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Variations of African lakes during the last two centuries

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Abstract The historical levels of numerous African lakes have been derived, using detailed geographical and historical descriptions of the lakes. Reconstructions have been completed for Lakes Chad, Victoria, Naivasha, Turkana, Stefanie, Tanganyika, Rukwa, Malawi, Chilwa and Ngami. In all cases information is available back to the beginning of the nineteenth century; it becomes plentiful, allowing for almost year-to-year histories, around the 1850s. For numerous lakes, a general overview of levels during prior centuries has also been derived. For select lakes, a comparison is made with the modern hydrological regime. The most striking periods are early in the nineteenth century when dramatic recessions were ubiquitous, and during the latter decades of the century when dramatic rises of the lakes occurred. Water balance models are used to approximate the changes of rainfall associated with these periods. Comparisons are made with anomalous periods during the twentieth century: the 1910s and the 1960s and 1970s.

INTRODUCTION

The numerous lakes of East Africa are important indicators of climatic and environmental change and their sediment cores provide "archives" of long-term environmental history. The lakes' fluctuations register the pulse of rainfall variability in the equatorial tropics. Their geological records unequivocally demonstrated Ice Age aridity some 15 000 years ago, dramatically refuting the presumed glacial/pluvial correlation. They also showed the existence just 5000 years ago, of a major low-latitude "pluvial", when some lakes were 150 m deeper than at present. Historical witness of the lakes has also provided a wealth of information about fluctuations on time scales of centuries.

The collective records of the East African lakes can yield a spatially and temporally detailed picture of the region's long-term environmental history. This is important because the quantitative record of African climate currently extends from only 1900. In order to interpret the past history of the lakes in terms of climate, and to otherwise unlock the wealth of knowledge contained within their cores, it is necessary to have a rigorous understanding of the water balance of each lake.

In this paper, the fluctuations of 10 lakes since 1800 are summarized. These cover a broad latitudinal span (Fig. 1), ranging from Lake Ngami near 20°S to Lake Chad, around 15°N. Thus, they represent climatic fluctuations in the equatorial regions and in the subtropics of both hemispheres. The fluctuations of the lakes have

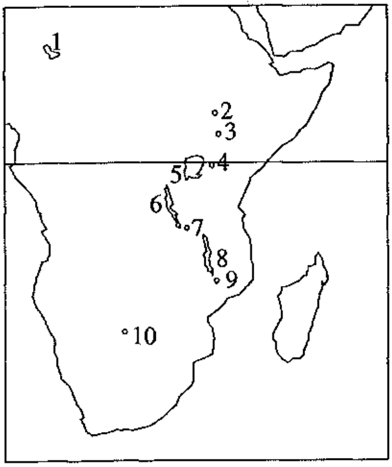

Fig. 1 Locations of the lakes in Fig. 2. Numbers 1–10 respectively represent Lakes Chad, Stefanie, Turkana, Naivasha, Victoria, Tanganyika, Rukwa, Malawi, Chilwa and Ngami. The horizontal line represents the equator.

been reconstructed using documentary sources for the historical period, as contained in the archive described in Nicholson (1998a), and modern lake-level data. The record suffices to provide nearly annual detail for most lakes going back to the middle of the nineteenth century and general detail earlier in the century. For some lakes the record is sufficient to provide the general details of their fluctuations during the last six centuries. These are not shown here but are described in Nicholson 1997b,c,d).

We also describe the results of a water balance model developed for Lake Victoria. At present, we are "inverting" the model, in order to apply it to interpreting Victoria's historical record. During the course of this work, the inadequacies in our current knowledge of the water balance of African lakes have become apparent. The shortcomings are described in a general sense and suggestions are made for improved balance calculations. Such calculations are a prerequisite for interpreting the tremendous historical and paleoclimatic records of the lakes.

DATA AND SOURCE MATERIALS

The major sources of material for developing the lake chronologies are diaries, journals, archives, maps and local oral histories. In some cases, geological studies providing sedimentary, geochemical and pollen information from lake cores complement the documentary evidence.

An excerpt from a typical lake chronology is presented in Table 1. Similar chronologies have been produced for the other lakes in Fig. 1. This information will be stored in a verbal archive that is available to the scientific community at large, most likely via an anonymous FTP server. The lake level fluctuations interpreted from this information, as described in the following section, will similarly be available.

Table 1 Excerpts from the long-term chronology of Lake Malawi; the chronology extends from the fifteenth to the early twentieth century, with scant detail prior to the nineteenth century.

c. 1825	Johnston (1897) records a tradition that "some 70 year ago (i.e. about 1825) the north end of the lake became so shallow between Deep Bay and Amelia Bay that a chief and his men waded across it where it is now many fathoms deep (Owen *et al.*, 1990).
c. 1820s	Ngonde king Mwangonde, whose reign genealogically dated to about 1815 to 1835, walked across northern part also to marry a woman. The North Rukuru River in northern Malawi dried up during the reign of Mwangonde (*c.* 1815–1835). There was a general view that widespread aridity in the late 1820s was a cause of the Yao dispersal towards the southern lake area (Owen *et al.*, 1990).
	Stewart, who visited the lake in 1879, spoke of the flooding of a small land area that had stood in the mouth of the Rukuru river some 60 years previous. Although a change in the river could account for its flooding, this is consistent with other evidence of drier conditions, including the above reference to the Rukuru drying up (Sieger, 1877).
1835	The Ngoni Gama clan of northern Malawi (i.e. the followers of Zwangendaba— see Curtin *et al.*, 1978) have a tradition of crossing the Zambezi near Zumbo on a sandy causeway in the dry season of 1835 (date established via reference to a solar eclipse) (Owen *et al.*, 1990).
1830s	Dixey reported very low levels for the 1830s, but gives no source of his information (Owen *et al.*, 1990). Further south, about the same time, tribal chief Amapunda walked across dry ground to Likoma Island on north end. Tribal chronology suggests his reign approx. the 1830s.
1840s	Informant at Chikowa's village near Mawudzu Hill on the southeast arm of the lake, who was born around 1910, said her father's village had once been close to Boadzulu Island "when the lake was small" about the time of the "fighting between the Yao and Ngoni". May refer to temporary period of alliance between the Msamala Yao and the Nyanja against the Ngoni around the 1840s. Since water near the island now about 40 m deep, implies very low levels in the 1840s. References to tribal fighting c. 1840s indicative of very low lake levels (Owen *et al.*, 1990).
late 1840s to late 1850s	Probably a gradual rise of Lake Malawi (Sieger, 1887).
1857–1863	Very high levels (Dixey 1924)
1859	The lake must have had a relatively high stand when Livingstone visited because the missionaries found no evidence of formerly higher stands. Also the Shire was a broad and deep current (Sieger 1887). No evidence that the lake rose or fell much; Livingstone suggested the fluctuations do not exceed 3 or 4 feet. Stewart's report from 1879 suggested fluctuations of a similar magnitude (see Sieger, 1887).
1860	Peak level in this year is based on the coincidence between the lake level deduced from Livingstone's soundings in Lake Malombe in 1861 and Dixey's (1924) report of marks (presumably aquatic algal lines) on lakeshore rocks up to that level (see Owen *et al.*, 1990).

RESULTS

Lake level fluctuations

The trends of the African lakes are depicted in Fig. 2. Their historical fluctuations show strong parallels. All but Ngami appear to have been low in the late eighteenth and early nineteenth centuries. Although Lake Ngami was then high, it was regressing, thus likewise indicating relatively dry conditions. The mid- and late nineteenth century was a period of high lake levels, with a rise beginning in the 1840s in the southernmost lakes but not until the 1860s or 1870s further north. The lakes rapidly regressed toward the end of the century and generally maintained relatively low levels during the first half of the twentieth century. The southern lakes Chilwa, Malawi and Rukwa began to rise again in the 1930s or 1940s. In the equatorial region, the lakes did not rise until the 1960s. In some cases a dramatic change of the order of several metres occurred in the early 1960s.

Thus, there are numerous similarities in the records of these various lakes, but the overall patterns are quite different. This reflects the hydrology of the individual basins more than it does variations in rainfall fluctuations in the various regions. For this reason, a true comparison of their fluctuations requires use of a hydrological model and consideration of the geographical differences of the lakes (e.g. basin shape

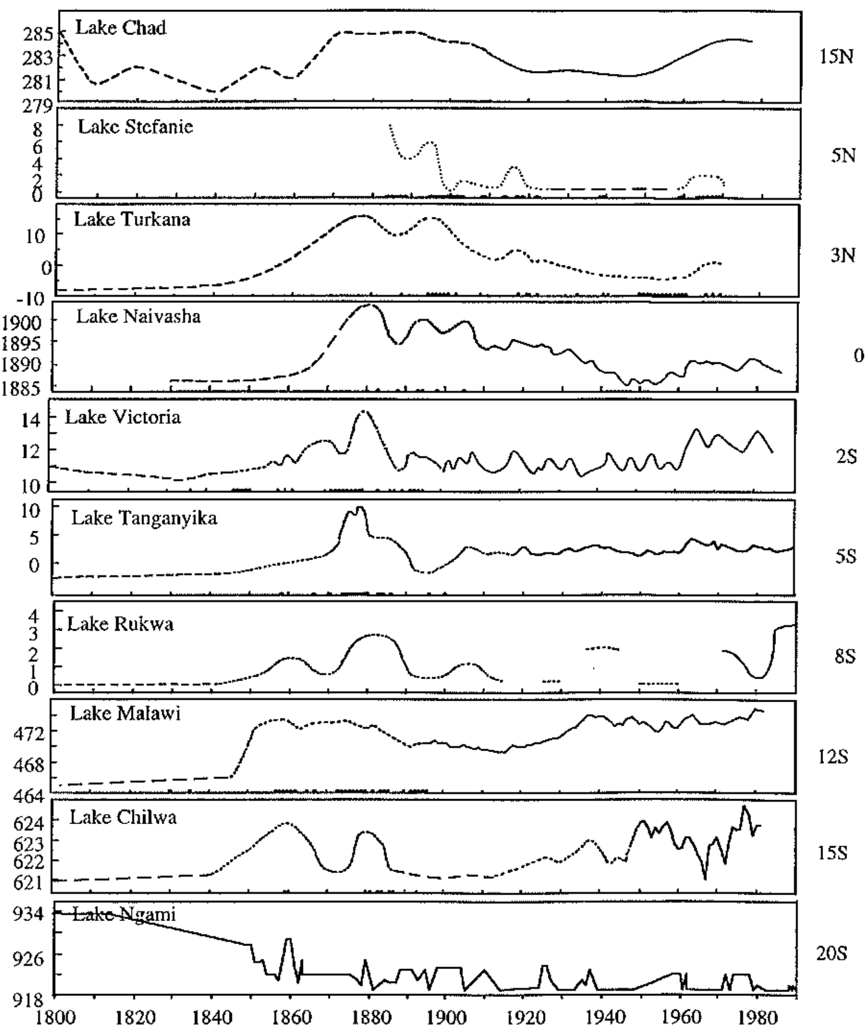

Fig. 2 Historical fluctuations of African lakes. Except for Lake Ngami, solid lines indicate modern measurements, short dashed lines indicate historical information, and long dashed lines indicate general trends. Where indicated, the dots on the *x*-axis represent years with actual historical references.

and size, closed or open basin). We will utilize a water balance model for the interpretation. Its development and application to the modern record of Lake Victoria is described below.

Modelling

The fluctuations of the lakes depicted in Fig. 2 provide an excellent record of long-term fluctuations in regional water balance. Interpreting this balance in terms of regional rainfall involves two steps. The first will be to determine which geographical region is best represented by each lake, i.e. the region with the highest correlation between rainfall fluctuations and lake levels. This is often not the entire catchment, but only a portion of it. The second step will be to derive water balance models for each lake and "invert" them to quantify the trends in rainfall represented by the lake-level fluctuations. Such a model has been developed for Lake Victoria (Yin & Nicholson, 1998); similar models for other lakes will follow.

In its simplest form, the water balance of a lake can be expressed as a balance between input and output, such that:

$$\Delta H = Pw + INFLOW - (Ew + OUTFLOW) \quad (1)$$

where ΔH is a change in lake level from the preceding year, input is precipitation over the lake (Pw) plus *INFLOW* from tributaries and output is evaporation over the lake (Ew) plus *OUTFLOW* primarily via discharge. In our Victoria study (Yin & Nicholson, 1998), we discovered that the major terms in the balance are not accurately known for most of the region's lakes. For example, published estimates of evaporation over Lake Victoria range from 1130 to 1600 mm year^{-1}, while estimates of rainfall over the lake range from 1145 to 1850 mm year^{-1} (Table 2). Similarly, one source states that the water balance of Lake Tanganyika is dominated by rainfall over the lake and evaporation, while another source states that tributary flow is the largest term in the balance.

Table 2 Published estimates of the mean annual water balance (mm) of Lake Victoria, including period of reference, when available.

	Over-lake Rainfall	Evaporation	Tributary flow	Discharge from Jinja	Reference period
OUR STUDY	1791	1532	338	524	1956–1978
Hurst & Phillips (1952)	1420	1350	230	305	
Merelieu (1961)	1145	1130	215–260	305	
De Baulny & Baker (1970)	1630	1523	260	306	1925–1959
WMO (1974)	1582–1690	1423–1496	238	426	
Hastenrath & Kutzbach (1983)	1650	1500	250	400	
Spigel & Colter (1996)	1450	1370	260	340	
Howell *et al.* (1988)	1810	1593	343	524	1956–1978
Flohn (1983)	1690	1470	280	450	1945–1984
Flohn & Burkhardt (1985)	1630–1660	1470		500	1950–1979
Kite (1981,1982)	1660	1590	420	570	1970–1974
Piper *et al.* (1986)	~1850*	1595	343	~500*	1956–1978
Balek (1977)	1476	1401	241	316	

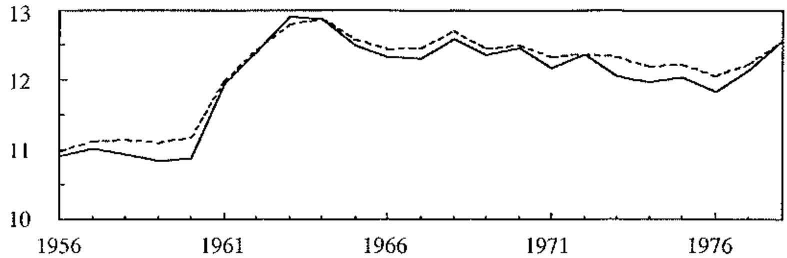

Fig. 3 The level in metres of Lake Victoria 1956–1978 as estimated by our model (solid line) and as measured at Jinja, Uganda (dashed line).

The main reason for the inadequacy of water balances estimates is the dearth of available hydrological and climate data, particularly over the lakes themselves. The evaporation and rainfall terms in the above equation are generally estimated from stations along the shore, however our Victoria study demonstrated how unsatisfactory this is. Conditions over the open lake are very different than along the shore and over the larger lakes a lake/land breeze system controls rainfall and evaporation. Over Lake Victoria the nocturnal land breeze (winds from the land to the lake) enhances rainfall compared to the surrounding catchment, producing a maximum in rainfall at night compared to afternoon maxima at shoreline stations (Flohn & Fraedrich 1966). This system also produces nocturnal cloud cover and clear skies during the day over the lake, while along the shore, the diurnal cycle is reversed, with daytime cloudiness. Preliminary evidence shows that similar effects control the water balance of Lakes Tanganyika, Malawi and probably Turkana.

In the water balance model we developed for Lake Victoria, improvements over past studies were made in two ways. First, two different parameterizations of evaporation were utilized and sensitivity tests were run. Second, rainfall over the lake was more directly estimated by using remote sensing techniques to determine the degree of rainfall enhancement by the lake/land breeze system. Inflow is derived from the lake's tributaries and the outflow is the lake discharge at Jinja, which provides the source of the White Nile. Further details are found in Yin & Nicholson (1998).

Figure 3 shows the predicted *vs.* the observed lake level using the model equation above, with terms assessed as described. The period 1956–1978 is that upon which the regressions are based. Close agreement is shown between predicted and observed heights, especially during the period of the regression. The model captures exceedingly well the discontinuity in levels *c.* 1961. We are currently inverting the model by expressing all input parameters of rainfall and/or lake level. Once, this is done, the past levels can be re-interpreted as a rainfall curve. This will allow a general assessment of the rainfall conditions that prevailed in the wet and dry periods of the nineteenth century.

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