

# HISTORICAL AND MODERN FLUCTUATIONS OF LAKES TANGANYIKA AND RUKWA AND THEIR RELATIONSHIP TO RAINFALL VARIABILITY

SHARON E. NICHOLSON

*Department of Meteorology, Florida State University, Tallahassee, FL 32306, U.S.A.*

**Abstract.** This paper describes the fluctuations of Lakes Tanganyika and Rukwa over the last two centuries. Lake chronologies extending back to the late eighteenth century are derived from reports of European visitors, settlers and explorers and from oral accounts of the local peoples. The historical fluctuations are meshed with the modern record to provide a picture of the lakes' fluctuations until the late twentieth century.

The historical fluctuations of the lakes are quite similar. The most important of these are low levels during the first half of the nineteenth century, very high stands in the last decades of the nineteenth century, and, around the turn of the century, a rapid fall to twentieth century levels. This pattern is ubiquitous throughout eastern Africa and is apparent in numerous other lakes, including Victoria, Naivasha, Stefanie, Turkana, Malawi and Chilwa. Driest periods were in the 1920s or earlier and in the 1950s. Lake Tanganyika returned to extremely high stands in the 1960s and has continued to maintain relatively high stands since that time. Lake Rukwa rose to high stands during the 1980s and maintained them for several years.

An analysis of rainfall variability shows that these trends are generally explained by variations in catchment rainfall. However, the lakes' responses to rainfall variability are sometimes dissimilar because Lake Rukwa is a closed basin. Our results demonstrate the complexity of the rainfall/lake-level relationships and the need to use water balance relationships in order to interpret the lakes' historical or paleo-fluctuations in terms of rainfall.

## 1. Introduction

Lakes throughout East Africa exhibited spectacular rises in the 1960s (Lamb, 1966), in response to a series of remarkably wet years (Flohn, 1987; Nicholson 1995). Though Lake Victoria's rise was the most dramatic, Lake Tanganyika rose over two meters in the early 1960s. The ubiquitousness and the magnitude of the fluctuations were thought to signal a major global climatic change (Lamb, 1966), not unlike that that occurred toward the end of the last century (Kraus, 1955; Nicholson, 1995). The East African lakes similarly provided the first comprehensive picture of vast climatic changes of the late Pleistocene and Holocene (Grove and Goudie, 1971; Butzer et al., 1972).

Thus, these lakes are excellent indicators of tropical climate on all time scales. They can provide images of past climate with good spatial resolution and excellent temporal continuity. Recent work on the lakes has also produced high-resolution cores (Halfman and Johnson, 1988; Stager, 1997; Verschuren, 1996). These can



*Climatic Change* **41**: 53–71, 1999.

© 1999 Kluwer Academic Publishers. Printed in the Netherlands.

potentially be interpreted quantitatively, if properly calibrated with historical data. With this goal in mind, as well as the intent to document historical climatic fluctuations, Nicholson (1997a,b) reconstructed the historical fluctuations of lakes in eastern equatorial Africa and in southeastern Africa.

In this article, reconstructions for Lakes Tanganyika and Rukwa are added to this picture. Geographically intermediate between these regions of equatorial and subtropical climate, the fluctuations of these lakes can provide a look at the long-term movements of critical climatic boundaries. Moreover, these lakes provide the opportunity to compare the response of a large and a small lake to long-term interannual rainfall fluctuations.

## 2. Physical Geography

Lake Tanganyika is the second largest lake in East Africa. With a surface area of 32,600 km<sup>2</sup>, it is less than half the size of Lake Victoria, but drains an area of approximately the same size, 198,400 km<sup>2</sup>. Its mean depth is 580 m, compared to a maximum depth of 1471 m (Spigel and Coulter 1996). Most of the coastline is precipitous, with the escarpment falling directly into the lake for long stretches (Beadle 1974). The lake extends north-south between the latitudes of approximately 3° S and 9° S, and is thus in the outer equatorial latitudes. Its surface lies on average at 773 msl, but its height generally varies by about one meter between the wet and dry seasons. The surrounding region is generally semi-arid, with mean annual rainfall ranging from about 800 mm to 1400 mm at stations within its catchment.

The water balance of Lake Tanganyika is not very accurately known. Balek (1977) gives mean annual rainfall over the lake and evaporation as 950 and 2418 mm, respectively. Spigel and Coulter (1996) give a similar value for rainfall, 1050 mm, but a mean evaporation rate of 1530 mm. They further indicate that the difference between rainfall and evaporation is largely accounted for by tributary inflow (the equivalent of 560 mm/an), with river outflow totaling only the equivalent of about 83 mm/year. This would suggest that evaporation and precipitation are the main components of the water balance. However, Beadle (1974) indicates that the main input is the rainfall falling on the surrounding highlands, and hence tributary flow. Our own analysis, in contrast to both, indicates a rainfall maximum over the lake itself, as in the case of Lake Victoria (Ba and Nicholson 1997). Thus, there is still considerable question concerning its water balance.

Tanganyika's approximate catchment area is shown in Figure 1. Its major tributaries include the Ruzizi flowing from Lake Kivu in the north and the Malagarasi, a swampy river in the east that drains the lands south of the Lake Victoria Basin. Its only outlet discharges into the Lukuga Channel and eventually into the Zaire/Congo River. This discharge has been interrupted occasionally during the

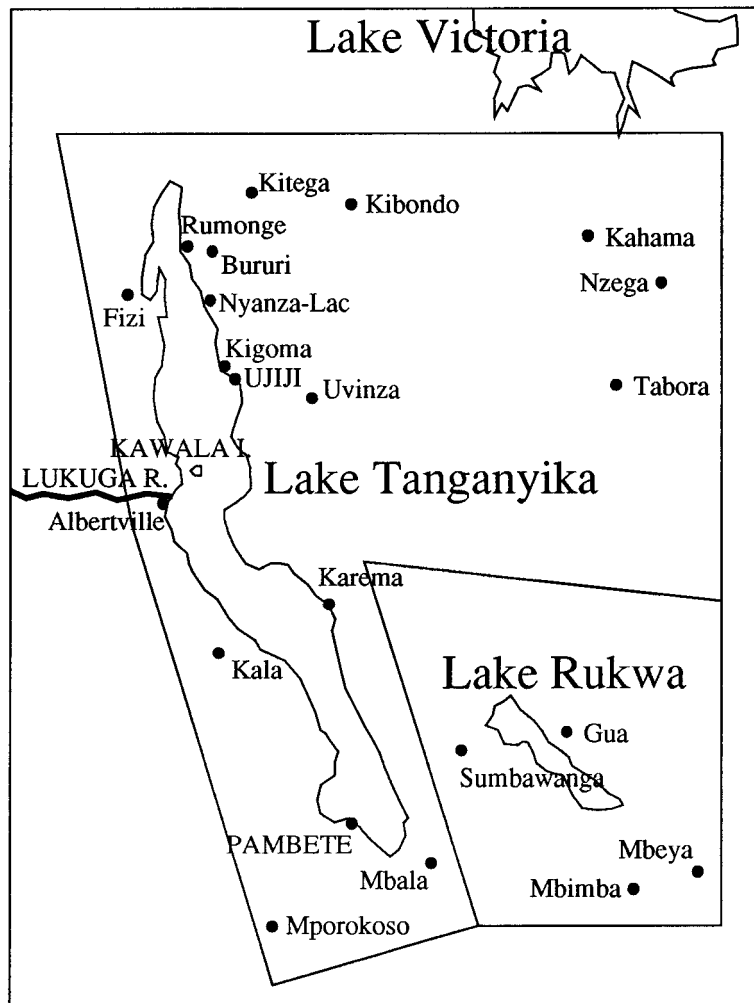


Figure 1. Map of the approximate catchment areas of Lakes Tanganyika and Rukwa. Rainfall stations utilized to calculate catchment rainfall are indicated with lower case names. Names in capital letters indicate places mentioned in the historical text.

last century (Beadle, 1974). The level of Lake Tanganyika has been measured at the pump house at Kigoma, on the eastern shore, since 1922.

Lake Rukwa, with some 3700 km<sup>2</sup> of surface area, lies to the southeast of Lake Tanganyika at about 8° S. Precipitation in the surrounding area is on the order of 800 to 1200 mm/an. As near Lake Tanganyika, precipitation in the region is highly seasonal so that the level of the lake may vary by about a meter between the wet and dry seasons. The lake is very shallow and is totally dessicated in some years. Its levels have been measured since about 1972 (Grove, 1996). Lake Rukwa is a closed

basin that has been described as a pan (Balek, 1977). Its catchment (Figure 1) includes vast areas of swamps (Beadle, 1974).

### 3. Historical Fluctuations

Several authors (e.g., Lamb, 1966; Hastenrath, 1988; Nicholson, 1981, 1995) have presented general descriptions of the fluctuations of Lake Tanganyika during the late nineteenth century. Sieger (1887) compiled much more extensive information, but did not attempt to produce an actual lake chronology. In view of the difficulty of obtaining the original source materials from a century ago, and Sieger's (1887) meticulous reporting, his compilation is utilized in lieu of the explorers' own reports. Brueckner (1890) also provided useful information, but his interest was in an overview and synthesis, hence he provides somewhat less reliable generalizations and less detail. Also, his sources are not always adequately described and information he presents may or may not be totally independent of that found in other sources described in this article.

The descriptions presented by Sieger, Brueckner and others, are summarized in Sections 3.2 and 3.3. This information is synthesized into the long-term chronologies of Lakes Rukwa and Tanganyika shown in Figures 2 and 3. The condition of the lake was of great interest to the various visitors. Lake Tanganyika was first discovered by Europeans in 1858, with the expedition of Burton and Speke. Extensive information also came from Livingstone, who traversed the region in the years 1867 to 1873, Stanley, who visited Lake Tanganyika in 1871 and 1876, and Cameron, who visited in 1874 and 1875. Later visitors included Hore (1878–1879), Stewart (1879), Thompson (1879–1880), von Wissmann (1882), Storms (1883), Giraud (1884), Lenz (1885–1887), von Wissmann und Wolf (1886–1887), Baumann (1892–1893), and Moore (1894 and 1897). These explorers related both personal observations and perceptions of the native population living along the lakeshore. From approximately 1871 to 1886, first hand reporting on Lake Tanganyika is available for nearly every year.

#### 3.1. EARLIEST GEOGRAPHICAL KNOWLEDGE OF THE LAKES

Speke and Burton had been sent by the Royal Geographical Society to find the rumored Lake 'Ujiji', believed to be the source of the Nile. They reached the lake now called Tanganyika but found that the Ruzuzi River, thought to carry the lake's outflow to the Nile, actually flowed into the lake. Lake Tanganyika was thus considered to be without outlet and hence not the Nile's source. It was later learned that surplus water is discharged into the Lukuga River, which was first seen in 1874 by Cameron. This river runs west to the upper Congo basin (Beadle, 1974), but in dry years sand bars build up and block the lake's outlet to the river. This occasional blockage, and the washing away of sandbars during wet years, complicates the evolution of the lake's levels (Lamb, 1966).

### Lake Rukwa

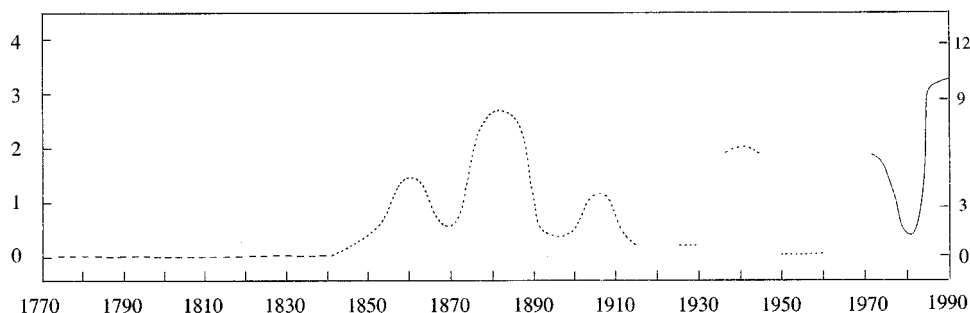


Figure 2. Fluctuations (depth in meters on left, feet on right) of Lake Rukwa since the late eighteenth century, based on historical and geographical information and modern records. Long-dashed lines indicate general periods of low levels, short-dashed lines indicate trends based on specific proxy data, and solid lines indicate the modern lake record. Depths are relative, not absolute.

### Lake Tanganyika

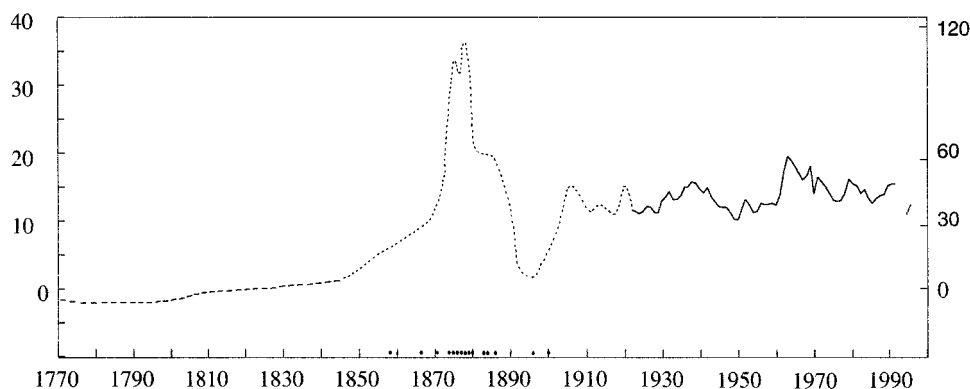


Figure 3. Fluctuations of Lake Tanganyika from the 1770 to 1990, inferred from historical and geographical information (to 1900), early rainfall records (1902 to 1921) and actual measurements (since 1922). The scale is in meters/feet above the modern gauge height. Otherwise, as in Figure 2.

There was also a certain amount of confusion about Lake Rukwa during the early days of exploration. Burton and Speke were the first Europeans to reach the area of Lake Rukwa, but they did not reach the lake itself. Natives told them in 1858 that it connected to Lake Tanganyika during wet periods. They were told that it was relatively shallow even during really large expansions, when its circumference was a six day journey or at least about 90 miles. Lake Rukwa was reportedly so shallow that even during these transgressions one could generally wade through it

Stanley, who arrived in the region in 1871, heard of a swampy plain called Likwa, the outflow of which supposedly flowed to Lake Tanganyika. On his map, he placed it where the plain of Katawi is, to the north of Lake Rukwa. The first to

step on this so-called plain was Livingstone's servant on the return trip c. 1872. He found a salty residue of a former lake bottom, crossed by a river (also called Likwa) that led to a salty inland lake. This lake was called Lake Likwa by Cameron, who visited the region in 1873/1874.

Cameron imagined Lake Rukwa to be a 'lagoon' on a plain below Lake Likwa. He was told that the Musamwira was its outlet. Lake Rukwa was actually discovered by Thompson in 1880. The basin was subsequently encircled several times by various explorers and no outlet was found.

It appears that what Cameron termed 'Lake Likwa' was the southern basin of what is today called Lake Rukwa. It did overflow into the northern basin in wetter years, becoming a freshwater lake in those years. Natives told Storms that it had previously been a fresh water lake but had become salty. To add to the confusion, nineteenth-century geographers, such as Sieger and Brueckner, apparently used the name Lake Likwa (and also Lake Leopold) to refer to the entire Lake Rukwa.

### 3.2. HISTORICAL FLUCTUATIONS OF LAKE RUKWA

Prior to the mid-nineteenth century, there are only scattered references from which to infer the condition of Lake Rukwa. Most of these refer to areas of northern Malawi some 150 to 200 km further south. Around 1770 Lake Rukwa totally dried up, leading to the deposition of a long-reigning Bungu chief (Owen et al., 1990). The rainmakers were called to Nkamanga (the Rumphu area of northern Malawi) during a severe drought in the time of the first Mlowoka or his son, within the period 1780 to 1840. Kalinga records describe an increase in emigration of people from the highlands into the Ngonde region on the northeast lakeshore, perhaps partly attributable to these drier conditions.

It is difficult to ascertain whether the latter two events were roughly synchronous with the drying up of the lake, or if they occurred in early nineteenth century. Both scenarios are possible, since there are other references to dry conditions at the latter time. During the reign of the Ngonde king Mwangonde, whose reign is genealogically dated to about 1815 to 1835, the North Rukuru River in northern Malawi dried up. The king reportedly walked across what is now the northern part of Lake Rukwa, in order to marry a woman (Owen et al., 1990). However, by the time of Burton and Speke's visit in 1858 the lake was again reasonably large (Sieger, 1887; Hobley, 1914).

In the early 1870s the lake must have again been quite low, since Livingstone's servant found only a dry plain covered by the salty residue of a former lake bottom (Sieger, 1887). Likewise Stanley, first visiting the area about the same time, had heard of the Likwa plain but not of Lake Likwa. During his second visit (1876) he had knowledge of an actual lake. Lake Rukwa probably began to rise shortly after the early visits of Livingstone and Stanley, because Cameron in 1873/1874 understood it to be a lake or lagoon, rather than the dry plain described earlier. Sieger (1887) suggests that 'Lake Likwa' probably continued to rise from about

1870 until 1875 or possibly 1878. Brueckner (1890) also interprets the descriptions to mean that 'Lake Likwa' had a high stand in the 1870s. Kjekshus (1977) indicates that Lake Rukwa reached its maximum water level when Thompson saw it in 1880 and that the lake was still at a very high stand when Kaiser was there in 1882.

The next information on Rukwa comes from Wallace and Langheld, both of whom reported in 1897 that the lake level was extremely low. By then Rukwa was perhaps one-third of its 1880 size and almost dry (Kjekshus, 1977). Langheld (1897) quotes local opinion that the lake would not return to its former level and he suggests no historical memory of earlier periods of prolonged drought. However, an early twentieth century rise did occur, because Meyer indicates that the level of Rukwa was very high in 1905 (Kjekshus, 1977). Nevertheless, this was a passing condition, as there are historical references to prolonged drought near the lake from c. 1905 to 1929 (Kjekshus, 1977). Lake Rukwa was quite small in 1914, having decreased in size considerably since first becoming known around 1860 (Hobley, 1914). It was also very low in 1929, but reached a very high stand again from 1937 to 1939. In 1950 it was again extremely low and nearly dry (Kjekshus, 1977).

The earliest rainfall data within the lake's catchment are from 1922, so these early twentieth century trends cannot be verified directly from catchment rainfall. However, the station Mbala in Zambia, some 100 km away from the lake, does show extremely low rainfall in the early 1900s and 1910s and moderately low rainfall in the 1920s. It also indicates extremely wet conditions in 1903 and moderate rainfall in 1904 and 1905, consistent with a high stand in 1905. The suggested high stands in the 1930s and the near desiccation in the 1950s correspond to high and low rainfall in the catchment itself (see Section 4), hence these historical observations are credible.

Figure 2 illustrates the general trends evident from this historical information, together with the modern record. No quantitative information is available for the historical levels except the statement, from the mid-nineteenth century, that even when the lake was large one could generally wade through it. This probably suggests a mid-nineteenth century depth of at most two to five feet. However, its two basins are separated by the relatively shallow delta of the Momba River (Grove, 1983); this could have provided a place to wade through the lake at even higher levels.

As with other African lakes, Rukwa was dry early in the nineteenth century and also during the eighteenth century, but the length of the arid interval is uncertain. It was relatively high in mid-century, reached its maximum around 1880, then fell rapidly in the last decade or so of the century. It may have been low also in the 1860s or early 1870s.

During the twentieth century, high levels occurred around 1905 and the 1930s, with low levels around 1929 and in the 1950s. During the most recent maximum of the 1980s, the lake was as deep as 3 to 4 meters, hence deeper than at any time in the nineteenth century. While this was not the case for lakes further north (Nicholson,

1997a), Lakes Malawi and Chilwa to the south did reach higher stands in recent times than during the nineteenth century (Nicholson, 1997b).

### 3.3. HISTORICAL FLUCTUATIONS OF TANGANYIKA

#### 3.3.1. *Early History of the Lake*

Very little is known about Lake Tanganyika prior to the mid-nineteenth century. Sieger (1887) suggests that the lake had a minimum during the eighteenth century, but presents scant evidence for this (see Section 3.3.2). He cites the explorer Stewart, who based his conclusions on the age of a dead tree near the lake. Stewart suggested that the high level the lake had attained in 1878 was quite unusual and had hardly ever been reached within the last 200 years (i.e., 18th and 19th centuries). Sieger (1887) also concluded that the lake had been without an outlet at least throughout the nineteenth century, since it was clear that neither Burton nor the Arabs were aware of any significant river like the Lukuga on the west bank and rumored outlets were by way of the Ruzizi or the Marungu. This would similarly suggest low lake levels throughout the early part of the nineteenth century.

Somewhat more reliable information comes from Stanley. During his visit in the 1870s, natives told him that the lake had been rising continually over the last thirty years (since c. 1845). During the 1840s the Arabs could cultivate rice on 3 miles of land to the west of the lake that was covered with water at the time of Stanley's visit (Lamb, 1966). Since that time, the western shore had advanced some 4.5 to 6 km and the depth had increased by about 0.3 m (1 foot) per year. From this, Sieger (1887) concluded that the lake was some 9 m lower in about 1845 than in 1876.

Sieger also suggested that the lake's rise had been gradual from the end of the 1840s to the end of the 1850s. He probably based this on the fact that Lake Tanganyika still had no outlet when the first European expedition (Burton and Speke) reached it in 1858 (Lamb, 1966). In 1867 Livingstone noticed signs that the lake had been rising (Sieger, 1887). Brueckner (1890) indicates a rise of Lake Tanganyika in the 1860s, presumably on the basis of Livingstone's observations, and he also accepted the idea that the lake had been rising since the 1840s.

#### 3.3.2. *High Stands in the 1870s*

From 1870 on the the rise of the lake was particularly steep, according to Thompson (Sieger, 1887). In 1871 the shore was at Ujiji, where Stanley and Livingstone met (Lamb, 1966). From then until about 1875 or possibly 1878 Lake Tanganyika continued to rise and maintained a strong maximum stand. The evidence for this is definitive, as there were frequent visitors to the lake in the 1870s and each left very detailed descriptions.

In 1874 Cameron (see Sieger, 1887) confirmed that the lake was steeply rising, noting an advance of the lake of about 1/2 km at Kawele (the capital of Ujiji) with respect to the time of Speke and Burton's visit in 1858. He also saw evidence of the rise at the mouth of the Musamwira at Mfume. An outlet formed in this year

from the Lukuga River, which previously flowed into the lake. Its water backed up over the flat divide and it became a discharge channel carrying lake water to the Zaire/Congo River, but its mouth was nearly barred by a double sandbar. The river was in high flood. Cameron wrote that in this same year he went four or five miles down the Lukuga river from the lake until navigation was rendered impossible owing to the masses of floating vegetation. The natives told him it might be possible to cut passages for canoes. Cameron also found a landward current of 1 to 1.5 knots and noted that the embouchures of some small streams flowing into the river were unmistakably turned from the lake, and that the weed set in the same direction (Lamb, 1966, Sieger, 1887). Thus Lake Tanganyika was very high in 1874 and had an outlet for the first time (Brueckner, 1890).

Thompson (1880) wrote in the Proceedings of the Royal Geographical Society that Lake Tanganyika rose 9 to 10 feet at Pambete, on the south shore, during 1875. The water reached to the village and to what later became Stewart's camp in 1879. The lake's rise was a result of excessive rains and the lake maintained this flood level for one month. Stewart suggested that this rise, and the excessive rainfall, had been in 1873, but he appears to have gotten the year wrong as a result of confusing Livingstone's 1869 and 1871 visits (Sieger, 1887). In the years immediately following 1875, the lake rose during each rainy season to a level 6 feet 6 inches above the level of autumn 1879, thus 2 feet six inches below the absolute maximum.

During his visit in 1876, Stanley saw at many locations evidence that the high stands continued after the time of Cameron's visit (1874). He observed signs on the western shore that confirmed the rise indicated by Cameron, stating that he had found at least a hundred points of evidence for this. On the eastern shore at Ujiji (Kawele) he saw trees underwater which had been on the marketplace 60 m from the shore in 1871 (Sieger, 1887). A landbridge that Livingstone had traversed was now underwater. Since Livingstone's visit to the lakeshore at Liende in 1867, the lake had advanced about 1 km. However, the outlet of the lake was once again barred. Visiting in the dry season (July), Stanley said that the Lukuga was blocked after only a few miles and that its mouth was 2500 yards wide, narrowing after a mile to 880 yards and after another mile to 400 or 500 yards (Lamb, 1966; Sieger, 1887). Within a further hour's journey downstream, the open water was ending; an abundance of papyrus narrowed it to 40 yards. The papyrus soon thereafter closed up the creek from bank to bank. At the point where Cameron had stopped in 1874, the river was so dry it could be crossed on 'dry' feet. The divide was marked by marsh, grass and standing pools, but then suddenly a westward current became perceptible. This small river, called the Mitwanzi, was colder than the Lukuga, to the east. However, the spring rains of 1876 led to a temporary spill over of the Lukuga into the Mitwanzi. Sieger (1887) concludes from this that in the years after 1874 the outlet was only intermittent: the Lukuga overflowed and carried water into the Congo during the wet season but this situation was interrupted during the dry season. Cameron, during his 1874 visit, was also of this opinion, as were Hore and Storms later.

Little information is available for the year 1877. Thompson initially thought that the lake's recession began in this year, but he later reported that the lake's maximum was in 1878, just prior to his own 1879 visit. There may have been a brief recession in 1877, but Lake Tanganyika clearly returned to higher stands in the following year. Brueckner (1890) also indicated that the maximum outflow occurred in 1878 and diminished afterward. However, Hore said natives indicated to him in 1878 that they considered the lake to be rising (Sieger, 1887). 1878 was a year of torrential rains that turned the Lukuga into an outlet, according to Arabs' reports reaching Ujiji. Hore's visit during the rainy season of 1879 confirmed the Arabs' reports that a true outlet had formed in 1878 (Sieger, 1887). The breaking through of the outlet supposedly caused a flood on the Zaire/Congo River. Sieger and Storms also felt that the Lukuga outlet was actually created in this year, having earlier been only intermittent.

Observations of both Stewart and Thompson in 1879 clearly indicated a further rise of the lake after Stanley's visit in 1876. One example is from Pambete on the south shore: trees not yet withered, but lying on newly inundated ground some 180 to 270 meters from the banks of the lake (Sieger 1887). Thompson, in December of 1879, found an indisputably openly flowing river, free of the vegetation obstructions found by Stanley in 1876. It was running in a deep channel between clearly cut banks (Lamb, 1966). Beadle (1974) indicated that the Lukuga had been in flood in 1879. Hore, visiting during the 1879 rainy season, and soon afterward Thompson saw a large river with a tremendous current. Lake Tanganyika was high in this year (Brueckner, 1890), but the breaking through of the outlet in 1878 caused the lake to stop rising (Sieger, 1887).

### 3.3.3. *Regression in the 1880s*

During Lake Tanganyika's maximum, the water level at Ujiji, on the east shore, rose 8 feet above the level during Cameron's time. It is unclear from the previous description if the maximum actually occurred in late 1878 or early 1879. It is indisputable, however, that the recession had begun by early 1879. According to Hore's measurements, the lake sank some 2 feet from March to the end of May in 1879. Newly emerged islands on Hore's map from this year provide further proof of the recession. On the south shore, at Pambete, Thompson also reported that a recession began in 1878 and that the lake fell 8 or 10 feet from the end of 1878 until Christmas 1879 and it paralleled a fall at Lukuga. Sieger (1887) thus concluded from the available observations that Lake Tanganyika (as well as Leopold, Malawi and Chilwa) began falling at the end of the 1870s and that the fall continued until 1886.

By the beginning of 1880, the lake level at Ujiji had fallen a total of 7 feet since March 1879 and at the end of June it reached the strandline of 1874. By August it was already 10 feet, 4.5 inches below the mark from March 1879 (Sieger, 1887). Even during the rainy season there was no rise of the lake, merely a break in this recession. Within the first two months of 1880 a recession of the Lukuga was also

quite noticeable and a sand bar, similar to that observed by Cameron at its mouth in 1874, had built up. The recession in 1880 was linked to very dry conditions in Tanzania in that year. Only 729 mm of rain fell at Tabora and there was famine at many places between Tabora and the Coast (Petermann's *Mitteilungen*, 1881). Nevertheless, the outflow to the Lukuga River was still strong (Lamb, 1966).

From about 1880 on the lake fell 30 to 40 feet over fifteen to twenty years (Lamb, 1966). By 1883 the lake was already relatively low, but it still had not reached the low level it had attained prior to its rise (Brueckner, 1890). Storms noted a 1 to 1.5 km recession of the lake at the Lukuga inlet by June of 1883. The station Karema, which was on the lakeshore at the mouth of the Musamwira in the winter of 1879/1980, was five years later some 1100 yards (1 km) landwards, indicating a significant recession of the lake by around 1884. In this year Giraud also noted signs of a recession. In 1886 Lenz found the city of Ujiji quite distant from the lake shore and observed signs of continued recession. Hore, on Kawala Island near the Lukuga, found that the lake had fallen 15 feet since his visit in 1878 (Sieger, 1887). Presumably the lake once again lacked an outlet. Lamb (1966) indicates that in 1900 there was no outlet and that the lake rose 4 or 5 feet. It remained more or less low, with only small fluctuations, for over half a century, until its sharp rise in 1961.

#### 3.3.4. *Synthesis and Overview*

The fluctuations described in Sections 3.3.1 to 3.3.3 are summarized in Figure 3, using very approximate levels. These are given in feet, as this unit was used in most of the explorers' reports. The levels in this graph must be considered imprecise. For the period 1858 to 1886 the relative levels with respect to the maximum of 1878 are probably reasonably accurate, within perhaps 3 feet. The heights relative to early twentieth century means are based only on Lamb's (1966) statement that the lake fell some 30 to 40 feet in the fifteen to twenty years after 1880. Hence, these are less precise. Trends in the early twentieth century are very roughly approximated from catchment rainfall (Figure 5).

Prior to 1845 Lake Tanganyika is known only to have been relatively low; the degree of recession and its year-to-year persistence are not known. The level indicated in Figure 3 is roughly on par with modern levels. However, it could have been considerably lower, because a major arid interval occurred in the early nineteenth century, producing extremely low levels and even desiccation of smaller lakes throughout eastern Africa and elsewhere on the continent (Nicholson, 1995, 1997a,b; Verschuren, 1996).

Lake Tanganyika began a general rise after 1845 and was relatively high by the time of Speke and Burton's visit in 1858. The lake began to rise steeply in the 1870s and reached a maximum in late 1878 or early 1879. It subsequently began a rapid recession, possibly accelerated by the creation of an outlet in 1878. The recession was particularly rapid in 1879 and 1880, but it appears to have continued until at least 1896 and possibly as late as 1899. It rose around 1900 but was

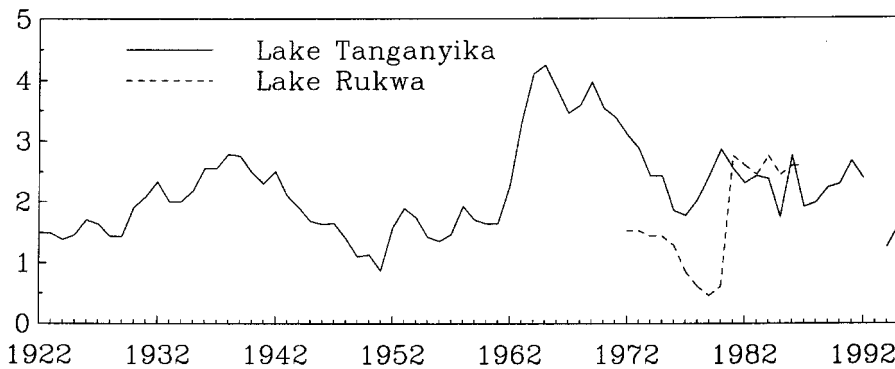


Figure 4. Measured fluctuations of Lakes Tanganyika and Rukwa during the twentieth century. Levels on the left axis are given in meters above gauge zero for Lake Tanganyika (the Kigoma pumphouse gauge) and in relative depth for Lake Rukwa.

nevertheless relatively low through the 1900s and 1910s. Subsequent trends are described quantitatively in Section 4.1.

Although the details of the lake's fluctuations cannot be reconstructed with great precision, the historical information suffices to definitely establish the nearly 30 foot rise of the lake in the 1870s and the subsequent recession in the 1880s. A similar high stand has not since been achieved.

#### 4. Relationships to Rainfall

##### 4.1. MODERN LAKE LEVEL FLUCTUATIONS

Figure 4 shows the fluctuations of Lakes Tanganyika and Rukwa since quantitative measurements commenced in the twentieth century (1922 for Tanganyika and 1972 for Rukwa). The levels of Lake Rukwa are based on a graph in Grove (1996). The data for Tanganyika have been obtained from four sources. Bargman et al. (1965) present minimum and maximum levels for each year from 1923 to 1964, presumably at Kigoma. Kite (1981) gives beginning of the year lake levels at Bujumbura from 1950 to 1979. Monthly levels at Kigoma for the period 1951 to 1960 are published in World Weather Records (U.S. Dept. of Commerce 1967). Monthly levels at the Kigoma pump house for the period 1975 to 1995 were provided by the government hydrologic service of Tanzania. This appears to be a continuation of the World Weather Record series. Because the January values are close to the annual mean, the mean of the minimum and maximum levels of Bargman are roughly comparable to those of the other sources. All data were plotted independently and showed very similar interannual fluctuations. Because of differences in the height of the gauge, the Bujumbura time series was adjusted to the January levels at the Kigoma gauge before being plotted in Figure 4.

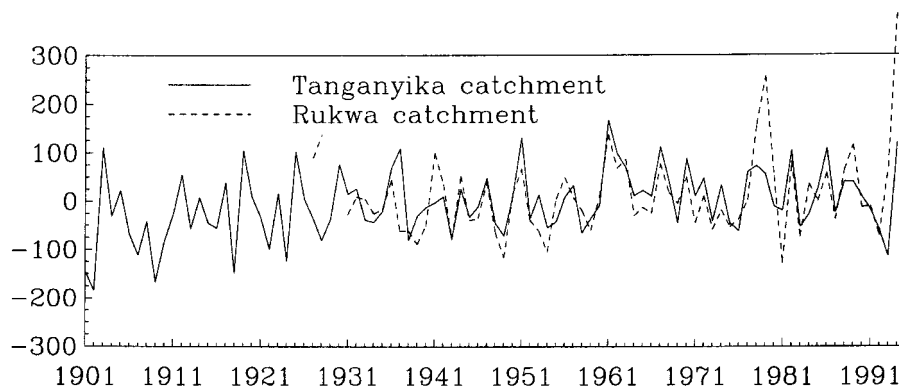


Figure 5. Rainfall in the catchment areas of Lakes Tanganyika and Rukwa, expressed as a regionally averaged percent standard departure.

The levels of Tanganyika were relatively low in the 1920s and 1950s, periods of low rainfall throughout East Africa (Nicholson, 1995). The lake rose dramatically, nearly 2 meters, between 1961 and 1962. Such an abrupt rise is evident in the lakes throughout East Africa (Nicholson, 1997a,b; Lamb, 1966). Lake Tanganyika's levels peaked in 1965 and the lake began to slowly recede. However, its levels remained relatively high until the 1990s, with brief recessions during the mid-1970s and mid-1980s. The lake fell nearly 1.5 m between 1990 and 1994. Lake Rukwa fell throughout the 1970s, but rose abruptly around 1980 and maintained high stands throughout that decade. These trends are quite different than those seen in Lake Tanganyika. Earlier in the century, the lakes showed more similar trends. Historical evidence (Section 3.2) indicates that Lake Rukwa was very low in the late 1920s and nearly dry in the 1950s, the times of the strongest twentieth century regressions of Lake Tanganyika.

#### 4.2. CORRELATIONS BETWEEN CATCHMENT RAINFALL AND LAKE LEVELS

The relationship between rainfall variability and lake level is examined, using rainfall data from the archive described in Nicholson (1986). Figure 5 shows rainfall fluctuations for the catchment areas of both lakes, with rainfall represented as a spatially-averaged standardized departure, based on the stations shown in Figure 1. The number of stations available in the catchment in each year is indicated in Table I. The series have been adjusted for the change in variance resulting from a change in the number of stations comprising the series, following the procedure described in Nicholson (1986). This step is required only when the number of stations falls below 6.

A close relationship between rainfall variability and lake levels is clearly apparent for Lake Tanganyika. Rainfall was low in the 1920s and 1950s, when the lake was low, and it was high in the 1960s and the late 1970s, as the lake began to rise.

TABLE I

Number of rainfall stations in the catchments of Lakes Tanganyika and Rukwa by year from 1901 to 1994

Year	Tanganyika	Rukwa	Year	Tanganyika	Rukwa
1901	1		1948	15	3
1902	1		1949	15	3
1903	1		1950	14	3
1904	1		1951	15	3
1905	2		1952	15	3
1906	2		1953	15	3
1907	2		1954	15	3
1908	2		1955	15	2
1909	2		1956	14	3
1910	2		1957	15	2
1911	2		1958	14	3
1912	2		1959	12	3
1913	1		1960	9	3
1914	1		1961	9	3
1915	1		1962	9	4
1916	1		1963	9	4
1917	1		1964	9	4
1918	1		1965	9	4
1919	1		1966	9	4
1920	1		1967	9	4
1921	2		1968	9	4
1922	5	1	1969	9	3
1923	5	0	1970	9	4
1924	5	0	1971	7	4
1925	6	1	1972	7	4
1926	6	0	1973	8	3
1927	9	1	1974	8	3
1928	11	2	1975	8	3
1929	9	0	1976	7	3
1930	9	0	1977	7	3
1931	13	1	1978	8	3
1932	13	2	1979	8	3
1933	13	2	1980	7	3
1934	14	2	1981	9	4
1935	14	2	1982	9	3
1936	11	2	1983	8	4
1937	14	2	1984	8	4
1938	16	2	1985	8	4
1939	13	2	1986	8	3
1940	14	2	1987	9	3
1941	14	2	1988	9	3
1942	14	3	1989	9	3
1943	14	3	1990	9	4
1944	15	3	1991	8	4
1945	15	3	1992	7	2
1946	15	3	1993	6	3
1947	15	3	1994	5	3

TABLE II

Correlation between the level of Lake Tanganyika and rainfall in its catchment. In the first five columns, rainfall is lagged 1 to 5 years with respect to the lake level. Since the lake level is given for the beginning of the year, a one year lag is equivalent to rainfall during the past twelve months. The sixth column is a five-year running mean. The last column is the correlation between the change of lake level in a given year and rainfall in the same year. For calculating correlations, the standardized departures of rainfall shown in Figure 5 are utilized

Lag-correlation (years)					Running	Lake level
-1	-2	-3	-4	-5	mean	change
0.35	0.46	0.35	0.26	0.20	0.80	0.43

Nevertheless, significant differences are apparent. For example, rainfall peaks in 1961, but the lake doesn't peak until 1965.

The relationship between lake levels and rainfall is quantified using linear correlations based on data for the period 1922 to 1994 (Table II). The lake level in year  $i$  is first correlated with rainfall in the previous year  $i - 1$ , since the lake levels utilized here represent its height at the beginning of the year. Correlations with rainfall lagged by two to five years and with five-year running means of rainfall are also indicated. The change in lake level between year  $i$  and year  $i - 1$  is also correlated with rainfall in year  $i - 1$ . All correlations are statistically significant at the 5% level or higher.

For individual years the highest correlation, 0.46, is between lake-level and rainfall two years prior. Both streamflow records and the rapid rise of the lake following the rains of 1961 indicate that this cannot be explained by the residence time of runoff in the soil. A likely explanation relates to the strong five-year quasi-periodicity in rainfall in the region, as demonstrated by Nicholson and Entekhabi (1986) and illustrated in Figure 6. About 30% of the variability of rainfall is associated with this cycle. Since the lake rises or falls in response to rainfall, a five-year periodicity suggests that the lake will generally be rising or falling for a two to three year period. Hence, the apparent lagged response. The equally high correlation between rainfall and the change in lake level (0.43) is consistent with this interpretation.

Despite this high degree of correlation, Lake Tanganyika (Figure 4) clearly exhibits lower frequency fluctuations than does catchment rainfall (Figure 5). For this reason, correlations with a multi-year integral of rainfall are also calculated. A five-year averaging period is chosen because of the five-year cycle in rainfall. The stronger similarity of the lake-level fluctuations and the running mean of rainfall is also clearly apparent in a graphical comparison (Figures 4 and 7). The correlation

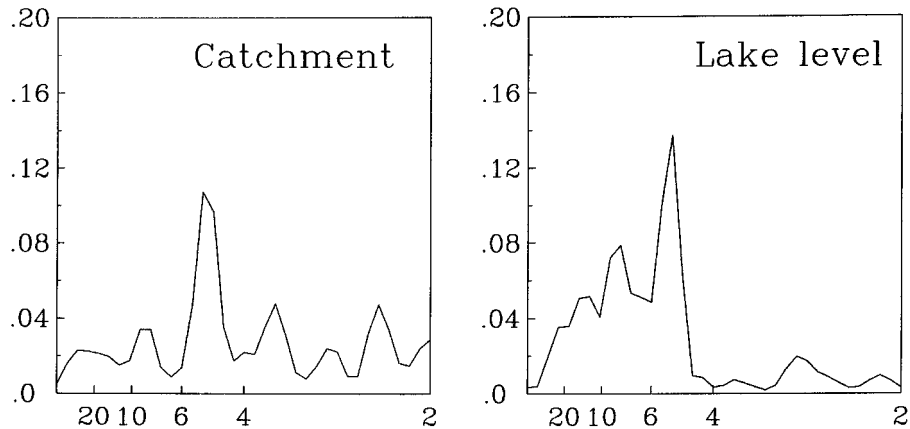


Figure 6. Spectra of rainfall in the Lake Tanganyika catchment and of lake-levels. For the latter, the dominant low-frequency fluctuations have been filtered out by using a five-year running mean on the data before the spectral analysis is applied.

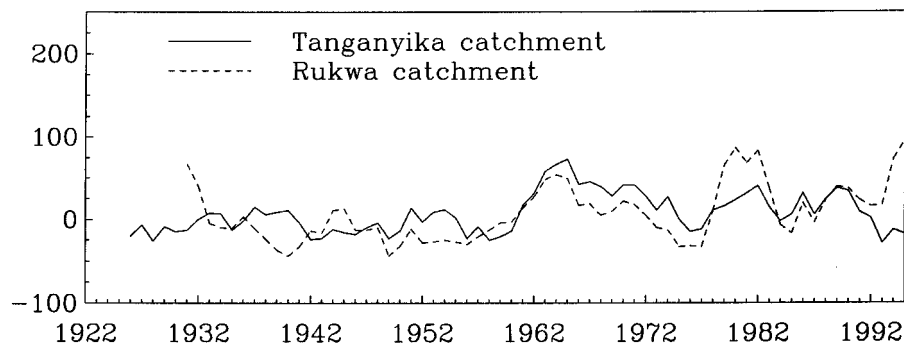


Figure 7. Five-year running means of rainfall in the catchments of Lakes Tanganyika and Rukwa. These are averages of the data in Figure 5.

between lake-levels and mean rainfall for the previous five years is 0.80. When the higher frequency fluctuations of the lake are filtered out by using a five-year running mean, a spectral analysis of its levels shows the same five-year peak apparent in rainfall in its catchment (Figure 6).

Rainfall in the Lake Rukwa catchment is also shown in Figures 5 (individual years) and 7 (five-year running means). Correlations are not calculated because the lake-level series is so short. A comparison with Figure 4, however, illustrates some aspects of the lake-level/rainfall relationship.

In the case of Lake Rukwa, a true lag of the lake with respect to catchment rainfall is apparent. Although rainfall had been decreasing since 1970, the lake showed little change until 1976; its minimum during 1979 corresponded to the strong peak in catchment rainfall. The lake did not begin to rise until 1980, although rainfall had been quite high since 1977. It peaked in 1981, but remained high until at least 1987, despite low rainfall in the early 1980s. The lagged response to higher rainfall

probably reflects the residence time of the inflow in the surrounding swamps. The maintainance of the high levels throughout the 1980s is probably related to the characteristic water balance of closed basin lakes. The lake will keep rising as long as rainfall on the lake plus inflow exceeds evaporation and it will maintain its level as long as the inputs are roughly equal to evaporation.

## 5. Summary and Conclusions

The historical fluctuations of Lake Tanganyika and Rukwa show strong parallels. Both appear to have been low in the late eighteenth and nineteenth centuries, with a rise beginning in the 1840s. Both rose rapidly in the 1870s, peaking within the period 1878 to 1880, and abruptly declining in the 1880s. A moderate regression of Rukwa likely took place prior to 1870. A similar trend is not evident in Lake Tanganyika, but neither can it be ruled out, since the observations of Speke and Burton (1858) and Livingstone (1867) are not very precise. Another lake minimum occurred in the 1890s, when both were extremely low. Both recovered to moderately high stands around 1905.

Within the twentieth century, the trends of these lakes show greater differences, perhaps due to the more precise record available. Both were low in the late 1920s, high in the late 1930s and extremely low in the 1950s. However, during the recent period when Rukwa was gauged, the trends are more dissimilar. Lake Rukwa fell during the 1970s, when Tanganyika was rising. It rose abruptly in 1980 and maintained high stands throughout that decade. Tanganyika maintained low to moderate levels throughout the 1970s and 1980s.

These general trends are remarkably similar to those of East African lakes further north: Naivasha, Victoria, Turkana and Stefanie (Nicholson, 1997a). Some of the trends are apparent further south, in Malawi and Chilwa as well (Nicholson, 1997b). These lakes were high in mid-nineteenth century and receded sharply in the 1880s, maintaining low levels from the 1890s or earlier throughout the first few decades of the twentieth century. However, the nineteenth century maxima in Malawi and Chilwa occurred earlier, in the 1850s, and a regression was apparent in the 1860s, as was the case with Rukwa. Like Tanganyika and Rukwa, Lakes Malawi and Chilwa rose to relatively high stands in the 1930s but retained them, while the more northern lakes again regressed to low stands in the 1950s. From the 1950s on their fluctuations are roughly out of phase with Lakes Tanganyika and Rukwa and others further north. This opposition between southern and equatorial Africa is the most common climatic pattern of the twentieth century (Nicholson, 1986).

The trends of Lakes Tanganyika and Rukwa are generally explained by rainfall in their catchments. Nevertheless, the responses to rainfall variability are sometimes dissimilar because Lake Rukwa is a closed basin and its level can fall only when evaporation exceeds the total input from precipitation plus inflow. This may

be why Lake Rukwa's regression in the 1880s occurred at least four years later than Tanganyika's. Likewise, it maintained a high stand throughout the 1980s, following the high rains of 1978 and 1979, despite relatively low rainfall in the 1980s.

Our analysis suggests that Lake Rukwa, owing to its closed basin nature, shows an immediate response to an increase in rainfall, but may exhibit a delayed response to a reduction in rainfall. Lake Tanganyika shows a clearer relationship to rainfall, with the best correlation being with five-year running means of rainfall. The most direct relationship is between annual rainfall and the change of lake level during the course of the year. Because of this, and the strong five-year cycle in rainfall variability in its catchment, its highest correlation with annual rainfall is when rainfall is lagged two years with respect to lake-level.

These results demonstrate the complexity of the rainfall/lake-level relationships. If one wishes to interpret the lakes' historical or paleo-fluctuations, the nature of the lakes' response to rainfall must be well understood. This requires that the water balance of each lake be well established, so that water balance models can be 'inverted' to quantify past lake level fluctuations in terms of rainfall.

### Acknowledgements

This work was supported by grants from NOAA (No. NA46GP0285) and the National Science Foundation (No. ATM9417063).

### References

- Ba, M. B. and Nicholson, S. E.: 1997, 'Analysis of Convective Activity and its Relationship to the Rainfall over the Rift Valley Lakes of East Africa During 1983–1990 Using the METEOSAT Infrared Channel', *J. Clim. Appl. Meteorol.*, in press.
- Balek, J.: 1977, *Hydrology and Water Resources of Tropical Africa*, Elsevier, Amsterdam, p. 208.
- Bargman, D. J., Lumb, F. E., and Moerth, H. T.: 1965, 'Lake Levels in East Africa', Proceedings of the 1965 Army Conference on Tropical Meteorology, Miami Beach, pp. 2–13.
- Beadle, L. C.: 1974, *The Inland Waters of Tropical Africa*, Longman, London, p. 365.
- Brueckner, E.: 1890. *Klimaschwankungen seit 1700*, E. Holzöl, Vienna, p. 324.
- Butzer, K. W., Isaac G. L., Richardson, J. L., and Washbourn-Kamau C.: 1972, 'Radiocarbon Dating of East African Lake Levels', *Science* **175**, 1069–1076.
- Flohn, H.: 1987, 'East African Rains of 1961/1962 and the Abrupt Change of the White Nile Discharge', *Palaeoecology of Africa* **18**, 3–18.
- Grove, A. T. and Goudie, A. S.: 1971, 'Former Lake Levels and Climatic Change in the Rift Valley of Southern Ethiopia and Elsewhere in Tropical Africa', *Nature* **234**, 403–405.
- Grove, A. T.: 1983, 'Evolution of the Physical Geography of the East African Rift Valley Region', in Sims, R. W., Price, J. H., and Whalley, P. E. S. (eds.), *Evolution, Time and Space: The Emergence of the Biosphere*, Academic Press, London and New York, pp. 115–155.
- Grove, A. T.: 1996, 'African River Discharges and Lake Levels in the Twentieth Century', in Johnson, T. C. and Odada E. (eds.), *The Limnology, Climatology and Paleoclimatology of the East African Lakes*, Gordon and Breach, Amsterdam, pp. 95–100.

- Halfman, J. D. and Johnson, T. C.: 1988, 'High-resolution Record of Cyclic Climatic Change During the Past 4 Ka from Lake Turkana, Kenya', *Geology* **16**, 496–500.
- Hastenrath, S. L.: 1988, *Climate and Circulation of the Tropics*, Dordrecht, Reidel.
- Hobley, M.: 1914, 'The Alleged Desiccation of East Africa', *Geogr. J.* **44**, 467–470.
- Kite, G. W.: 1981, 'Recent Changes in Level of Lake Victoria', *Hydrological Sciences Bulletin* **26**, 233–243.
- Kjekshus, H.: 1977, *Ecology Control and Economic Development in East African History*, University of California Press, Berkeley, p. 215.
- Kraus, E. B.: 1955, 'Secular Changes of Tropical Rainfall Regimes', *Quart. J. Roy. Meteorol. Soc.* **81**, 198–210.
- Lamb, H. H.: 1966, 'Climate in the 1960s', *Geogr. J.* **132**, 183–212.
- Langheld, W.: 1897, 'Bericht des Hauptmanns Langheld ueber seine Expedition nach Unyamwezi', *Deutsche Koloniale Berichte VIII*, pp. 511–512.
- Nicholson, S. E.: 1979, 'Revised Rainfall Series for the West African Subtropics', *Mon. Wea. Rev.* **107**, 620–623.
- Nicholson, S. E.: 1981, 'The Historical Climatology of Africa', in Wigley, T. M. L., Ingram, M. J., and Farmer, G. (eds.), *Climate and History*, Cambridge Press, Cambridge, pp. 249–270.
- Nicholson, S. E.: 1986, 'The Spatial Coherence of African Rainfall Anomalies: Interhemispheric Teleconnections', *J. Clim. and Appl. Meteorol.* **25**, 1365–1381.
- Nicholson, S. E.: 1995, 'Environmental Change within the Historical Period', in Goudie, A. S., Adams, W. M. and Orme, A. (eds.), *The Physical Geography of Africa*, Oxford University Press, Oxford, pp. 60–75.
- Nicholson, S. E.: 1996, 'A Review of Climate Dynamics and Climate Variability in Eastern Africa', in Johnson, T. C. and Odada, E. (eds.), *The Limnology, Climatology and Paleoclimatology of the East African Lakes*, Gordon and Breach, Amsterdam, pp. 25–56.
- Nicholson, S. E.: 1997a, 'Historical Fluctuations of Lake Victoria and Other Lakes in the Northern Rift Valley of East Africa', in Lehman, J. T. (ed.), *Environmental Change and Response in East African Lakes*, Kluwer, Dordrecht, pp. 7–35.
- Nicholson, S. E.: 1997b, 'Fluctuations of Rift Valley Lakes Malawi and Chilwa During Historical Times: A Synthesis of Geological, Archaeological and Historical Information', in Lehman, J. T. (ed.), *Environmental Change and Response in East African Lakes*, Kluwer, Dordrecht, pp. 207–231.
- Nicholson, S. E. and Entekhabi, D.: 1986, 'The Quasi-Periodic Behavior of Rainfall Variability in Africa and Its Relationship to the Southern Oscillation', *J. Clim. Appl. Meteor.* **34**, 311–348.
- Owen, R. B., Crossley, R., Johnson, T. C., Tweddle, D., Kornfield, I., Davison, S., Eccles, D. H., and Engstrom, D. E.: 1990, 'Major Low Levels of Lake Malawi and Their Implications for Speciation Rates in Cichlid Fishes', *Proc. R. Soc. Lond. B* **240**, 519–553.
- Sieger, R.: 1887, 'Schwankungen der innerafrikanischen Seen', *Verein der Geographie, Jahresbericht*, University of Vienna, Vienna, pp. 1–60.
- Spigel, R. H. and Coulter, G. W.: 1996, 'Comparison of Hydrology and Physical Limnology of the East African Great Lakes: Tanganyika, Malawi, Victoria, Kivu and Turkana (with reference to some North American Great Lakes)', in Johnson, T. C. and Odada, E. (eds.), *The Limnology, Climatology and Paleoclimatology of the East African Lakes*, Gordon and Breach, Amsterdam, pp. 103–139.
- Stager, J. C., Cumming, B., and Meeker, L.: 1997, 'A High-resolution 11,400-year Diatom Record from Lake Victoria, East Africa', *Quatern. Res.* **47**, 81–89.
- U.S. Department of Commerce: 1967, *World Weather Records 1951–60*, Washington, D.C., p. 545.
- Verschuren, D.: 1996, 'Comparative Paleolimnology in a System of Four Shallow Tropical Lake Basins', in Johnson, T. C. and Odada, E. (eds.), *The Limnology, Climatology and Paleoclimatology of the East African Lakes*, Gordon and Breach, Amsterdam, pp. 559–572.

(Received 27 August, 1997; in revised form 6 May, 1998)