8. DECADAL AND CENTURY-SCALE CLIMATE VARIABILITY IN TROPICAL AFRICA DURING THE PAST 2000 YEARS

D. VERSCHUREN (dirk.verschuren@UGent.be)
Research group Limnology
Department of Biology
Ghent University
Ledeganckstraat 35
B-9000 Gent
Belgium

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Introduction

Holocene climate in high-latitude regions of the world has been relatively stable compared to glacial climates. In contrast, tropical Africa and other low-latitude continental regions were marked by a succession of millennium-scale wet and dry episodes, separated by rather abrupt transitions (Gasse and Van Campo 1994; Lamb et al. 1995; Gasse 2000). These continent-wide fluctuations in the balance of rainfall and evaporation must somehow have resulted from large-scale variation in the position or intensity of large-scale tropical monsoon systems, but their relationship to Holocene climate variability in extra-tropical regions (e.g., Bond et al. (2001)) and the likely mechanisms of external climate forcing are only just beginning to be revealed (Gupta et al. 2003; Hoelzmann et al., this volume).

Compared to this marked hydrological instability of African climate during the early and middle Holocene, the last 2000 years have commonly been thought of as rather stable and uneventful. This idea can be traced back to the first reviews of late-Quaternary vegetation and lake-level change in Africa (Butzer et al. 1972; Livingstone 1975; 1980; Hamilton 1982), which in their focus on the prominent late-Glacial and early-Holocene events found little worth mentioning in the late Holocene. Low time resolution and poor age control meant that the last 2000 years were typically represented by just a few data points floating on an interpolated section of the time line. In addition, evidence for 20th-century landscape disturbance was often missing because soft surface muds had not been recovered, or had been discarded. This lack of a reference frame for signatures of pre-modern human impact, together with the assumption of relative climatic stability, helped perpetuate among palaeoecologists, archaeologists, and geomorphologists the paradigm that most evidence for vegetation and landscape change in tropical Africa younger than 2000 years is due to human activity (Taylor 1990; Jolly et al. 1997; Eriksson 1998).

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Yet already 20 years ago, Crossley et al. (1984) assembled dated geomorphological and archaeological evidence from the fluctuating shorelines of lakes Chilwa and Malawi which suggested that climatic conditions during the last millennium in south-eastern tropical Africa must have been quite unstable, involving moisture-balance fluctuations large enough to seriously affect the living conditions of indigenous peoples. Early geomorphological and sedimentary data from Lake Bosumtwi in Ghana (Talbot and Delibrias 1980) likewise indicated that humid West Africa experienced at least one episode of severe drought within the last millennium comparable in magnitude to the major droughts of the middle Holocene. Possible synchroneity with similar events reported from Lake Chad in the Sahel (Maley 1973) and Lake Abhé near the Red Sea (Gasse 1977) clearly suggested that the last 2000 years of Africa's climate history were punctuated by major, century-scale climatic anomalies of possibly continent-wide extent. Recognising the ambiguity of some disturbance indicators in African pollen records (Taylor et al. 2000), modern palaeoecological studies attempt to distinguish between the effects of climate change and human activities on African vegetation, and these now yield clear signatures of climate-driven vegetation change during the last millennium, both in semi-arid Central Kenya (Lamb et al. 2003) and the humid forests of Western Uganda (Marchant and Taylor 1998).

Given the reality of African climatic instability at all time scales (Nicholson 2000), one of the great challenges of tropical palaeoclimatology today is to reconstruct Africa's climate history with a time resolution and precision sufficient to elucidate the causes and pace-makers of decadal to century-scale rainfall variability, to help evaluate how future interaction of anthropogenic climate forcing with natural climate dynamics may change the frequency and intensity of severe, socio-economically disruptive drought.

This chapter presents a brief review of the available evidence for climate change in tropical Africa during the past 2000 years, in an attempt to identify patterns of spatial coherence which may reveal links with the climate history of extra-tropical regions, and hint at possible causal mechanisms. It will be evident that the limited age control of much of the older published work hampers evaluation of the synchroneity of climate events between sites: only a handful of the available climate-proxy records extend beyond the last 300–400 years with better than century-scale resolution and age control.

High-resolution climate-proxy archives in tropical Africa

Documentary records

For all practical purposes, in tropical Africa the 'historical' period can be said to have started in the mid-19th century with state-sponsored European exploration, and then colonisation, of the continent's interior. Instrumental weather records are mostly limited to the last 120 years, and Africa's long cultural history notwithstanding, documentary records of weather-related information extending to before AD 1800 are rare (Fig. 1; see Nicholson (2001a, b) for the period from AD 1800). Old chronicles that do exist are often discontinuous, deal with the societal impact of anomalous weather rather than the weather events themselves, and are difficult to normalise with regard to long-term climate variability because of interference from various factors other than climate. One of the least tractable of these factors is the reference period for a particular observation. Often this is only a decade or so, and rarely longer than the observer's own life-time experience. Consequently, a few

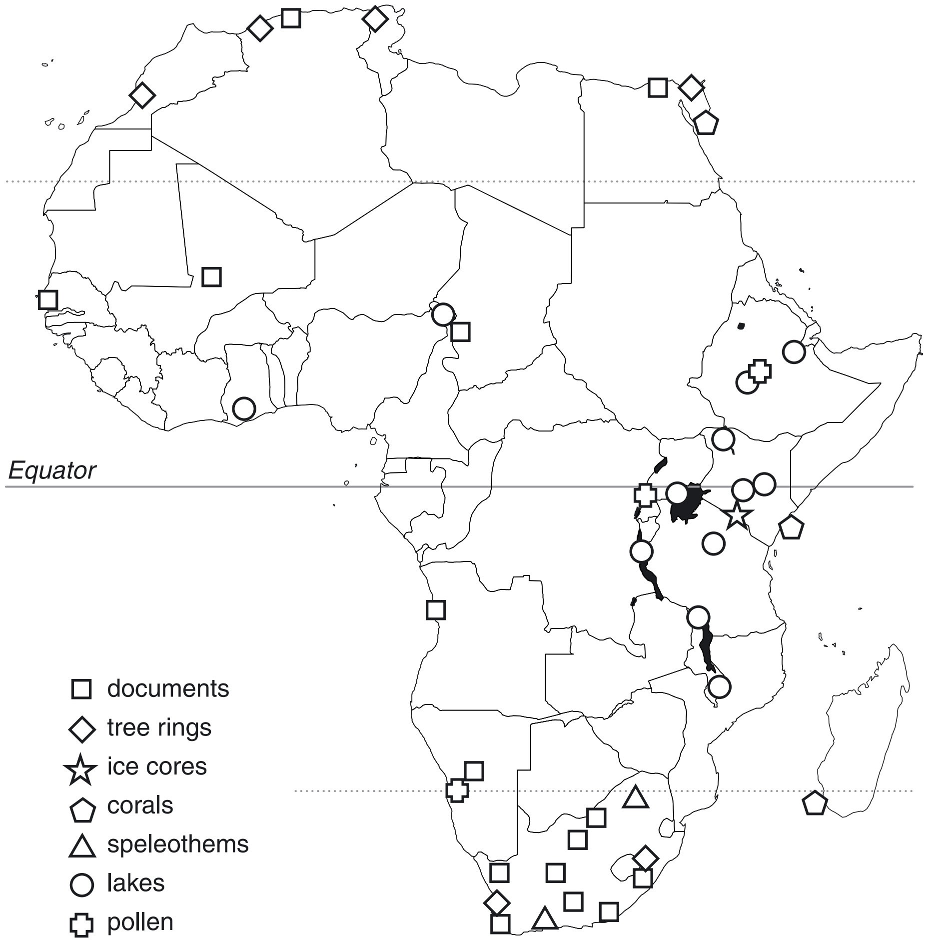

Figure 1. Distribution of high-resolution climate-proxy records on the African continent and in adjacent oceans extending beyond AD 1800. Localities of regionally integrated documentary records are approximate.

consecutive dry years punctuating a humid episode may be long remembered but rather unimportant from a long-term perspective (Nicholson 1996a). However, the scarcity in tropical Africa of natural climate-proxy archives with annual resolution (cf. below) renders each of these chronicles highly valuable, and certainly warrants their detailed evaluation. For example, a documentary record of drought and disease in coastal Angola from AD 1560 to the 1870s (Dias 1981; Miller 1982), based mainly on Portuguese colonial archives, is the only source of high-resolution climatic information from western equatorial Africa extending to before AD 1800. The documentary record with which high-resolution proxy records from tropical Africa are usually compared is the Rodah Nilometer of flood and minimum levels in the Nile River since AD 622. But this record is not without its share of problems (Nicholson 1996a), and the climatic information it is said to contain on inter-annual to century time-scales continues to be the subject of re-evaluation (Herring 1979;

Hassan 1981; Quinn 1993; Fraedrich et al. 1997; Nicholson 1996a; 1998; De Putter et al. 1998).

Dendroclimatology

Tree-ring-based climate studies in tropical Africa face significant obstacles. Limited temperature seasonality and strong inter-annual variability in the strength or duration of dry and rainy seasons causes most trees to lack the distinct annual growth rings which provide superior chronological precision to tree-ring-based climate reconstruction in temperate regions. Trees that do form well-defined growth rings in certain parts of their range (e.g., *Juniperus procera* and *Vitex keniensis* in Kenya, *Pterocarpus angolensis* in Zimbabwe) usually do not long survive the attacks of fungi and termites once dead or cut down. Consequently, there is little potential to extend calibrated tree-ring chronologies beyond the lifetime of currently living trees (Dunbar and Cole 1999). In inter-tropical Africa, possibly only Ethiopia and Zimbabwe have both the material cultural heritage and a sufficiently dry climate to yield reasonably long, cross-dated tree-ring sequences from surviving sections of old timber and furniture. So far, however, long African tree-ring records all come from South Africa, the Maghreb region of Northwest Africa, and the Sinai desert (Nicholson 1996a), except for one 145-year record of deuterium excess (a water-balance proxy) in a *Juniperus procera* tree from the Mau Escarpment in Central Kenya (Krishnamurthy and Epstein 1985).

Ice cores

Compared to South America and Asia, Africa is not well endowed with snow-capped mountains. Ice cores from Lewis Glacier on Mt. Kenya (at 4870 m asl) were among the first ones recovered from a tropical mountain, but yielded little information because intermittent melt-water percolation had evidently corrupted any previously incorporated climate signatures (Hastenrath 1981). Similar conditions may also occur in the glaciers of the Ruwenzori Mountains (4500–5100 m asl). Of Africa's three snow-capped mountains, possibly only the ice fields on Mt. Kilimanjaro (above 5500 m asl) have preserved a high-resolution proxy record of past climate change (Thompson et al. 2002), and even this record is troubled by lack of an independent chronology (Gasse 2002). While the precise timing of climate events inferred from the Mt. Kilimanjaro ice archive should be regarded with caution, it will likely remain a truly unique record of Holocene variability in atmospheric dust loading and aerosol composition in equatorial Africa.

Corals

The oxygen-isotope and trace-element composition of growth rings in massive corals provide better-than-annual resolution records of sea-surface temperature and salinity, and thus rank among the best natural archives of inter-annual to decade-scale climate variability in the tropics. In suitable coastal locations their trace-element composition can also produce annual records of river discharge and soil erosion (Cole 2003). Intensive exploration of coral reefs along Africa's coast (Gagan et al. 2000) is now yielding its first results with

$\sim$200-year climate-proxy records from the Indian Ocean coast (Cole et al. 2000) and the Red Sea (Felis et al. 2000), and one 320-year record from Madagascar (Tyson et al. 2000). About 400 years may be the practical limit of coral-based climate reconstruction, unless unique fossil coral formations are found that would permit construction of cross-dated sequences.

Speleothems

Cave speleothems have yielded several important late-Holocene climate-proxy records from South Africa (Holmgren et al. 1999; 2001; Lee-Thorp et al. 2001), the Arabian Peninsula (Burns et al. 2002) and Israel (Bar-Matthews and Ayalon, this volume), and their unexplored potential remains large. However, the known distribution of high-quality speleothems is still largely limited to Africa's extra-tropical north and south. And, like with the scarce natural lakes in those regions, the recording of climatic signals in speleothems is sometimes interrupted during phases of severe drought.

Lake sediments

Lake sediments are the most ubiquitous climate-proxy archives in tropical Africa (Fig. 1), both in space and in time. But given the long history of palaeolimnological research in Africa, still few lake-based climate records possess the time resolution and dating control required to say anything meaningful about decadal and century-scale climatic anomalies during the past 2000 years. Dating uncertainty due to poorly constrained reservoir effects or the presence of reworked terrestrial organic carbon, aggravated by missing core tops, have long compromised attempts to correlate sub-millennial climate events between study sites. With the introduction of appropriate methods to recover and date soft surface sediments, comprehensive exploration of Africa's many climate-sensitive lakes has now become feasible. The main challenge in this effort is to find those lakes (undoubtedly only a fraction of the total) which combine adequate hydrological sensitivity to decade-scale climate variability with persistence of favourable sedimentation conditions throughout the past 2000 years (Verschuren 1999).

Decadal and century-scale climate change reflected in African lake levels

Similarity of 20th-century lake-level trends across eastern equatorial Africa (Nicholson 1996a; 1998) suggests that spatial complexity in the seasonality of rainfall is underlain by more uniform patterns of long-term temporal variability controlled by large-scale atmospheric dynamics (Nicholson 2000; 2001b). Amplifier lakes (Street 1980) in the Eastern Rift Valley of Kenya (Fig. 2: Turkana, Baringo, Bogoria, and Naivasha, among others) show very similar historical trends including: (i) a major 1890s transgression leading to peak levels in the 1900s and 1910s; (ii) a long decline to a marked lowstand in the 1940s–1950s; (iii) recovery to intermediate levels, starting in the late 1950s and accelerating after heavy rainfall in 1961–1962; and (iv) low to intermediate levels in recent decades, displaying ENSO-type cyclicity. In contrast, lakes in south-eastern tropical Africa (Fig. 2: Malawi and Chilwa) show broadly opposite historical trends: (i) mid-19th century intermediate levels

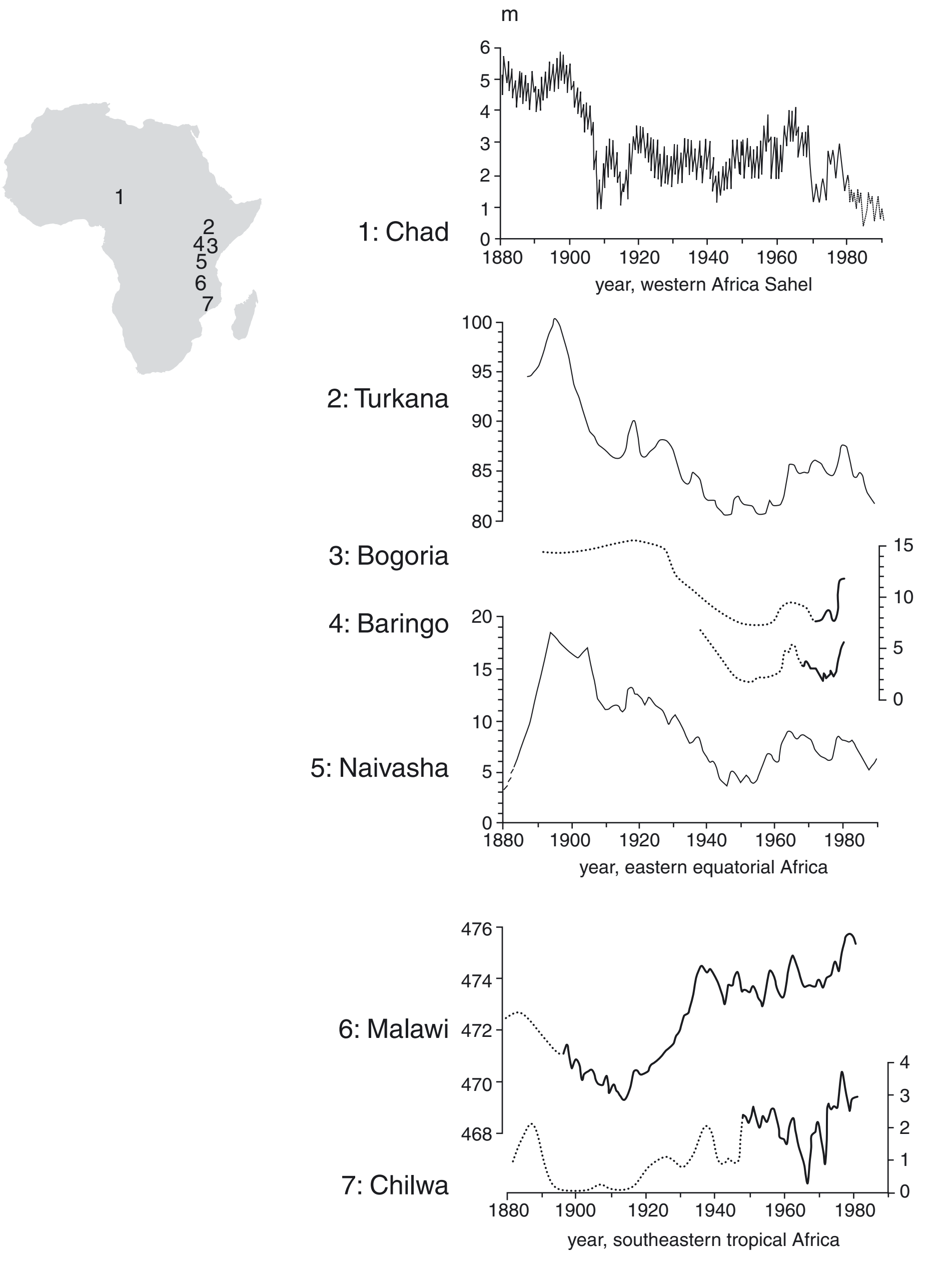

Figure 2. Historical lake-level trends in eastern and south-eastern Africa, and the Sahel region of North Africa: Chad (1; Thambiyahpillay (1983)), Turkana (2; Kolding (1992)), Baringo and Bogoria (3–4; Tiercelin et al. (1987)), Naivasha (5; Verschuren (1996)), Malawi (6; Owen et al. (1990)), and Chilwa (7; Crossley et al. (1984)). Vertical axis is metre asl in Lake Malawi, water depth in the other lakes.

continuing until the 1880s; (ii) lake-level decline in the 1890s leading to a pronounced lowstand in the 1900s and 1910s; (iii) recovery during the 1920s–1930s to reach peak level in the 1950s–1960s; and (iv) continuously high levels since then. The historical lake-level curve of Lake Chad in the Sahel region of North-Central Africa (Thambiyahpillay 1983) is also distinct (Fig. 2). Some decade-scale fluctuations are shared among all or some regions (e.g., regression during the period ∼1908–1916 shared by eastern equatorial lakes and Lake Chad, and the late-1970s rise shared by eastern and south-eastern lakes), in agreement with historical patterns in the geographical distribution of rainfall anomalies (Nicholson 1993; 2001b). Importantly, this evidence for regional coherence in lake-level trends gives credence to the use of lake-level records to evaluate the regional coherence and synchroneity of decade-scale climate anomalies further back in time. Even at this fairly short time scale, past moisture-balance fluctuations appear to have been large enough to over-ride site specificity in the lakes' response, at least for amplifier lakes with large catchments, where river inflow makes a significant contribution to the water budget.

One such lake, Lake Naivasha in the Eastern Rift Valley of Central Kenya, has so far yielded the best-resolved record of moisture-balance variations in equatorial East Africa during the past two millennia with suitable time control. A combination of diatom- and chironomid-inferred salinity reconstructions with a lake-level reconstruction based on sedimentological characteristics (Verschuren et al. 2000; Verschuren 2001; D. Verschuren, K.R. Laird, H. Eggermont, B.F. Cumming, unpublished data) shows that the climate of Central Kenya over the past 1800 years was characterised by a succession of (at least) seven decade-scale episodes of aridity more severe than any drought recorded during the 20th century (Fig. 3). To facilitate correlation with climate events elsewhere, these droughts can be identified as Naivasha Drought (ND) 1 to 7, in recognition of the apparent magnitude of the hydrological anomalies involved while acknowledging uncertainty in the determination of their exact age (Verschuren 2001).

The timing of ND1, ND2 and ND3 is supported by the pre-colonial history of drought-induced famine, migration, and clan conflict recorded in the oral traditions of agriculturalist peoples from the so-called Interlacustrine Region in present-day Uganda, Rwanda, north-eastern D.R. Congo, north-western Tanzania, and southern-most Sudan (Webster (1979), see Schoenbrun (1998) for an evaluation of these data). ND1 and ND2 are also coeval with the two most important episodes of drought recorded since AD 1560 in Angola (Miller (1982), Fig. 3), suggesting that the rainfall history of Central Kenya may be representative for equatorial Africa over at least the last 500 years. Interestingly, the three episodes of positive water balance bracketed by ND1, ND2, ND3 and ND4 are broadly coeval with the Wolf (AD 1290–1350), Spörer (1450–1540), and Maunder (1645–1715) minima in solar activity. Judging from the Naivasha record, equatorial East Africa appears to have been fairly wet during the Little Ice Age (LIA) period between AD 1270 and 1750, compared to mean 20th-century climate. During the Maunder Minimum, Lake Naivasha stood higher than at any other time in the past 1800 years. The period bracketed by droughts ND4, ND5 and ND6 (∼AD 870–1270) is broadly coeval with the Medieval Warm Period (MWP) in north-temperate regions, and ND7 reflects a pre-MWP drought tentatively dated to the 6th or 7th century AD. Irregularities in Naivasha's radiocarbon chronology (Verschuren 2001) suggest that accumulation in Crescent Island Crater may not have been continuous during ND5, consequently that the local record of Medieval climate variability is incomplete.

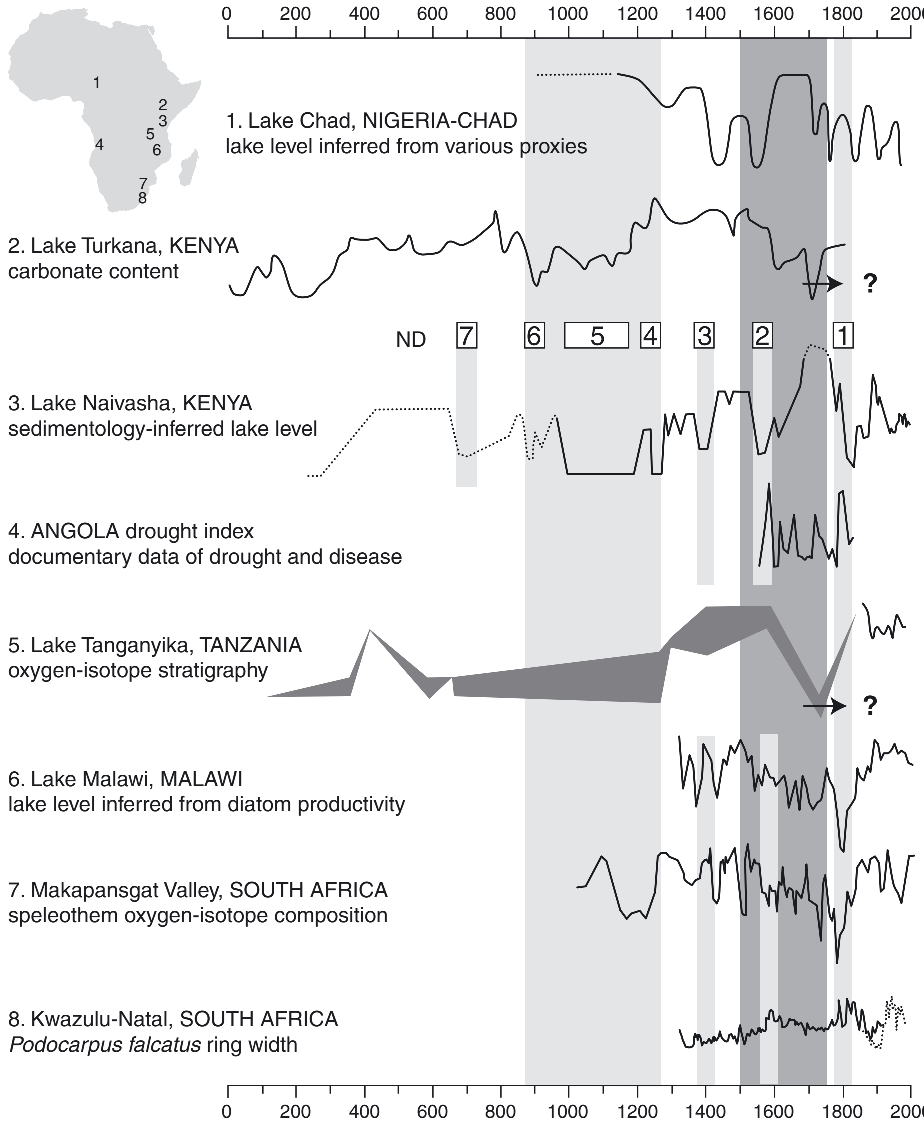

Figure 3. Lake-level reconstruction for Lake Naivasha (3; Verschuren (2001)) over the past 1800 years compared with other African proxy records presumed to reflect moisture-balance variation. From North to South: Lake Chad (1; Maley (1993)), Lake Turkana (2; Halfman et al. (1994)), Angola drought index, summed per decade (4; Miller (1982)), Lake Tanganyika (5; Cohen et al. (1997)), Lake Malawi (6; Johnson et al. (2000)), Mapakansgat speleothem oxygen isotopes (7; Holmgren et al. (1999)), and Kwazulu-Natal *Podocarpus* ring width (8; Hall (1976)).

Lake-based climate-proxy data from elsewhere in East Africa, though less well resolved, generally agree with the main features of the Naivasha record. To the north, stacked records of carbonate content in Lake Turkana sediments (Halfman et al. 1994), a proxy indicator of Omo River discharge, indicate relatively dry conditions over the Ethiopian Plateau before 1700 ^{14}C yr BP (∼AD 370) and during Medieval time (∼AD 900–1200), while relatively humid conditions prevailed ∼AD 700–900, and from ∼AD 1200 to 1550 (Fig. 3). In the Ethiopian Rift, Lake Abiyata stood high until shortly before AD 1800 but then receded with the shift to drier conditions which characterised the late 18th and early 19th centuries (Legesse et al. 2002). In the Afar region bordering the Red Sea, Lake Abhé stood low during the first half of the last millennium, and then high from the 16th to 18th century (Gasse and Street 1978). As at Abiyata, this was followed by regression during much of the 19th century, and eventually halted by a late 19th-century transgression. To the west of Kenya, high-resolution fossil-diatom data from Damba Channel between the mainland and a string of islands in Lake Victoria (Stager and Mayewski 1997; Stager et al. 1997; Stager 1998) record a marked increase in benthic diatom taxa, reflecting a ∼500-yr lowstand which was initially interpreted to represent LIA drought. New data from shallow, protected Pilkington Bay along the north shore of Lake Victoria, and revision of the Damba Channel chronology (Stager et al. 2003), re-assigned this inferred lowstand to between ∼AD 800 and 1300, i.e., matching the timing of MWP drought at Naivasha. In the sub-humid western branch of the African Rift, Lake Tanganyika fluctuated ∼25–30 m between marginally open and marginally closed states for much of the past 2800 years (Cohen et al. 1997). Patterns through time in the oxygen-isotope composition of stromatolites and molluscs suggest relative aridity from about 800 BC to AD 400 and from AD 600 to 1250, separated by a brief period of positive water balance in the 4th or 5th century (Fig. 3). After AD 1250, Lake Tanganyika rose to its overflow at about the time that a switch to positive water balance ended the MWP drought at Naivasha, and it maintained this level from AD 1350 to at least 1550. In broad agreement with the Lake Tanganyika record, pollen data from Mubwindi Swamp in Southwest Uganda show trees of the humid montane forest to reach their strongest representation between ∼AD 1350 and 1500 (Marchant and Taylor 1998). Then at some time between 1550 and the early 1800s, Tanganyika fell at least 15 m (maybe up to 40 m) to perhaps its lowest level in the past 2800 years. It rebounded during a strong mid-19th century transgression, reached overflow in 1877, and has remained open since then.

Lake-based climate-proxy data from further afield display some similarity but also distinct differences with the Naivasha record. Fluctuations of Lake Chad in Central North Africa reflect precipitation over large parts of Niger, Chad, Cameroon and the Central African Republic, but most river inflow derives from humid southern portions of the drainage basin around 7–10 °N. The history of Lake Chad over the past 900 years (Maley 1973) has been revised and updated several times. Compilation of the sedimentological and palynological data (Maley 1981), anchored in three radiocarbon dates (Maley 1993) and tuned with available documentary proxy data (Maley 1989), indicate that Lake Chad stood high from before AD 1100 to 1400 and again in the 17th century, separated by low to intermediate levels during the 15th and 16th centuries when the East African lakes stood high (Fig. 3). The recent half of the Lake Chad record agrees with many historical records from West Africa, and possibly reflects a climatic opposition between West Africa and equatorial East Africa which has also occurred several times during the 20th century (Nicholson 1986; 1994; 2001b). Yet other parts of the Sahel were clearly moister than today during the 17th and 18th centuries (Nicholson 1996a), i.e., more similar to the East African pattern.

The best-resolved climate-proxy data for south-eastern tropical Africa come from the North basin of Lake Malawi, where lake history over the last 700 years is preserved in an annually-laminated sequence of diatom-silica accumulation, a proxy for nutrient upwelling that would be inversely related to lake level (Johnson et al. 2001) or may indicate intensification of northerly winds (Johnson et al. 2002; this volume). When interpreted in terms of lake-level change, the diatom-silica record suggests that Lake Malawi stood lower than today between AD 1570 and 1850, most of this period being one prolonged regression towards a pronounced lowstand shortly before AD 1800. Sediment records from the shallower South basin contain an erosional hiatus likewise testifying to an extreme lowstand (possibly >120 m below present level) from which the lake recovered during the mid-19th century (Owen et al. 1990). Consistent with these core data from both basins, archaeological and geomorphological evidence from the Lake Malawi shoreline (Crossley and Davison-Hirschmann 1981; 1982) suggest that the lake reached its highest level of the past 1700 years during the 14th and 15th centuries in a possible double-peaked event. Other highstands occurred in the 10th century and during the first half of the first millennium AD (Crossley et al. 1984). Johnson et al. (2002, this volume) suggest that the strong upwelling which stimulated diatom production in Lake Malawi's North basin from about AD 1570 to 1850 was generated by more frequent or stronger northerly winds than today, a possible indication that the Intertropical Convergence Zone migrated further southward during austral Summer coincident with Little Ice Age cooling of the Northern Hemisphere.

When comparing the high-resolution records of lakes Naivasha and Malawi, it would seem that the frequent opposition between eastern equatorial and south-eastern tropical Africa in modern patterns of both inter-annual rainfall variability (Nicholson 1986; 1996b; Ropelewski and Halpert 1989) and decade-scale rainfall and lake-level trends (Nicholson (1993, 2001b), Fig. 2) may have persisted through much of the last millennium. But this is only partly the case. First, both lakes Naivasha and Malawi experienced their most pronounced inferred lowstand of the last 700 years between AD 1780 and 1830. This timing matches records of severe 1790s drought from tropical and subtropical regions worldwide, including South Africa, Australia, and Mexico (Grove 1998). In ice-cores from Tibet (Thompson et al. 2000), evidence for failure of the South Asian Monsoon during the 1790s is recorded as the largest dust peak of the last millennium, dust which must have originated from semi-arid source regions in India and North Africa. Second, both lakes Naivasha and Malawi as well as lakes Turkana, Victoria and Tanganyika discussed above, and also the Mt. Kilimanjaro dust and oxygen-isotope records (Thompson et al. 2002), all show relatively dry conditions during the 11th to early 13th centuries, switching to a distinctly wetter climatic regime in the late 13th or early 14th century. Evidence for this transition from the Lake Malawi region is found in the temporal distribution of Iron Age ceramic traditions on the present-day Lake Malawi shoreline, which reveals major settlement gaps not only from AD 1700 to the mid-1800s but also from shortly after AD 1000 to 1300 (Owen et al. 1990). The marked shift to a positive water balance around AD 1250–1300 is not limited to tropical Africa but has also been reported from the North American Great Plains (Laird et al. 1996). Allowing for dating uncertainty in the available records, it appears to coincide with a pronounced shift in trade-wind regime over the tropical Atlantic Ocean (Black et al. 1999), cooling of the North Atlantic (Keigwin 1996), and the earliest evidence for LIA glacier advance in the European Alps (Holzhauser 1997).

The principal contrast between the Naivasha and Malawi records concerns their history of the 16th to 18th centuries. Whereas the sedimentology-based reconstruction from Lake Naivasha (Verschuren 2001) infers a prolonged trend of *increasing* moisture from the 14th to the late 17th century with a temporary reversal in the late 16th century and a dramatic ending in late 18th-century aridity, the Lake Malawi diatom-productivity record (Johnson et al. 2001) infers a prolonged trend of *decreasing* moisture starting in the 16th century and culminating in the same late 18th-century aridity. Presently, few other published studies have both the time resolution and age control to contribute meaningfully to the discussion of this apparent climatic contrast between eastern and south-eastern tropical Africa during the main phase of the Little Ice Age. The Lake Tanganyika reconstruction (Cohen et al. 1997) in its present form is compatible with both the Naivasha and Malawi records, because the period from AD 1500 to ~1850 is without data except for the probable occurrence of an extreme lowstand (Fig. 3). While we can assume this lowstand to have been coeval with the 1790s-centered lowstands of lakes Naivasha and Malawi, it remains unclear whether Tanganyika stood at its overflow level until the mid-1700s, implying a climate history similar to that of Central Kenya, or if regression started soon after AD 1500, similar to what happened at Lake Malawi. Some on-shore data from Lake Chilwa in southern Malawi are difficult to reconcile with the inferred lake-level record of Lake Malawi nearby. Differences in the age distribution of *Adansonia digitata* (baobab) trees (calculated by calibrating girth measurements by ring-width data) above and below 631 m elevation seem to indicate that a pronounced Little Ice Age-equivalent highstand of Lake Chilwa persisted at least until AD 1750 (Crossley et al. 1984). The implied humid conditions during the 17th and early 18th centuries also seem to have prevailed in the Northern Kalahari desert another 5° latitude further South, where Lake Ngami was flooded by increased discharge from the Okavango River delta (Nicholson 1996a). The Chilwa and Ngami records better agree with the alternative interpretation of the Malawi diatom-silica record (Johnson et al., this volume), which does not require a pronounced LIA lowstand.

Evidence for temperature change in Africa during the past 2000 years

A well-known obstacle to direct climatic interpretation of lake-level records is the dependence of net moisture availability on both precipitation and temperature. If tropical Africa experienced significant temperature variation over the past 2000 years, then similar temporal patterns of rainfall variability among drainage basins could still result in quite dissimilar lake-level records depending on the exact effect of a particular temperature anomaly on evaporation rates from land and water surfaces within each drainage basin. The history of Lake Naivasha, where a mostly positive water balance since ~AD 1270 appears to have culminated in a pronounced highstand coeval with the Maunder Minimum, mirrors reconstructed temperature anomalies over the past 1000 years for the Northern Hemisphere continents (Jones et al. 2001), begging the question to what extent a temperature-driven decrease of evaporation during the main phase of the Little Ice Age (~AD 1550–1750) may have contributed to the increase in moisture availability implied by the Naivasha record.

Unambiguous evidence that tropical Africa experienced significant temperature change during the last two millennia is scarce, since excursions in most climate-proxy indicators can be interpreted as evidence of both rainfall or temperature variation. A pollen record from a swamp above treeline (3600 m asl) on Mt. Arsi in south-eastern Ethiopia reveals expansion of ericaceous shrubland at the expense of forest trees during the period ~AD 1250–1700. Bonnefille and Umer (1994) interpret it to reflect a 400 m shift of vegetation belts down the mountain, equivalent to a maximum cooling of 2 °C (Fig. 4). At Kuiseb River in western Namibia just south of the Tropic of Capricorn, pollen preserved in a chronosequence of ^{14}C-dated hyrax middens (Scott 1996) show expansion of grasses and herbs at the expense of trees during the period ~AD 1300–1800. Here this vegetation change can be explained both by the region having been colder than today, since the frost-sensitive trees *Acacia albida* and *Salvadora persica* approach the southern limit of their modern distribution near Kuiseb River, and/or it having been wetter than today, since greater rainfall favours grassland expansion there (Scott 1996). On the other hand, high-resolution oxygen-isotope and colour variations in a cave speleothem from Mapakansgat Valley indicate that at about the same latitude (24 °S) in north-eastern South Africa, colder periods (up to 1 °C in the 18th century) were drier than today while warmer periods (up to 3 °C in the 13th century) were wetter than today (Holmgren et al. (1999, 2001), Tyson et al. (2000), Scott and Lee-Thorp (this volume); revised chronology from Lee-Thorp et al. (2001)). Moisture-balance changes inferred from the oxygen-isotope variations in this speleothem record broadly agree with the reconstructed fluctuations of Lake Malawi some 15° latitude farther North (Fig. 3), supporting the reality of a long-standing, though not necessarily continuous, inverse correlation between century-scale rainfall patterns in eastern and south-eastern tropical Africa (Tyson et al. 2002). This inverse relationship is also hinted at in a uniquely long ring-width record of a *Podocarpus falcatus* tree from ~28 °S in Kwazulu-Natal, Eastern South Africa (Hall 1976; Tyson 1986), which shows strongest growth in the past 700 years to have occurred during AD 1580–1620 and AD 1770–1840, i.e., coincident with the ND1 and ND2 droughts at Lake Naivasha (Fig. 3). Assuming that tree growth at this particular sub-tropical locality is drought-limited rather than temperature-limited (which has yet to be confirmed), it would again indicate positive rainfall anomalies in eastern south Africa to have coincided with drought in equatorial East Africa.

Another potential proxy indicator for past temperature variation can be found in the history of glacier advance and retreat on Africa's three snow-capped mountains, which all occur within 3° latitude of the Equator. Ice cores from Lewis Glacier on Mt. Kenya revealed that the 'eternal snow' on Mt. Kenya is only ~500–600 years old (Hastenrath 1981), suggesting that this 5200 m high mountain may have been completely ice-free under the relatively warm, or dry, climatic conditions which prevailed in Medieval time. The small Furtwängler Glacier on Mt. Kilimanjaro appears to be even less then 300 years old (Thompson et al. 2002); oxygen-isotope data suggest it to be a remnant of unusually cold, or wet, conditions prevailing during the Maunder Minimum. Moraines reflecting LIA glacier advance are prominent both on Mt. Kenya (Karlén et al. 1999) and the Ruwenzori Mts. (de Heinzelin 1962), now standing about 100–250 m below the present ice margin. A continuous record of late-Holocene glacier activity on Mt. Kenya, based on the organic-carbon content of pro-glacial lake muds in Hausberg Tarn (Karlén et al. 1999), indicates that the glaciers stood in an advanced position from ~200 BC to AD 300 and from ~AD 650 to 850 (Fig. 4). This was followed by retreat from AD 850 to ~1250, i.e., coeval with the ND4 to ND6 lowstands of Lake Naivasha. Although radiocarbon age control on the last 1000 years of Hausberg Tarn's history is rather poor, it appears that the most recent, LIA-equivalent glacier advance peaked between 400 and 250 years ago.

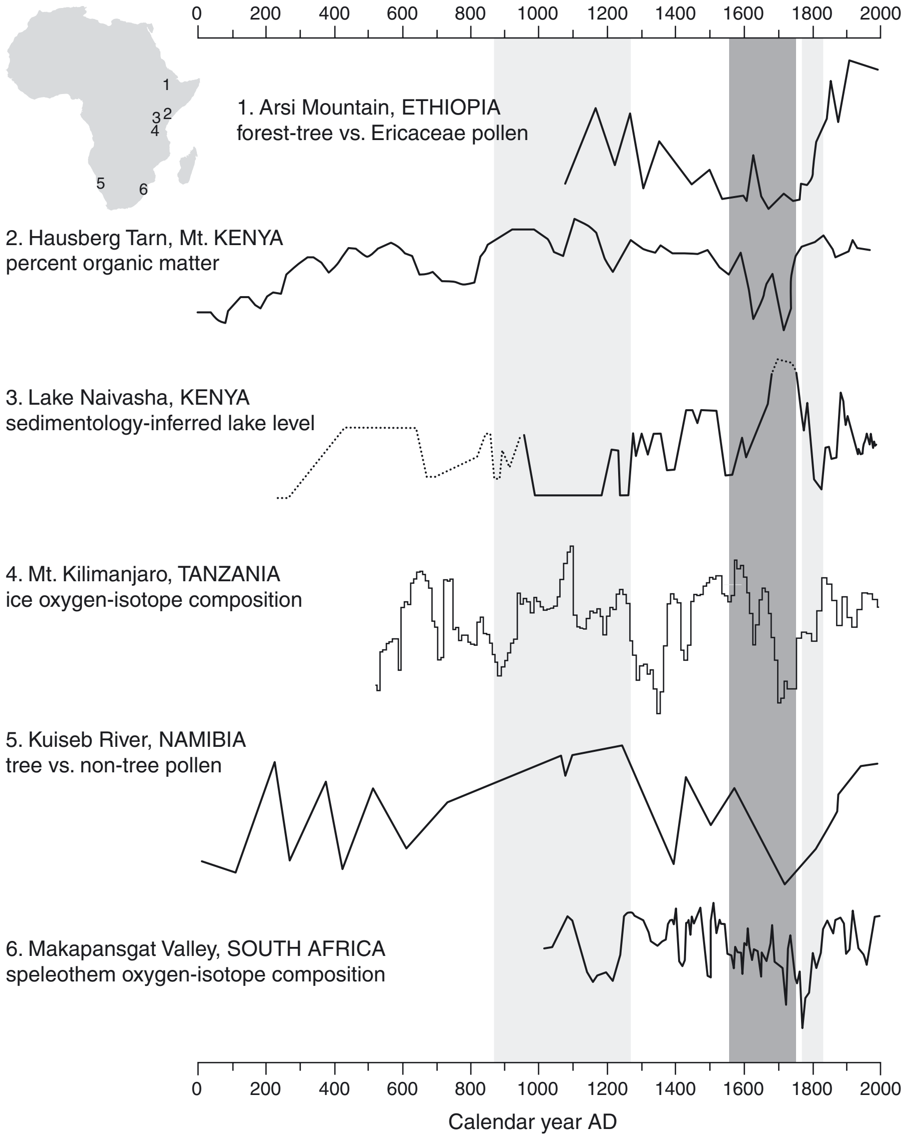

Figure 4. Lake-level reconstruction for Lake Naivasha (3; Verschuren (2001)) over the past 1800 years compared with African proxy records presumed to at least partly reflect past temperature variation. From North to South: Arsi Mountain tree pollen (1; Bonnefille and Umer (1994)), Mt. Kenya glacier activity (2; Karlén et al. (1999)), Mt. Kilimanjaro ice-core record (4; Thompson et al. (2002)), Kuiseb River tree pollen (4; Scott (1996)), and the Makapansgat speleothem record (5; Holmgren et al. (1999)).

Thompson et al. (2002) interpret pronounced δ^{18}O minima in the Mt. Kilimanjaro ice-core record around AD 1250 and during the Maunder Minimum (Fig. 4) to reflect episodes of substantial cooling. However, African rainfall δ^{18}O correlates far stronger with rainfall amount than with air temperature (Rozanski et al. 1993). Thus, Barker et al. (2001) argued that oxygen-isotope signals in fossil-diatom silica from alpine lakes on Mt. Kenya primarily reflect variations in moisture and cloud height driven by sea-surface temperature anomalies over the tropical Indian Ocean, and hence that Holocene ice advances in equatorial Africa were caused by enhanced rainfall rather than cold. This would explain obvious resemblance between the Hausberg Tarn record of Mt. Kenya glacier activity (Fig. 4; reversed) and the Naivasha lake-level record. Indeed, most of Lake Naivasha's river inflows originate in the moist highlands flanking the eastern Rift Valley, less than 80 km from Mt. Kenya. Unfortunately, it leaves open the question to what extent regional temperature variation during the last millennium may have contributed to the substantial changes in effective moisture recorded by Lake Naivasha.

Summary and concluding remarks

Reconstructing the climatic history of tropical Africa over the last 2000 years, including the environmental background of its eventful political and cultural history, is hampered by scarcity of documentary records from before the colonial period, and the limited potential of traditional high-resolution climate-proxy archives such as tree rings and ice cores. To correct this situation, various initiatives are now underway to systematically explore all suitable speleothem, coral, and lake-sediment archives throughout the continent and adjacent oceans. Lake-sediment archives in particular have great potential to document the climate history of tropical Africa in both space and time. Continuously varved sediment records are rare, however, so that the chronology of most lake-based climate reconstructions will continue to rely on a combination of lead-210 and radiocarbon dating. Still, careful site selection and application of modern paleolimnological methods may eventually yield the spatial array of high-resolution climate reconstructions needed to elucidate the mechanisms of decadal and century-scale climate variability over the African continent.

Currently available proxy data indicate that most areas of inter-tropical Africa were drier than today ~AD 900–1270, broadly coeval with Medieval warming in north-temperate regions. Drought was also widespread in the late 1700s and early 1800s, with maximum aridity possibly occurring during the 1790s. For two to three centuries before this drought, however, i.e., the period equivalent with the main phase of the Little Ice Age, rainfall anomalies in eastern and southeastern tropical Africa appear to have been inversely related, suggesting prominent influence of a forcing mechanism which generates regional rather than continent-wide rainfall patterns. In equatorial East Africa, relatively moist conditions from ~AD 1270 to the mid-18th century were interrupted at least twice by decade-scale episodes of severe aridity dated to around AD 1400 and the late 1500s, matching historical records from Angola, Uganda, Tanzania, and Rwanda describing drought-induced famine, migration, and conflict between pastoralist and agriculturalist peoples. This succession of wet and dry episodes correlates with the tree-ring reconstructed record of atmospheric radiocarbon production, indicating a discernible influence of solar forcing on Little Ice Age climate in equatorial Africa. High-resolution lake-level records can be an excellent indicator of past variations in net moisture available for natural ecosystems and human societies, but whether the high lake levels in East Africa during the Little Ice Age were sustained only by an intensified hydrological cycle, or also by reduced evaporation associated with lower temperatures, remains unclear.

New lake-based climate-proxy records from lakes Naivasha and Malawi possess appropriate time resolution and age control to serve as templates for regional analysis of decadal and century-scale climate anomalies in tropical Africa during the last 2000 years. Although age control on most other proxy records covering this period is not as good, many of them display a characteristic succession of century-scale climatic anomalies that are consistent with the patterns observed in the two high-resolution records. The combined evidence suggests that one of today's continent-scale spatial patterns of inter-annual rainfall variability, characterised by opposite anomalies in south-eastern Africa and eastern equatorial Africa (Nicholson 1986; 1993; 2001a), has also been expressed at longer time scales in the past, for instance during the period equivalent with the Little Ice Age of temperate regions. At other times, for example in Medieval times, the 1790s and early 1800s, and the early 20th century, regional patterning of rainfall anomalies seems to have been overridden by widespread drought. This apparent alternation of episodes characterised by inter-regional contrasts and episodes characterised by continent-wide spatial coherence is not unexpected, as it may simply reflect the varying influence through time of several distinct climate-forcing mechanisms (Nicholson 2000).

The reality of the reconstructed climate patterns discussed here ultimately rests on our understanding of the relationships between climate-proxy indicators and climate, which are archive-dependent and always complex. Climate inferences from each of Africa's many climate-sensitive lakes depends on: (i) justified extrapolation of a presumed or established relationship between the sedimentary proxy indicator and lake level, from the historical period through the entire period of climate inference; and (ii) existence of a simple, constant relationship between lake level and rainfall at the relevant time scale. Using these criteria, neither the Naivasha, Malawi, nor any other lake-based climate record from tropical Africa is at present beyond discussion, and many more high-resolution climate histories from other sites, using different archives and different climate-proxy indicators, will be required to elucidate the mechanisms which control African rainfall at the time-scales relevant to society. Limits on the geographical distribution and temporal coverage of high-resolution climate archives will continue to challenge efforts to reconstruct Africa's climate history with better than decade-scale resolution and age control. But steady improvements in the methods, rigour, and scale of palaeoclimate research in Africa create great promise that its treasure trove of natural climate archives will eventually realise its full potential.

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