785. Also, throughout Africa evidence indicates that a trend towards drier conditions commenced around that time. Nile levels further give an indication of the levels of the lake that would have been sustained around 1785 and early in the nineteenth century. The 1785 peak in Nile flow was roughly equivalent to that around mid-nineteenth century, hence the mid-nineteenth value of 11.5 m was selected for the 1785 lake level. The Nile record also suggests that during the subsequent minimum, flow was much lower than at any time in the twentieth century. On this basis, a value of roughly 10 m above gauge datum was selected for the early nineteenth century minimum. However, a value of 1 to 2 m lower is plausible but much less likely.

Equation (7) is applied to assessing rainfall during four periods of the nineteenth century: two periods of sharply rising lake levels (1875–1878 and 1858–1878) and two periods of falling lake levels (1879–1889 and 1785–1835). The lake level change and mean height of the lake during these periods, as assessed from Figure 3, are indicated in Table II. Rainfall for these periods, as predicted by Equation (7), is also indicated in absolute terms and as a percent departure the modern mean for the 1956–1978. For the periods of rising lake levels, 1875–1878 and 1858–1878,

TABLE II

Lake level change during four historical and two modern periods and the corresponding changes in evaporation and over-lake rainfall

Period	\bar{H} (m)	$\delta\bar{H}$ (m)	\bar{P}_w (mm)	ΔP (%)	ΔE (mm)
1785–1835	10.75	–1.5	1552	–13	+228
1858–1878	12.65	+3.3	1941	+9	–160
1875–1878	12.95	+2.7	2433	+37	
1879–1889	12.00	–3.6	1528	–14	+248
1960–1968	12.48	+1.7	1939	+9	
1978–1986	11.84	–1.1	1651	–7	

For the historical periods rainfall is predicted by the model; for the modern periods it is assessed from actual rainfall data. The second column is the mean height from the end of the first indicated year to the end of the second indicated year, the third is the change in level between those years, and the fourth is the mean rainfall during the period bracketed by those years (i.e., for lake level changes between 1858–1878, mean rainfall calculated by the model is for the years 1859 to 1878). The fifth column expresses this as a percent of the 'modern' mean for the period 1956 to 1978. The final column indicates the change in evaporation that could produce the change in lake level indicated in the third column.

our model predicts means of 2433 and 1941 mm, respectively. Thus, the moderate rise of about 3.3 meters during the longer period could have been produced by persistent wet conditions with rainfall only 10% above the modern mean, but the abrupt 2.7 m rise in the late 1870s would have required that rainfall for the five-year period be about 37% higher than the modern mean. During the period 1879–1889, when the lake fell nearly 4 m in ten years, rainfall would have been about 1528 mm, or 14% below the modern mean.

It is more difficult to estimate rainfall during the earlier period of sustained fall from 1785 to 1835 because of the uncertainty in the estimates of lake level. However, this timeframe is of great interest because it was a protracted period of droughts and desiccation of lakes throughout most of Africa (Nicholson, 1995, 2000). Based on the fluctuations shown in Figure 3, the model estimates mean rainfall for the 50 years to have been about 1552 mm, or about 13% below the modern mean. Had the lake reached a minimum that was 1 or 2 m lower, the estimates would be approximately 1469 and 1386, respectively. These would correspond to rainfall over the lake that is about 17% and 22% lower than the modern mean.

The above calculations assume that rainfall is the only meteorological variable contributing to the observed lake-level changes. In view of the continental-scale synchronicity of the historical fluctuations and the similarity of the spatial patterns of the changes to patterns in the modern rainfall record (Nicholson, 1981, 1995, 2000), this is quite likely. Nevertheless, changes in air and water temperature,

wind speed, humidity and cloudiness can also affect the lake's water balance via evaporation.

An estimate is made of their potential impact by first determining the change in annual evaporation over the lake that would be required to produce the changes in lake level indicated in Table II. This is equivalent to the difference between mean rainfall calculated for the indicated periods and mean rainfall for the period 1956–1978. The change in the other variables that is required to have a comparable influence on evaporation is estimated from model sensitivity studies (Nicholson, 1999). Calculations are carried out only for the three longer periods, because changes in evaporation are unlikely to produce a change as large as that indicated for the three-year period 1875–1878.

The resultant calculations indicate that the desiccation early in the nineteenth century would require an increase in annual evaporation of at least 228 mm (100 to 200 mm more, if the lower lake level estimates were considered). To produce the rise from 1858 to 1878 or the fall from 1879 to 1889, similar changes would be required, 160 and 248 mm respectively. Since mean evaporation over the lake (Table I) is 1537 mm, a change of only 10–16% is required.

Thus, in all cases the required change in evaporation is on the order of 200 mm/year. The sensitivity studies (Yin and Nicholson, 1998) indicate that such a change could be accomplished via a 4 °C change in air temperature. Such a change is quite unlikely for the tropics and is nearly an order of magnitude larger than observed changes over the last few decades (Lehman et al., 1998). A decrease in water temperature of roughly 3 °C could increase evaporation by this amount, via the associated reduction in relative humidity over the lake. However, Lake Victoria is relatively warm (Ochumba, 1996) and a much larger increase would be required to reduce evaporation by 200 mm. By comparison, over the last 30 years water temperature has changed by less than 0.5 °C (Lehman et al., 1998), despite significant warming on a global scale. A 200 mm/year change in evaporation would require a change in wind speed of 2 m s⁻¹ which is roughly the mean wind over the lake and twice as large as observed changes (Lehman et al., 1998). Hence a change in wind speed could not account for the observed changes in lake water balance.

A 200 mm/year could also be accomplished by a relative reduction or increase of mean cloudiness of about 20% (10% absolute change). Such variations in cloud cover are conceivable and have occurred near Lake Victoria over the last 30 years (Nicholson et al., 1999). Moreover, some change in mean cloud cover would probably accompany the rainfall changes that produced the high and low stands of the lakes. If the high rainfall that produced the mid-nineteenth century rise were accompanied by a change in mean cloudiness from 50% to 55%, the rise of the lake could be explained by an increase in rainfall of only 5% compared to the modern mean.

In conclusion, our model suggests that the apparent desiccation of East Africa early in the nineteenth century could have been accomplished via a reduction in rainfall equivalent to 12% of the modern mean, or half that if accompanied by a

small reduction in cloud cover. The lake rise commencing in mid-century could have been accomplished by an increase in rainfall of only 10%, or half that if cloudiness were increased by a small amount. This is consistent with the 11% change needed to produce the high nineteenth century stands of Lake Ngami (Shaw, 1985).

A comparison with modern rainfall trends show that these stark environmental changes could have resulted from rainfall conditions not unlike those of the twentieth century. The 2 m lake level rise from 1961–1968 was associated with an increase in rainfall of about 10% (Table II). The 1 m rise in 1961 occurred as a consequence of over-lake rainfall on the order of 2486 mm/year (Nicholson et al., 2000), hence 41% above the long-term mean. Elsewhere in East and Southern Africa rainfall was some 20–40% above normal during sustained periods of the 1960s and 1970s (Nicholson, 1995). The 7% reduction in rainfall that caused Lake Victoria to fall nearly a meter from 1978 to 1986 is only marginally smaller than 13% that may have produced the early nineteenth-century desiccation.

Our results further underscore how sensitive the lake is as an indicator of climatic change. Exceedingly high rainfall in a single year (such as 1878 or 1961) can produce high stands that can be maintained with much more moderate rainfall. Hence even single El Niño events can trigger persistent changes in the lakes. In fact, the lake level rise in 1876 to 1878 occurred during one of the strongest El Niño events of the last few centuries (Quinn, 1992). This is consistent with the well-known association between El Niño and abnormally high rainfall in East Africa (Nicholson, 1996). The high levels of the early 1960s were also coincident with two major El Niños in 1963 and 1965 and the dramatic rise in 1961 was coincident with an El Niño-like warming in the Atlantic and Indian Oceans surrounding Africa.

Our study also shows that the period of time over which a change is sustained is as critical as the magnitude of the change. This has implications for the interpretation of paleo-environmental changes (Hastenrath and Kutzbach, 1983) and for the question of sustained, future global change. As for the latter, relatively small changes in ambient conditions of rainfall, cloudiness and temperature might drastically alter the surface hydrology, such that some regions might see a change from desiccated lake beds overgrown by vegetation to expansive lakes.

The model presented here is an excellent tool for interpreting historical and paleoclimatic fluctuations of lakes. The accuracy of the interpretation is limited not by the lake model but by the accuracy of the historical or paleoclimatic lake reconstructions. The interpretation is also limited by the fact that there are few indicators of ambient conditions of cloudiness, temperature, humidity and wind speed during pre-modern times. Nevertheless, the results clearly show that moderate changes of rainfall can suffice to explain relatively large fluctuations of Lake Victoria. This is presumably true of the other East African lakes, whose stands mimic those of Victoria.

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