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Lake-based climate reconstruction in Africa: progress and challenges

Dirk Verschuren
Department of Biology, Ghent University, Ledeganckstraat 35, B-9000 Gent, Belgium
E-mail: dirk.verschuren@UGent.be

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Abstract

Lake sediments are and will continue to be the principal source of information on the climate history of tropical Africa. However, unequivocal interpretation of the various sedimentological, biological, and geochemical climate-proxy data extracted from lake sediments with respect to past variations in temperature, rainfall, and wind is an extremely complex and challenging exercise. Outstanding problems are: (1) the inherent conflict between a lake's sensitivity to climate change (its ability to respond to and record relatively modest, short-lived climatic anomalies) and its persistence as an archive of climate change (the probability that it survived the most arid events without desiccation or erosion, allowing it to preserve a continuous record of climate history); (2) the scarcity of annually laminated sediment records, which in other regions can provide superior chronological precision to lake-based climate reconstructions; (3) lack of a quantitative (sometimes even qualitative) mechanistic understanding of the chain of cause and effect linking sedimentary climate-proxy indicators to particular climatic variables; and (4) lack of a proxy indicator for past temperature changes unaffected by simultaneous changes in moisture balance. Clearly, a climate-proxy record with high stratigraphic resolution does not represent a high-resolution record of past climate change without demonstration that the sedimentary archive is continuous and undisturbed; that the lake system responds to climate variability at the appropriate time scale; and that any threshold effects in the relationship between the proxy indicator and climate are accounted for. Calibration and validation of climate-proxy indicators is tantamount to establishing accurate reconstructions, but in Africa historical validation of proxy indicators is handicapped by the scarcity of long-term lake-monitoring data. The reliability of lake-based climate reconstructions is enhanced when inferences derived from several proxy indicators (sedimentological, biological, or geochemical), that each have an independent mechanistic link to climate, show a high level of coherence. Given the scarcity of annually-resolved sediment records in tropical Africa, we may have to accept the limitations of ^{210}Pb- and ^{14}C-based chronologies when evaluating the synchrony of reconstructed climate events between sites and regions; however, careful site selection and detailed lithostratigraphic analyses can go a long way to optimise depth-age models and reduce uncertainty in the timing of past climate changes.

Introduction

An important part of the paleoclimate research enterprise today has shifted attention from the long-term dynamics of Quaternary ice ages and interglacials to the comparatively modest, short-term, and regionally specific natural climate variability that is more directly relevant to human society in the context of global climate change. Improved understanding of this interannual to century-scale climate variability requires a global network of accurate, trustworthy climate reconstructions with which climate modellers can test and validate the computer models developed for long-term climate prediction. Accordingly, much emphasis is placed on natural climate archives with high, preferably annual, resolution and time control. Special attention also goes to the tropics, for which the current paucity of relevant paleoclimate data contrasts with its prominent role as the heat engine of the global climate system.

Africa is the quintessential tropical continent. Unfortunately, reconstructing the climate history of tropical Africa over the last few thousand years, and thus the environmental background for its complex precolonial cultural history, is hampered by the scarcity of instrumental and documentary records from before the colonial period (Nicholson, 2001) and by the limited potential of traditional high-resolution climate-proxy archives such as tree rings and ice cores. Very few African trees develop distinct annual growth rings, those that do rarely grow older than 100 years, and dead logs or old construction timber is rarely preserved long enough to be of any use in extending the historical instrumental record (Dunbar & Cole, 1999). Ice cores from Mt. Kilimanjaro have now provided a unique window on Holocene climate and atmospheric composition in equatorial Africa (Thompson et al., 2002), but the reconstruction is handicapped by the lack of an independent chronology for the inferred climate events (Gasse, 2002). Further, the known distribution of high-quality speleothems is still largely limited to Africa's extra-tropical north and south. Compared to these three types of natural climate archive, sedimentary climate records accumulating on the bottom of Africa's many climate-sensitive lakes have great potential to document the continent's patterns of past climate change, with respect to both geographical and temporal coverage.

This paper presents an overview of current research methods available for lake-based climate reconstruction in tropical Africa, with some emphasis on biological climate-proxy indicators and the aspects of lake hydrology and sedimentation that affect their stratigraphic distribution in sediment cores. No attempt is made to review current knowledge about the Holocene climate history of tropical Africa; for this the reader is referred to Gasse (2000) and the relevant chapters in Batterbee et al. (2003). Neither do I review and evaluate state-of-the-art statistical methods in biological paleolimnology, which is the subject of several excellent publications (Birks, 1998; Birks et al., forthcoming). Rather, this contribution represents a personal view of notable recent advances and unresolved problems in lake-based climate reconstruction in tropical Africa. To illustrate such unresolved problems, reference is often made to research in which I have been personally involved, if only because of greater awareness of the hidden weaknesses in my own results than in the work of others in the field.

African lake sediments as archives of Holocene climate variability

Lakes are excellent sensors of environmental change, and sediments accumulating on the bottom of suitable climate-sensitive lakes can provide continuous records of past climate variability with high (inter-annual to decadal scale) temporal resolution (Battarbee, 2000). However, in Africa it is necessary to use the conditional tense here, because the very sensitivity of the continent's many hydrologically-closed lake basins to relatively modest, short-term rainfall variability (or, more precisely, the balance between precipitation and evaporation) also makes them prone to drying out completely, resulting in truncation or partial destruction of the high-resolution climate archive that has been accumulating (Verschuren, 1999a). Hydroclimatic fluctuations in tropical Africa over the past 10 000 years were so dramatic (Gasse, 2000) that most lakes studied thus far which were sensitive enough to record clear evidence of climatic variability within the wet early Holocene have dried out repeatedly during the dry late Holocene; and lakes that survived the most arid episodes of the late Holocene had been less sensitive, hydrologically open systems during the early Holocene. Indeed, most African lakes where a documented 20^{th}-century history of significant lake-level or salinity fluctuation provides opportunity to calibrate and validate their sedimentary climate-proxy record with appropriate temporal resolution do not have a continuous sediment record covering the last 2000 years, let alone the entire Holocene. Consequently, in African lake-based paleoclimate studies, site selection is crucial.

The second major issue is chronology. Proper understanding of the mechanisms of global climate variability at decadal to century time scales critically depends on establishing coherent regional pictures of climate history involving many study sites, and on the ability to compare this history with independently constructed and dated records of the climate drivers that are directly or indirectly responsible for the observed patterns of past climate change. Finely laminated lake-sediment records with annual signal resolution and time control (so-called varved records) are naturally preferred for this purpose, but in tropical Africa such varved records are extremely rare, because the seasonal cycle (the succession of dry and wet seasons, and the timing of deep mixing events) is too complex, or not strong enough, to consistently generate the annual packets of distinct sediment laminae that can give a sediment record superior chronological precision.

The third complicating issue involves the often uncertain relationship between a sedimentary climate-proxy indicator (sedimentological, geochemical or biological) and the primary climatic variables of temperature, rainfall, and wind. In contrast to hydrologically stable study lakes in north-temperate regions, where a range of sedimentary climate proxies can be reasonably assumed to be mostly controlled by temperature variations, a reliable proxy indicator for past temperature change in Africa (and other tropical regions) is still lacking. For example, whereas the oxygen stable-isotope ratio of fossil-diatom silica in northern European lakes appears to be mainly under temperature control (Shemesh et al., 2001), its promise as a temperature indicator for tropical regions was diminished by the finding that even in a high-altitude setting (4300–4600 m) on Mt. Kenya its Holocene signals are better explained by moisture-balance changes (Barker et al., 2001) than by temperature-induced fractionation (Rietti-Shati et al., 1998). Because of the dramatic hydroclimatic changes in Africa during the Holocene, all sedimentary climate-proxy indicators currently in use at least partly reflect moisture-balance variations expressed via changes in lake level, water chemistry and isotopic composition, water-column stratification, and/or sedimentation dynamics. And as mentioned above, without exception the strength of their signatures is inversely related to the probability that the sediment column is a continuous archive of climate history. Lack of an independent proxy indicator for temperature also complicates interpretation of lake-level fluctuations in terms of rainfall variability (Verschuren, 2003). Lake-level change reflects variation in the balance of rainfall and evaporation over the drainage basin, and is thus at least partly controlled by temperature. This temperature effect on lake level is most pronounced in closed-basin amplifier lakes with large drainage basins, because of the dependence of river inflow on basin-wide evapotranspiration (e.g., Vallet-Coulomb et al., 2001). In the large African Rift lakes with comparatively smaller drainage basins, wind speed may have a stronger influence on overall evaporation than temperature (Lehman, 2002).

Lake-based reconstruction of Holocene climate variability in Africa

At glacial-interglacial time scales, the recent climate history of inter-tropical Africa is divided into a fairly wet late Glacial and early Holocene (∼15,000–5500 cal. yrs BP; the so-called African Humid Period) caused by strengthening of the equatorial westerlies and the Indian Ocean monsoon system during the Northern Hemisphere insolation maximum, and mostly drier mid- and late-Holocene climatic regimes (deMenocal et al., 2000). Both periods were punctuated by severe dry spells lasting several 100s of years, centered at 12 400, 8200, 6600, and 4000 years ago (Gasse, 2000). The first of these droughts corresponds to the Younger Dryas period in the North Atlantic region, and re-establishment of wetter conditions at 11 500–10 800 years ago coincides with the Pre-Boreal warming of northern temperate regions which marks the onset of the Holocene there (Verschuren et al., 2003). Most probably also the later droughts have mechanistic links to millennium-scale climate variability in the North Atlantic region (Gupta et al., 2003) but their timing has not been sufficiently constrained to explore this in detail. In southern Africa up to Lake Malawi (∼10° S), a wet Late-Glacial period appears to have given way to a relatively dry early Holocene followed by a wetter mid-Holocene (Gasse, 2000; Scott & Lee-Thorp, 2003), but with scant evidence of the millennium-scale droughts that occurred in northern inter-tropical Africa.

To date, the only nearly continuous African climate-proxy records spanning the entire Holocene with decade-scale resolution are two fossil-diatom records from Lake Victoria (Stager et al., 1997; Stager & Majewski, 1997; Stager et al., in press, Fig. 1), and one record of biogenic-silica accumulation in Lake Malawi (Johnson et al., 2002, 2003); a third fossil-diatom record from Lake Victoria (Stager & Johnson, 2000) has century-scale resolution, but suffers from an apparent mid-Holocene discontinuity. Lake Victoria has overflowed into the Nile for the past 13 000 years (Talbot et al., 2000), hence sedimentation conditions in deep-water areas (the central basin is 68 m deep) might be expected to have been relatively stable throughout the Holocene. However, ^{210}Pb-dating of recent deep-water sediments (Verschuren et al., 1998) confirms predictions based on wave theory that fine-grained sediments across the entire offshore lake bottom are periodically (once in several decades) subject to erosion and re-deposition,

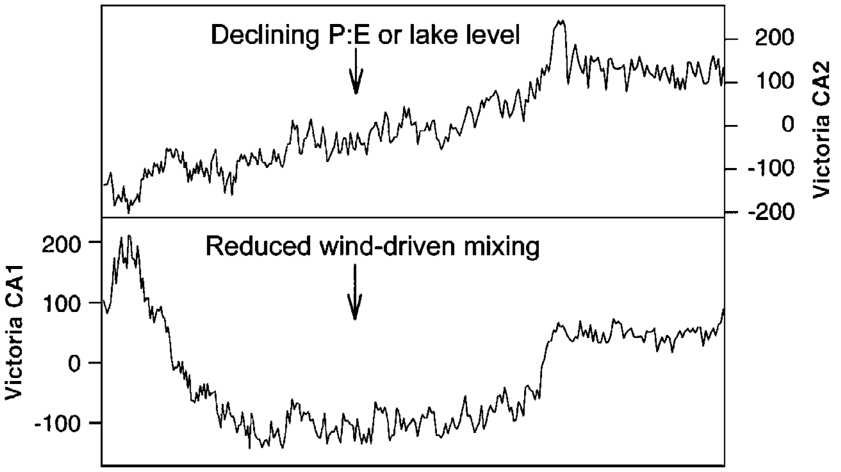

Figure 1. Climate-driven changes in the physical limnology of Lake Victoria (East Africa) over the past 11 000 years inferred from variability in fossil-diatom species assemblages. CA1 and CA2 refer to sample scores along the 1st and 2nd principal Correspondence Analysis ordination axes, summarising the variability in fossil-diatom species composition; P:E refers to the balance of precipitation and evaporation. From Stager & Mayewski (1997).

due to wave turbulence during exceptionally violent storms. This sediment disturbance effectively limits the realised time resolution of Lake Victoria's offshore climate-proxy record to centuries, rather than decades. Higher-frequency signals evident in the offshore fossil diatom record may result from the alternating burying and re-suspension of the surface deposits in which differential diatom preservation occurs, rather than reflecting decade-scale ecological or climatic variability. Site-specificity of sedimentation conditions and the associated taphonomic processes is evident in poor correlation of inferred climate events between the fossil-diatom records from a 30-m deep channel between offshore islands (Stager et al., 1997), the middle of the lake (Stager & Johnson, 2000), and a small protected bay along its northern shore (Stager et al., in press), beyond the broad millennium-scale climate trends shared by all three records.

Pilkington Bay, only 12 m deep today, has probably produced the highest-quality climate-proxy record from Lake Victoria because wind shelter promoted quiet sedimentation dynamics, and proximity of the core site to near-shore benthic habitat translated even modest lake-level fluctuations during the past 1000 years into clear interpretable changes in the fossil diatom flora (Stager et al., in press). Less clear, however, is whether relationships between lake level and benthic diatom abundance in the sub-recent sediment record can be extrapolated to the mid- and early Holocene, when local water depth may have been ∼30–36 m due to the combination of high lake level (raised strandlines of assumed early-Holocene age stand 12–18 m above present lake level; Stager et al., 2002) combined with 6 meter less sediment filling the bay. Even if Holocene lake-level fluctuations can be quantified, a direct diatom-climate link at short time scales would seem tenuous because the hydrologically open condition of Lake Victoria mutes its lake-level response to short-term moisture-balance changes, and because a significant portion of presumed mid-Holocene lake-level lowering may be due to the down-cutting of its outflow rather than the transition to a drier climate.

This observation does not reduce the significance of the Lake Victoria fossil-diatom records; rather, it illustrates the notion that a high-resolution climate-proxy record can not uncritically be taken to represent a high-resolution record of past climate change. Indeed, the first purpose of high-resolution stratigraphical analyses is to produce a level of data redundancy that, as the paleo-ecological equivalent to replicate data series, gives credence to the most prominent, and relatively long-term, climate signals present. High-resolution climatic interpretation requires demonstration that the proxy record is continuous and undisturbed; that the lake system responds to climate variability at the appropriate time scale; and that the complex relationships are understood between a buried climate-proxy indicator (e.g., fossil diatom species composition; oxygen-isotope ratio in authigenic carbonate) and its original form (e.g., diatom community composition and annual production; oxygen-isotope ratio of dissolved inorganic carbon), between the proxy indicator and lake hydrology, and between lake hydrology and climate.

African lake-based climate-proxy records that cover the full Holocene with century-scale resolution and time control include a multi-indicator reconstruction (geochemistry, diatoms, and ostracod trace elements) from Lake Tigalmamine in the Atlas Mountains of Morocco (Lamb et al., 1995) and a diatom-based salinity reconstruction from Lake Abiyata in Ethiopia (Chalié & Gasse, 2002). The latter study carries particular interest, because it involves a highly climate-sensitive closed-basin amplifier lake in the semi-arid Ethiopian Rift Valley, and because the paleolimnological studies are part of a wider research programme that includes long-term weather monitoring and hydrological modelling (e.g., Vallet-Coulomb et al., 2001), the kind of process-oriented supporting studies which may eventually allow one to read the record of lake history as a true climate record. However, given the inferred shallowness of Lake Abiyata for much of the past 5000 years (Chalié & Gasse, 2002), it is possible that phases of (near-) complete desiccation created one or more century-scale sedimentary hiatuses that the ^{14}C-based sediment chronology is unable to resolve. Consequently, despite understanding of contemporary lake-climate relationships, correlation of the relatively short-lived climate events revealed in this record with those from other African sites and extra-tropical regions may be difficult.

Selecting study sites for lake-based climate reconstruction

As indicated above, lakes in stable hydrological settings are not typically selected for high-resolution climate reconstruction in Africa, except when the targeted climate-proxy indicator is external to the lake system (e.g., wind-blown dust or glacier advance and retreat) or when the main interest is in long-term vegetation dynamics rather than climate variability per se. Climate-sensitive lakes include hydrologically closed lakes, where water output only occurs through evaporation; hydrologically open lakes where surface or subsurface outflow is low compared to evaporation; and amplifier lakes, where any stabilising effect of a permanent outflow is overridden by highly variable river inflows from a large and well-drained catchment. Several hundred such climate-sensitive lakes occur in the parts of Uganda, Kenya, Ethiopia, and Tanzania which together form the vast sub-humid and semi-arid regions of the East African Plateau. Still, finding lakes with just the right balance of climatic sensitivity (their potential to respond to and record clear signals of short-term rainfall variability) and longevity (their potential to preserve these signals in an uninterrupted sediment sequence) is difficult. Selection of suitable study sites starts with an assessment of basin topography, lake morphometry, and mean and peak annual wind speeds and directions. Together these factors permit application of wave theory (Håkanson & Jansson, 1983) to predict the dominant processes of sediment distribution (Hilton, 1985; Fig. 2) and determine if local sedimentation conditions allow undisturbed, continuous accumulation of a climate-proxy record (Dearing, 1997). Field-monitoring data or equivalent documentary evidence (for example, temporal sequences of aerial photographs and satellite images) on the magnitude of seasonal and inter-annual lake-level fluctuations relative to current lake depth permit educated guesses about the probability that today's favourable sedimentation conditions persisted throughout the period of interest (Verschuren, 1999a). These predictions of the integrity of a lake's climate-proxy record can be tested, by lithostratigraphic analyses and high-resolution ^{210}Pb-dating of short sediment cores representing lake response to climate change during the past $\sim$150 years.

Given that high-resolution climate-proxy records are so easily compromised by decade- to century-scale cryptic hiatuses which (mostly ^{14}C-based) sediment chronologies are unable to resolve, one might be tempted to minimise the risk for such hiatuses by selecting among Africa's many crater lakes that are sheltered against wind-driven turbulence by a high crater rim and are deep enough to tolerate substantial lake-level fluctuations without sedimentation being interrupted or disturbed. However, the steep bottom slopes in these lakes bring increased risk of sediment slumping (Hilton, 1985), so that the integrity of the climate-proxy record is affected by interbedded turbidites. Steep bottom topography also means that appreciable lake-level change is not accompanied by significant changes in lake surface area or volume, thus weakening the signals of most biological and geochemical climate-proxy indicators (e.g., Barker et al., 2000). The main advantage wind-sheltered crater lakes have over larger, more exposed tectonic and floodplain lakes is that favourable sedimentation conditions can

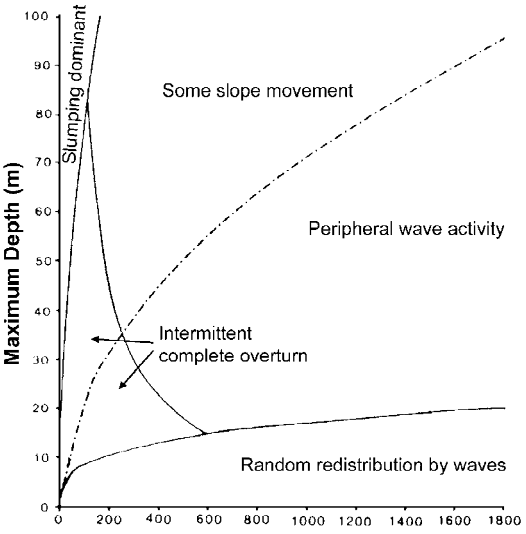

Figure 2. Relationship between lake depth, lake surface area as a measure of effective wind fetch, and prevalence of the four main processes of sediment distribution. From Hilton (1985).

be maintained in very shallow water depths, allowing greater relative amplitudes of lake-level change to be registered intact (Verschuren, 1999a). Hence crater lakes of intermediate depth, which combine adequate wind shelter with gentle bottom topography, appear to be the preferred sites for high-resolution climate reconstruction from a sedimentological standpoint. A potential weakness of crater lakes as climate recorders compared to large tectonic lakes is that their local hydrogeological setting may add complexity to the link between lake level and climate, a problem which must be circumvented by parallel studies of several crater lakes within crater-lake districts.

A unique category of climate recorders are the crater basins confluent with or hydrologically connected to river-fed tectonic lakes, which combine a wind-sheltered sedimentation regime with the climatic sensitivity of an amplifier lake. The best-known example is Crescent Island Crater in Lake Naivasha (Kenya; Verschuren et al., 2000a); others are Lake Sonachi near Lake Naivasha (Verschuren, 1999b), and several unexplored peripheral basins of Lake Turkana (Kenya). The Kibengo crater basin in Lake George (Uganda; J. Russell et al., unpublished data) also provides a locally favourable sedimentation environment, but its hydrological response to rainfall variability is muted by the fact that the Lake George-Lake Edward system is hydrologically open.

Key problems of chronology

Many African lakes deposit finely laminated sediments. Testifying to the absence of significant sediment disturbance (either physical or by burrowing organisms), finely laminated sediment records are invaluable to climate reconstruction because of the superior temporal resolution they can provide. However, truly annual laminations have so far only been demonstrated (through parallel varve counting and ^{210}Pb-dating) in Lake Malawi (Johnson et al., 2001), Lake Hora in Ethiopia (Lamb et al., 2002), and Lake Bosumtwi in Ghana (J. Overpeck et al., unpublished data). In Lake Malawi, varved sediments interrupted by a few homogenites extend from the present to ~AD 1300; down-core the lamination desintegrates into alternating varved, banded, and massive sediments. A second section of apparent varves covers the period ~6500–9000 cal. yr BP, but discrepancy with bracketing ^{14}C dates suggests that up to 25% of the annual couplets there may be unclear or missing (Barry, 2001). Often, when sections of distinct annual lamination do occur in African lakes, they are usually too short (10–50 years) to significantly improve ^{14}C-based age models. Since most lakes suitable for varve formation and preservation have now been surveyed, a distinct possibility exists that tropical Africa will never yield a full Holocene lake-based climate record with annual time control.

Lake-based chronologies of Holocene climate and hydrological change in Africa will thus continue to rely mostly on a combination of ^{210}Pb- and ^{14}C-dating. This entails several problems. First, the most spectacular records of millennium-scale dry spells during the early Holocene (Gasse, 2000) are based on ^{14}C-dating of materials recovered from ancient shorelines and exposed lacustrine sections, limiting their dating resolution and precision. These dry spells have yet to be clearly documented in a continuous lake-sediment sequence supported by a well-constrained AMS^{14}C-chronology. The high-resolution Holocene ice-core record of Mt. Kilimanjaro (Thompson et al., 2002) displays exquisite detail at decadal to millennium time scales, but climatic inferences are weakened by the assumption that the observed oxygen-isotope variability is entirely due to temperature variation (contra Rozanski et al., 1993; see also Barker et al., 2001), and because the inferred timing of events has not been not absolutely dated but based on correlation with ^{14}C- and U/Th dated climate-proxy records both nearby (Lake Naivasha, Kenya) and far away (Soreq Cave, eastern Mediterranean). Consequently, detailed comparison of these millennium-scale events on the African continent with records of Holocene monsoon variability from Oman (Neff et al., 2001) and the Arabian Sea (Gupta et al., 2003) may remain pending for some time. Second, in large African lakes such as Victoria and Malawi, which can be expected to accumulate a continuous sediment record (but see section 3 above), ^{14}C dating is complicated by the scarcity of large terrestrial plant macrofossils at offshore coring sites. Such fossils tend to yield more trustworthy sediment ages because terrestrial plants obtain their starting ^{14}C concentration from atmospheric CO_2. The alternative, measuring the ^{14}C of aquatic algae (as preserved in bulk organic matter) tends to over-estimate true sediment age because aquatic algae obtain their starting ^{14}C concentration from dissolved organic carbon, which in closed-basin lakes with long residence times often has a reduced ^{14}C/^{12}C ratio relative to the atmosphere. In large lakes, where sediments may go through several cycles of resuspension and redeposition before reaching their final burying site offshore, dating bulk organic matter can also over-estimate true sediment age because of contamination with old organic materials (for example, pollen) which are refractive enough to have survived these redeposition cycles intact (Russell et al., in press). The age offsets due to reservoir effects can be corrected by parallel ^{14}C- and ^{210}Pb-dating of pre-1945 sediments. Ideally this is supplemented by parallel ^{14}C-dating on bulk organic matter and terrestrial plant macrofossils at intervals further back in time, to confirm that the lake's reservoir age remained constant throughout the period of the reconstruction, but in large lakes this is rarely an option. In the case of old-carbon contamination, age offsets are also site-specific within a lake, and require ^{14}C age correction for each coring site separately.

Given these complications, the preferred strategy to obtain reliable sediment chronologies is to: (1) select lakes that are small enough to bury adequate quantities of large terrestrial plant fossils at mid-lake coring sites; (2) obtain ^{14}C dates at intervals approaching the 2σ counting error on each date (± 100 years); (3) carefully select which individual dates can be included in the age model, based on understanding of the evolution of local sedimentation dynamics as reflected in lithostratigraphy; and (4) if feasible, increase the precision of the age model further by wiggle-matching sediment ages against the atmospheric ^{14}C calibration curve (Stuiver et al., 1998). This ^{14}C wiggle-matching procedure (van Geel & Mook, 1989) has proved a powerful tool to improve time control in Holocene peat deposits (e.g., Speranza et al., 2000), but so far it has not been applied to African lake sediments. Besides the high cost of close-interval ^{14}C-dating, at least two other complications can be envisioned. First, in peat deposits the dated material is certain to represent the time of peat formation, as the peat mosses themselves make up most of the peat matrix. By contrast, burial of terrestrial plant remains in offshore lake sediments may involve significant delays, due to retention in soils, peripheral swamps, or nearshore sediments. Sturdy plant remains, such as pieces of wood and sedge rhizome, can survive several decades or even centuries of such temporary storage and the transport to their final burial site offshore. For example, Verschuren (2001) excluded three out-of-sequence ^{14}C dates that were 150–300 year older than the expected ages based on a polynomial regression of historical marker horizons, ^{210}Pb-ages, and ten other ^{14}C dates covering the 1100-year history of Lake Naivasha (Kenya). In this particular case, exclusion was justified because all three dates were measured on single pieces of wood or sedge, whereas most of the others were measured on charred grass fragments; and all three were extracted from a single lowstand horizon during which reworking of older littoral deposits is most likely. When pre-burial storage lasts decades rather than centuries, identification of out-of-sequence dates is nearly impossible. Variation in retention times before permanent burial then simply increases the noise in age-depth relationships, with the result that the short-lived ^{14}C-plateaux and reversals in the ^{14}C-calibration curve, which are the time anchors in ^{14}C-wiggle matching, are no longer evident in the sediment chronology despite better-than-century dating resolution. One feasible solution to this problem is to date only those terrestrial plant macrofossils that are likely to be destroyed by prolonged aerial exposure or in the process of sediment reworking, such as brittle leaves of trees and marsh plants, or fragments of grass charred by bush fires. When such plant remains are found in offshore sediments, they most likely reflect direct deposition from the air. A second complication for ^{14}C wiggle-matching in lake records is the requirement that sedimentation rate be relatively uniform at multi-decadal time scales; large sedimentation-rate changes would create spurious ^{14}C plateaux and ramps.

When ^{14}C-wiggle matching is not possible, detailed correlation of high-resolution climate-proxy records, and evaluation of possible leads and lags between them in the expression of specific climatic anomalies, requires that age models at least capture the distortions of the age-depth relationship caused by the changes in sediment-accumulation rate that usually accompany lake-level fluctuations. Without such correction, for example, the duration of a lowstand episode can be either over- or underestimated depending on the severity of the drawdown relative to the lake's critical depth of sediment accumulation (Verschuren, 1999a). When accumulation is continuous throughout the lowstand, accumulation rates tend to increase with falling lake level (see section 7 below); however, when water depth becomes less than the critical depth of sediment accumulation, sediment erosion and redistribution results in little net sediment accumulation during the lowstand (Verschuren, 1999a). Given that some African lakes have been documented to experience up to six-fold changes in mid-lake sediment-accumulation rate within a decade (Verschuren, 1999b; Fig. 6), full correction may prove elusive. Similarly, while a lake desiccation lasting for several centuries typically leaves clear stratigraphical signatures and can be accounted for in an age model, decade-scale hiatuses due to non-deposition or erosion at low lake level may be difficult to recognise because mixing of unconsolidated muds deposited before and after the lowstand obliterates the evidence that the climate-proxy record has been truncated (Verschuren, 1999a).

In these circumstances, demonstrating leads and lags between sub-century scale climatic anomalies across a region becomes challenging. One possibility is to restrict high-resolution climatic inferences to those sections of the individual proxy records with a high probability of continuity and relatively stable sedimentation rates. A coherent picture of high-frequency climate variability throughout the Holocene will then ultimately require combination of early-, mid-, and late-Holocene records from different sites.

Salinity inference as indicator for climate-driven hydrological change

Quantitative paleoclimatology in Africa with biological proxy indicators is currently limited to diatom-based inference of lake-water conductivity (salinity), pH, and ionic composition (Gasse et al., 1995), and chironomid-based salinity inference (Verschuren et al., 2000a; in press). The statistical performance of the African diatom-based salinity-inference model is better than the chironomid-based model, because of more frequent species turnover along the salinity gradient (i.e., average tolerance ranges of diatom species are narrower), but in saline lakes or during saline phases in lake history chironomid-based inferences are potentially more reliable because their chitinous remains are less prone to diagenesis than diatoms (species composition of fossil diatom assemblages being affected by differential dissolution; Barker et al., 1990).

A more fundamental problem with salinity inference, however, is that the relationship between salinity change and climate forcing is indirect and complex (Gasse et al., 1997), involving memory effects of previous hydrological history on current salinity (Langbein, 1961; Barton et al., 1987) and salinity regulation via groundwater seepage (e.g., Telford et al., 1999). Even when a case can be made that long-term salinity variation has been proportional to the climatic fluctuations causing it, the relationship is non-linear and characterised by threshold effects. Apparently, when combined rainfall, river inflow and groundwater seepage fail to keep a tropical lake fresh (below $\sim$1500 μS/cm), perpetual high temperatures and a pronounced local hydrological deficit move it very quickly to true salt-lake conditions ($>$6000 μS/cm) and a shift to specialised fauna and flora. This is attested to by the scarcity of modern African lakes with intermediate salinities (Talling & Talling, 1966; Wood & Talling, 1988); one notable exception is Lake Turkana (3500 μS/cm; Kolding, 1992) the only hydrologically-closed basin among the large African Rift lakes. In fossil records from high-sedimentation-rate environments (e.g., Verschuren et al., 2000a; Fig. 3) it is evident in very sudden transitions between freshwater and salt-lake species assemblages, unduly suggesting very sudden transitions between wet and arid climate regimes. A possible corollary of this observation is that more gradual salinity trends inferred from other fossil records may often be due to post-depositional mixing of freshwater and saline species assemblages, through bioturbation or wind-induced sediment reworking.

Given the complex relationship between lake-water salinity and climate, quantitative salinity reconstruction should ideally be accompanied by site-specific and time-dependent modelling which can transform the inferred trajectories of past salinity change into histories of lake-volume (and thus water-balance) change (e.g., Vallet-Coulomb et al., 2001). Unfortunately, the local meteorological and hydrolo-

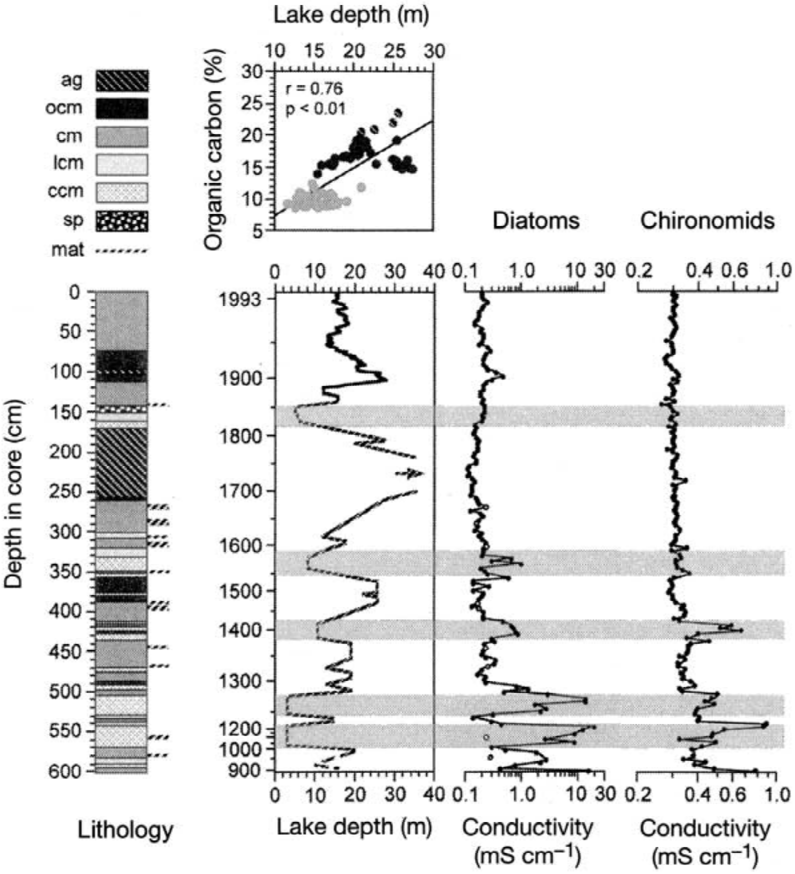

Figure 3. Lake-level and salinity fluctuations in Crescent Island Crater, Lake Naivasha (Kenya) over the past 1100 years reconstructed from sediment texture and organic-matter content, and from fossil diatom and chironomid species composition. Sediment types include algal gyttja (ag), organic clayey mud (ocm), clayey mud (cm), low-organic clayey mud (lcm), calcareous clayey mud (ccm), and silty peat (sp); the relationship between organic-carbon content and lake depth is based on the historical record, AD 1883–1993. Modified from Verschuren et al. (2000a).

gical data required for such modelling are available for only very few African lakes. When quantitative modelling is not an option, salinity reconstructions are validated by comparing the upper part of proxy-indicator records with independent time series of historical data, and using the match between the two as a guide to assess the validity of inferred patterns further downcore. Such comparisons involve direct correlation with instrumental weather data and drought indices (e.g., Laird et al., 1996), or with climatically controlled limnological variables (e.g., Fritz, 1990; Legesse et al., 2002), including historical salinity data.

One particular series of studies (Verschuren, 1999a–b; Verschuren et al., 1999a–b, 2000a) investigated the biological effects of climate-driven lake-level change in the Lake Naivasha system (Kenya), a complex of four distinct lake basins that because of their hydrological interconnectedness have a common recorded lake-level history spanning the last 120 years. In the three basins for which a diatom-based salinity reconstruction is now available, inferred salinity matches the main patterns displayed by historical instrumental data. The main significance of these studies, however, is their illustration of the complexity of chemical and biological response to climate-driven lake-level change at decadal time scales, and how the signatures of this response in the sediment record is affected by sedimentation dynamics and taphonomy. For example, although reconstructed salinity and lake-level changes in Lake Oloidien displayed the expected inverse correlation, this relationship was modulated by apparent delayed dilution of dissolved salts following modest lake-level rise in the late 1950s–1960s (Fig. 4). Given tight sediment chronology, Verschuren

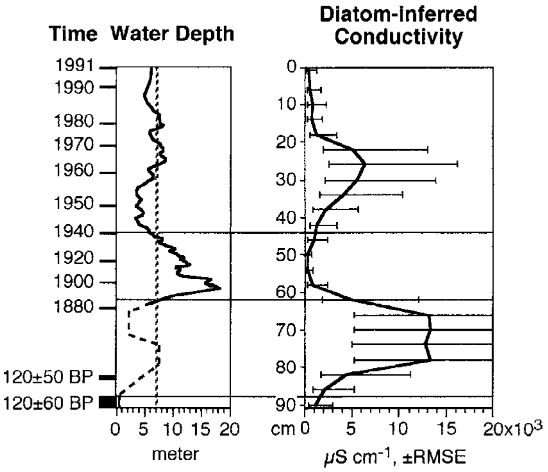

Figure 4. Measured lake-level fluctuations and diatom-inferred salinity variations in Lake Oloidien (Kenya) over the past 120 years (~AD 1870–1993). Due to its dependence on nearby Lake Naivasha for freshwater input, freshening is rapid when transgression results in broad confluence (the 1890s rise), but slow when transgression only increases seepage inflow (1950s–1960s rise). From Verschuren et al. (1999b).

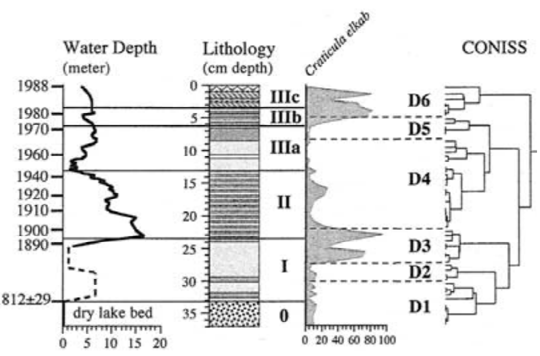

Figure 5. Measured lake-level fluctuations, sediment lithology, CONISS fossil-diatom zonation, and stratigraphic distribution of the dominant shallow-water diatom *Craticula elkab*. The boundary between diatom zones D3 and D4 post-dates the lithostratigraphic transition from massive (zone I) to finely laminated (zone II) deposits by a decade, probably not because the diatom flora responded slowly to 1890s lake-level rise and establishment of meromixis, but because previously buried shallow-water diatoms were resuspended during the transgression and redeposited offshore. Modified from Verschuren et al. (1999a).

et al. (2000a) suggested that this reflects the threshold on salt removal determined by the elevation of the sill separating Lake Oloidien from the main basin of Lake Naivasha. It is also possible, however, that the 1960s transgression caused some reworking of 1950s lowstand deposits containing halophilic diatoms.

In nearby Lake Sonachi, the diatom community responded quickly to a major 1890s lake-level rise leading to stable density stratification of the water column, but in the sediment record this response appears delayed by almost a decade because of redeposition during the transgression of previously buried shallow-water diatoms (Fig. 5; Verschuren et al., 1999a). Further, in all three groups of aquatic invertebrates studied (ostracods, cladocerans and chironomids), only a limited number of species appeared to respond strongly to salinity change itself; or actually, the osmotic stress associated with it. Most species responded more strongly to the substrate changes associated with lake-level change, or to changes in the distribution of aquatic vegetation, which itself is a function of both lake level and salinity (Verschuren et al., 2000b). While it is well known that lake depth, salinity, and substrate quality are all important factors in structuring aquatic invertebrate communities, it is sobering to realise that at the time scale of climate events sought for in modern high-resolution paleoclimate studies, the intuitive co-variation among these factors may be strongly modulated by transient system dynamics. Nonetheless, aquatic biota remain powerful proxy indicators of past hydrological change, especially in combination with one or more non-biological climate proxies.

(Semi-) quantitative lake-level inference

Provided that the calibration data set is developed from a suitably diverse collection of reference lakes, fossil diatom species composition can also be exploited for quantitative reconstruction of former lake-level changes (Cumming et al., 2002), succeeding a long tradition of more qualitative diatom-based approaches for lake-level reconstruction (see Wolin & Duthie, 1999). However, Birks (1998) suggests that because the relationship between diatom species composition and lake level much depends on local lake morphometry that may not be adequately represented in the reference data set, lake-depth inference models may best be calibrated with a collection of surface-sediment samples taken along depth transects in the study lake itself. However, this approach increases the risk of no-analogue fossil assemblages down-core (Cumming et al., submitted), particularly when lake-level fluctuations are accompanied by water-chemistry change. Cumming et al. (submitted) recommend both the use of calibration data sets in which lakes represent the full modern-day environmental gradients, as well as knowledge on how diatom floras change with depth within the lake in question. As with salinity-based climate inference, the relationship between lake-level and hydrologic balance can be exceedingly complex, requiring site-specific modeling efforts to transform lake-level data into paleoclimate records relevant to the paleoclimate community.

Quantitative diatom-based lake-depth reconstruction has so far not been attempted in Africa. Trials (K.R. Laird et al., unpublished data) suggest that diatom-based lake depth and/or surface-area inference is feasible for the chemically uniform subset of East African lakes but will require expansion of the current data set (Gasse et al., 1995) with more linked diatom and lake-morphometric data. Chironomid-based depth-inference models for African lakes are also now being developed (H. Eggermont & D. Verschuren, unpublished data). In the case of diatoms, lake depth and surface-area inference is based on the relative abundances of near-shore (typically epiphytic or benthic) and pelagic (open-water) species, their habitat preferences being determined by local differences in nutrient availability, water-column turbulence and transparency, or substrate texture. In the case of chironomids, depth inference is based on the relative abundances of littoral and shallow- and deep-water offshore species, and how the importance and composition of the offshore component is influenced by seasonal or permanent oxygen loss in the lower water column. One expected complication is that in permanently stratified lakes, persistent anoxia of the water column below the thermocline eliminates the deep-water faunal component, such that fossil assemblages deposited at deep-water coring sites will consist exclusively of shallow-water species, and may thus corrupt the reconstruction of lake-depth variation through time (Hofmann, 1998). A comparable problem may complicate diatom-based lake-depth reconstruction in relatively deep but turbid lakes. At short time scales, erosion and redeposition of shallow-water muds with their associated fossil flora and fauna during regressive-transgressive cycles (cf. section 5) may also here cause additional complications.

Given that lake-level fluctuations impact the species composition of lake biota mostly through associated changes in water-column dynamics and the distribution of various types of substrate (besides the osmotic stress caused by water-chemistry changes), the question arises why climate-driven changes in a lake's physical limnology cannot be reconstructed more directly from the composition and texture of the sediments in which the biological fossils are buried.

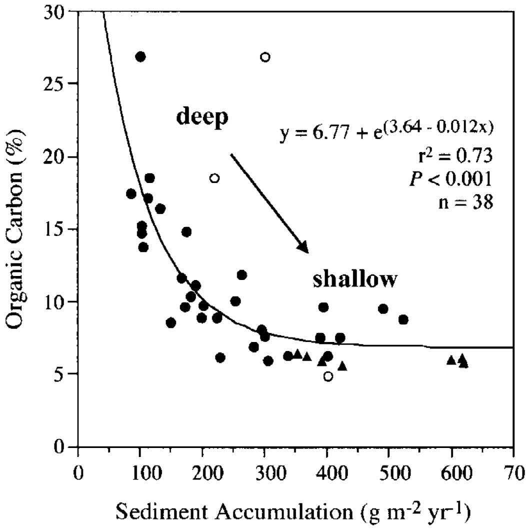

Figure 7. Relationship between sedimentary organic-carbon content and ^{210}Pb-derived sediment accumulation rate over the past 150 years (~AD 1840–1993) in a mid-lake core from Lake Sonachi (Kenya). The transition from decreasing to near-constant organic-carbon content (~8%) occurs when lake depth is ~4 m, the modern chemocline depth. Triangles represent low-organic muds deposited during an 1870–1880s lowstand when water depth was less than 2 m and random sediment redistribution occurred. Open circles are passive data points representing event horizons. Modified from Verschuren (1999b).

Climate reconstruction based on lithostratigraphical analysis of lake deposits has a long tradition (Lundqvist, 1927; Richardson, 1969; Digerfeldt, 1986), but high-resolution interpretations have often been qualitative and ambiguous, hampered by incomplete understanding of the local hydrological and sedimentation dynamics that control such basic sediment features as organic and inorganic carbon content. Yet relatively simple analyses of the local relationships between basin morphometry, physical limnology, and local sedimentation regimes, supplemented by short-core studies of how these relationships have changed through time due to historical lake-level fluctuation, can add considerable rigour to the interpretation of sediment composition, and permit (semi-) quantitative reconstruction of climate-driven lake-level change at decade-to-century time scales.

One basic principle is that the organic-carbon proportion of offshore lake sediments is usually not a function of organic production (mostly in-lake algal productivity), but reflects the dilution of organic matter by mineral sediment input, and/or exposure to oxidation before its permanent burial (Rowan et al., 1992). Progressive lake-level decline in a small strati-

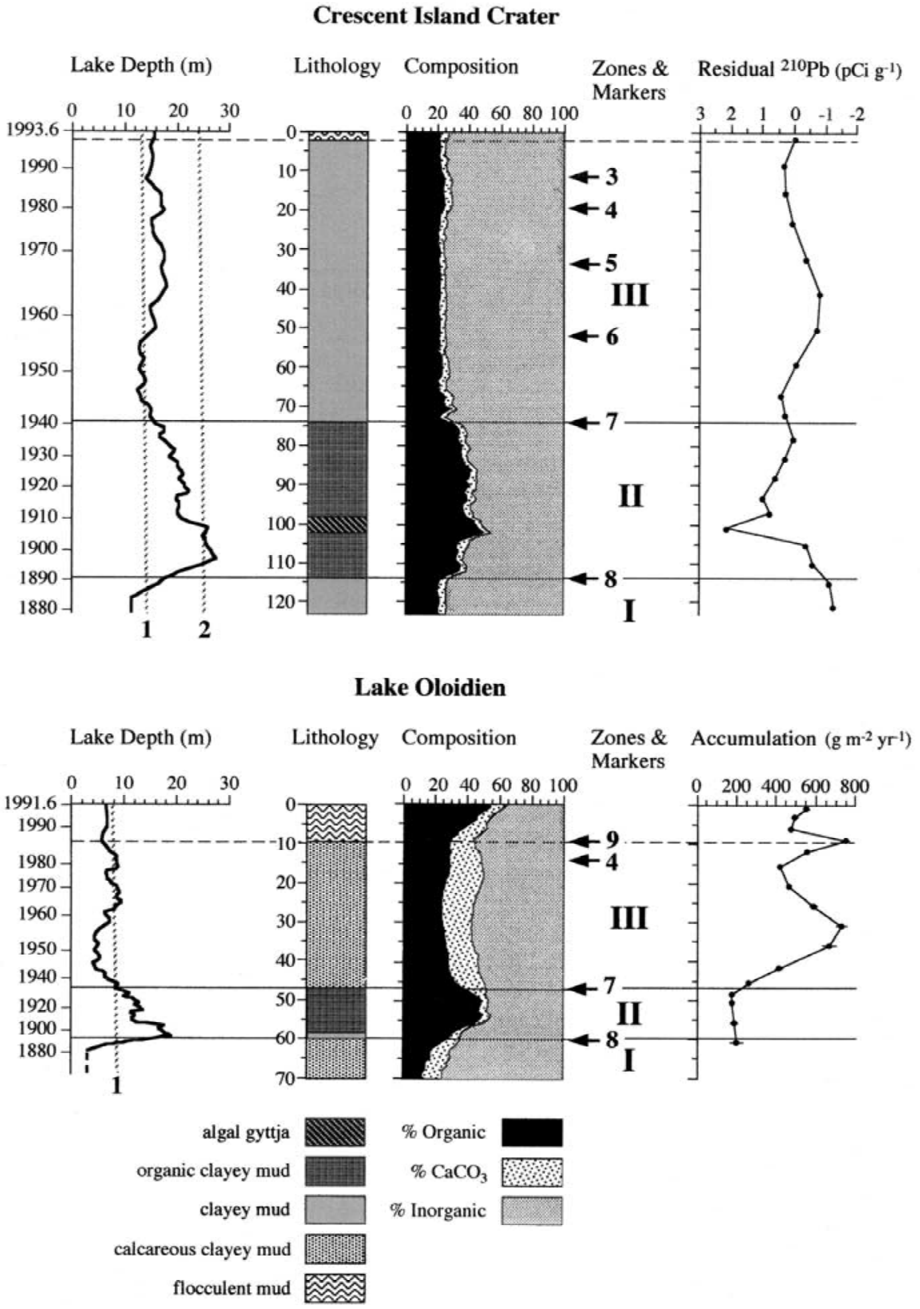

Figure 6. Relationship between lake depth, sediment composition, and sedimentation rate over the past 120 years (~AD 1870–1993) in mid-lake cores from Lake Oloidien and Crescent Island Crater in Lake Naivasha (Kenya). Organic-matter content is positively correlated with lake depth in a sequence from low-organic clayey mud to algal gyttja. Numbered arrows show historical marker horizons. From Verschuren (2001).

fied lake first causes increased focusing of low-organic (because partly oxidised) shallow-water sediments to offshore profundal areas, which dilutes the organic matter derived from pelagic algal production that has settled locally. In this phase, organic-matter content is inversely related to sediment-accumulation rate (Verschuren, 1999b; Fig. 6). By the time the lake has become so shallow that its entire bottom is well-aerated and subject to wind-driven turbulence, accelerated oxidation of sedimentary organic matter coupled with frequent horizontal redistribution has reduced organic-matter content to a constant level, representing the more refractive organic materials which remain. As a result, organic-carbon content is positively correlated with lake depth at the time of deposition in a lithological sequence from inorganic clayey mud to highly organic algal gyttja (Verschuren, 2001; Fig. 7). In a typically productive tropical lake, oxygen in warm (>20 °C) waters below the thermocline is consumed quickly, so that thermocline depth places a pronounced threshold on the depth gradient of organic-matter oxidation. Since thermocline depth among a set of lakes located within a single climatic region is primarily controlled by effective wind fetch (e.g., Shuter et al., 1983) and the wind shelter provided by surrounding topography (Melack, 1978), thermocline depth can be calculated, and transitions between sediment types in profundal areas can be tied to specific total depths of the water column. With certain limitations, this permits quantification of the absolute magnitude of past lake-level changes, at decadal to century-scale resolution (Verschuren, 2001). At the short end of this time scale, reliability of lake-depth inference based on percent organic matter alone will again suffer from hysteretic effects in sedimentation dynamics during a regressive-transgressive cycle; caution is also recommended when extrapolating a historical relationship between sediment composition and lake level to periods beyond the current lacustrine episode (i.e., prior to a desiccation phase), as this may have affected basin morphometry (Verschuren, 2001). Interpretative support from grain-size data and authigenic minerals can help to constrain the limits of this methodology. On the other hand, trustworthy lake-level inferences, even of a semi-quantitative nature, have the advantage over salinity inferences to more directly reflect the climate-driven changes in moisture balance that are the subject of climate reconstructions.

Conclusion

Climate reconstruction is arguably the most difficult discipline in paleolimnology. In no other application of paleolimnological methods is the cascading chain of cause and effect linking a sedimentary proxy indicator to the variable of interest so long and complex. No other application needs to strain the limits of chronological methods so much to produce a valid story. And most other applications typically do not deal with a long sequence of events, but can be content to identify pre-disturbance, disturbance, and recovery phases. Partly because of the complexities involved, some commentators on the future of paleoclimatology (e.g., Broecker, 1997; Berger & Maslin, 1999) do not envision a prominent role for lake-based climate reconstruction. But given the low potential of tree-ring and ice-core archives in tropical regions and the restricted distribution of high-quality cave speleothems, achieving the world-wide coverage of regional climate histories that is crucial to understand decade- to century-scale climate variability will not be possible without optimal exploitation of tropical lake records.

Lake-based paleoclimatologists must keep focus on the principal objective of high-resolution paleoclimate research, which is to produce histories of local climate variability of such quality that climate modellers can use them to constrain and validate the models being developed for long-term climate prediction. Strong, trustworthy paleodata yield unique insights in the patterns and modes of climate variability that can not be gained from instrumental meteorological data alone, and can compel modellers to produce a mechanistic explanation for them. With this in mind, all the methodological difficulties addressed in this paper reduce to two major challenges. The first is to produce high-resolution records of climate-proxy indicators whose particular relationship with climate variability is sufficiently well understood for them to validly represent climate history. Lake histories with high stratigraphical resolution cannot be treated as high-resolution climate records if the link between the climate-proxy signals and climate variability at the relevant time scale is not properly understood. The second is to produce local climate reconstructions that are fully independent with respect to both chronology and proxy-record validation. Climate-proxy records cannot claim their place in a regional or continental network of reconstructions when their interpretation or chronology is a priori tuned to or dependent on other records, either within or outside that region.

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