7. LATE QUATERNARY CLIMATIC VARIABILITY IN INTERTROPICAL AFRICA

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Introduction

Tropical Africa is at the geographical heart of the PEP III transect and forms part of the heat engine which drives the meridional circulation of the atmosphere. The tropics are therefore central to studies of climate change not only in the equatorial belt but also in sub-tropical regions (Yin and Battisti 2001), and may even lead some high latitude climate changes (Henderson and Slowey 2000). Despite this pivotal role, the tropics have historically been the poor relation of temperate regions in palaeoenvironmental research. Here we synthesise new palaeoclimate information derived primarily from forest and savanna regions of tropical Africa. These recent studies have helped to close some empirical gaps in data coverage within the region and at the same time have led to a new conceptual understanding of past tropical climates. The latter has been achieved through the rigorous application of classical methods as well as the development of several new proxies of environmental change.

We focus our discussion on several key palaeoclimate issues that fall within the scope of PAGES time stream 2 (cf. Gasse and Battarbee (this volume)). Although this is defined as spanning the last two glacial cycles, we will place greatest emphasis on the events since the penultimate glacial (marine isotope stage 6, hereafter MIS 6) and especially on the last 30,000 calendar years BP (abbreviated below to kyr) (broadly MIS 1-3). At these long time-scales, orbital-forcing factors, modified by earth-surface feedback mechanisms, ought to be dominant and be recognisable in the biotic and hydrological systems. We will then examine the evidence for abrupt events at century to millennial scales, which are prominent features in many climate reconstructions since the Last Glacial Maximum (LGM). Climate forcing at these time-scales is tightly coupled to oceanic changes and so we will extend our discussion to a number of offshore sites. Numerous terrestrial archives are now being explored including some excellent high-resolution speleothem records (Holmgren et al. 2001), but to limit our study we will confine our discussion to lakes and the major river systems (Fig. 1).

Few proxies are directly related to the fundamental climate variables of precipitation and temperature. Even in the tropics where shifts from wet to dry conditions commonly outweigh temperature changes, it is difficult to tease these variables apart. Moreover, the part played by atmospheric gases such as CO_2 in terrestrial environmental change is now also recognised (Street-Perrott 1994; Jolly and Haxeltine 1997; Street-Perrott et al. 1997). Identifying the specific contribution of the different variables is of primary concern to tropical palaeoenvironmental studies and has promoted the development of several novel approaches to environmental reconstruction.

Climate forcing factors and contemporary processes

At the glacial-interglacial time-scale the major forcing factors controlling the tropical African climate include orbital configuration, the volume of the Northern Hemisphere ice sheets, surface boundary conditions, oceanic properties and atmospheric transparency (Street-Perrott et al. 1990; Kutzbach and Liu 1997; Texier et al. 2000). The dominant paradigm for the last two decades has been that much of the hydrological variability in the region stems from the control exerted by the 19–23 kyr Milankovitch precessional cycle (Kutzbach and Street-Perrott 1985; Kutzbach and Guetter 1986). Insolation controls the strength of the monsoon circulations through the differential heat capacity of land and

Figure 1. Location of the lakes, rivers and marine cores mentioned in the text. The base map was drawn online at www.aquarius.geomar.de.

oceans, and fuels the large-scale convective overturning in the tropics. A sensitivity analysis for the northern tropics suggests that a 10% increase in insolation would create an average 35% (range 25–50%) increase in precipitation (Prell and Kutzbach 1992) and a similar figure of 45% has been calculated for the southern tropics (Partridge et al. 1997). Lake level fluctuations across the northern and equatorial tropics provide strong support for orbital forcing as a dominant climate mechanism from the late-glacial to the mid-Holocene (Kutzbach and Street-Perrott 1985; Street-Perrott et al. 1990). It is less clear to what extent the Northern and Southern hemisphere tropics responded in antiphase as the theory would predict.

In addition to orbital configuration, atmospheric CO_2 and CH_4 are essential in forcing climate changes, especially through the amplification of insolation changes (Shackleton 2000). High-resolution gas records from polar ice cores have confirmed the magnitude of global average changes in these variables between the LGM and the Holocene (Indermühle et al. 1999). The impact of trace-gas levels on tropical ecosystems and conversely, the role of tropical wetlands in regulating the global carbon dioxide and methane cycles, cannot be ignored. The East African great lakes are major methane producers (Craig 1974; Tietze et al. 1980; Adams and Ochola 2002), but of even greater significance in terms of their global climatic impact are the vast wetlands that develop during periods of enhanced humidity (Petit-Maire 1990; Petit-Maire et al. 1991; Street-Perrott 1992; 1994).

Nicholson (2000) suggests that the major glacial-interglacial shifts in African climate are caused by climate dynamics similar to those operating today, even if the boundary conditions differ. This general pattern is contradicted by events within the last millennium that show a negative relationship between high latitude temperatures and East African rainfall (Verschuren et al. 2000), demonstrating that complex and poorly understood climate processes operate at sub-millennial time-scales. Nevertheless, on the historical time-scale, major climate shifts can be traced across the continent and are coupled with large-scale features of the general circulation (Nicholson 2000; Verschuren, this volume). Precipitation is associated with the proximity of atmospheric convergence zones. Classical climatological theory implies that the double passage of the Intertropical Convergence Zone (ITCZ) explains the bimodal rains of the equatorial region (Nicholson and Flohn 1980). In addition, a marked west-east rainfall gradient is maintained by the moist southwesterly air flows from the Atlantic. The broadly North-South Congo Air Boundary in the central-southern part of the continent marks the convergence of low level flows from the Atlantic and Indian Oceans. Both northern and southern parts of the tropical region receive rainfall carried by monsoon circulation. Synoptic patterns for the intertropical region are strongly affected by topography and localised factors such as lake effects or coastal influences rendering the development of coherent syntheses difficult (Nicholson 2000).

From marine isotope stage 6 to the LGM

A key aim of scientists working within this sector of the PEP III transect is to evaluate the role of the precession cycle in forcing the monsoon circulations and whether their response was asymmetrical between the hemispheres (Kutzbach and Street-Perrott 1985; Partridge et al. 1997). Until recently, no records of sufficient duration and resolution were available to examine this prediction through several precession cycles, but within the last 5 years several records have been published that contain relatively continuous sequences extending back to the last interglacial (MIS 5e or Eemian). The marine record GeoB1008-3 (Fig. 2) off the Congo river mouth (6.5 °S, although the Congo basin extends to ~6 °N) is one of the most complete to encompass this period (Schneider et al. 1996). Glacial and interglacial stages are well distinguished by sea-surface temperatures (SST), with the last interglacial in particular being warmer than the present day. Figure 2 also shows that the northern hemisphere precession 19–23 kyr cycle is an important component of the alkenone-derived SST curve. The pollen record corresponds closely to the alkenone curve with the lowland rainforest pollen sum peaking during MIS 5e, 5c and 5a (Jahns 1996). Peaks of the Afromontane coniferous tree *Podocarpus* mark cooler intervals within stage 5 (sub-stages 5d and 5c). Herbaceous pollen indicative of vegetation that is more open is most abundant during the glacial maxima of stage 6 and 2.

The study of new sections from Lake Naivasha (0.7 °S) and the application of $^{40}Ar/^{39}Ar$ dating have extended the 30 kyr-long lake level record from Central Kenya (Richardson

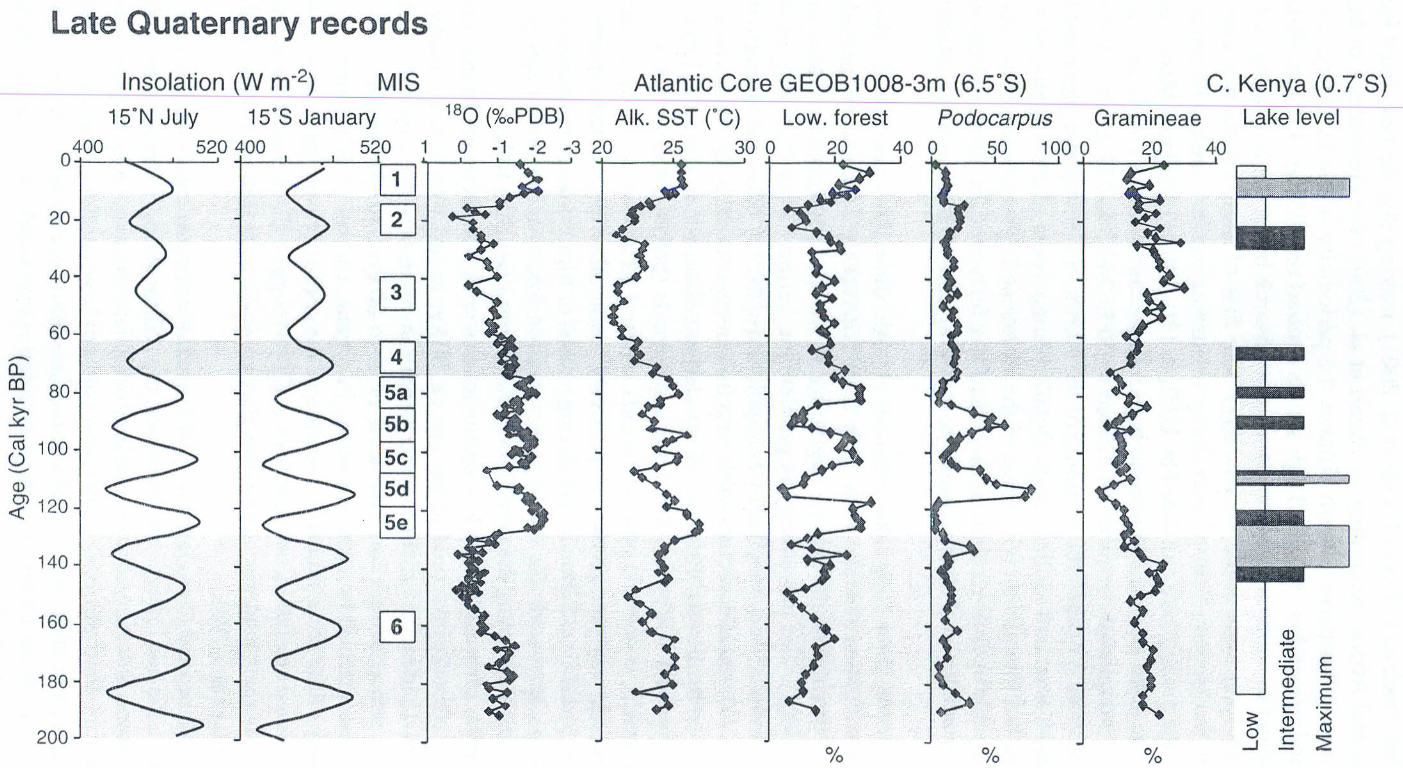

Figure 2. Late Quaternary records of $\delta^{18}O$, alkenone derived SST and pollen percentages (lowland forest, the Afromontane conifer *Podocarpus* and Gramineae) from marine core GeoB1008-3 (Schneider et al. 1996; Jahns et al. 1996) compared to relative lake level changes from Central Kenya (primarily from Lake Naivasha with additional data from Nakuru and Elmenteita) (Richardson and Dussinger 1986; Trauth et al. 2001). Summer insolation curves for 15 °N and 15 °S are from Berger and Loutre (1991). Marine isotope stages (MIS) 1-6 are labelled and the colder stages 2, 4 and 6 are shaded grey.

and Dussinger 1986) back to 175 kyr (Trauth et al. 2001), making this the best dated long record from equatorial Africa. According to Trauth et al. (2001) the chronology of high stands identified during this period mainly follows the periodicity of the 19–23 kyr cycle generated by orbital precession (Fig. 2). High stands centred on 135 kyr, 110 kyr, 90 kyr and 66 kyr correspond to maxima of March insolation (March being the beginning of the period of equatorial long rains at the present day). The first of these events was coeval with a highstand in the Magadi-Natron basin (Kenya-Tanzania border) marked by stromatolites 47 m above the present lake and dated by U/Th to 130–140 kyr (Hillaire-Marcel and Casanova 1987). The Lake Naivasha highstand began significantly earlier ($\sim$146 kyr) than the onset of the last interglacial (termination 2 dated by SPECMAP to 127 ± 6 kyr; Imbrie et al. 1984) and therefore preceded the warming of the Northern Hemisphere predicted by orbital calculations (Karner and Muller 2000). Detailed comparison of the structure of wet episodes during the last interglacial with those of the Holocene is now needed to ascertain whether millennial-scale hydrological instability was also a feature of the Eemian (MIS 5e). Moreover, the Kenyan lake level changes must be tested against other records to establish their regional extent.

South of the equator, three long lake sediment records show the signature of orbital forcing. The combined pollen and lake level study from Tritrivakely, Madagascar, provides a continuous palaeoenvironmental record beginning in the last interglacial (Gasse and Van Campo 1998; 2001). The chronology is problematic before 41 kyr (the limit of the radiocarbon series) and has been modelled by extrapolation of the ^{14}C dates and tuning to the Vostok $\delta^{18}O$ record. Nevertheless, recognisable structure emerges in the pollen record where warm phases indicated by the establishment of wooded grassland occur at around 125 kyr, 100 kyr, 83 kyr, 60 kyr and $10\ \text{kyr} \pm 5$ kyr. Lake high stands (before 143 kyr and around 115 kyr if the age model is correct) and low stands (around 125 kyr and 105 kyr) match pollen-inferred cold and warming phases, respectively. As in other records the separation of climate variables is difficult. Summer rain during phases of high summer insolation was not heavy enough to compensate for the large evaporation losses during warm summers and dry winters, especially during the cold LGM, which was drier than today.

A new core recently obtained from a low sedimentation site on the Kyrvala Island ridge in Lake Tanganyika preserves a record of the last ca. 80 kyr in just over 9 m of sediment (Scholz et al., 2003). Evidence of shallow water conditions with possible exposure of the core site indicates a period of very low lake level prior to 80 kyr ago. Above this section the sediments are characterised by large variations in organic carbon (TOC) content. The uncertain chronology of the pre-radiocarbon section of the core at present precludes direct comparison with regional insolation, but Scholz et al. (2003) suggest that some of the shorter periods of enhanced organic matter accumulation may coincide with Heinrich events in the North Atlantic (Bond et al. 1993).

Orbital forcing can be used to explain many of the major environmental changes shown in these records since the last interglacial. However, the sedimentological studies from the Tswaing Crater (Pretoria Salt Pan) demonstrate how orbital mechanisms may be overridden by other forcing factors. Partridge et al. (1997, this volume) have shown, using a grain-size record calibrated against rainfall, that austral summer insolation correlates with wet events at this site from 200 kyr to the LGM. However, the relationship breaks down at the LGM, where the phase of the precession cycle predicts wetness, yet the grain-size and diatom data (Metcalfe 1999) indicate aridity. It seems that when orbital eccentricity is small, direct insolation effects can be overridden by higher latitude changes during full glacial periods (deMenocal et al. 1993).

On Mt Kenya the response of vegetation to multi-faceted environmental change has been recognised through compound-specific carbon isotope determinations of organic matter (Street-Perrott et al. 1997; Huang et al. 1999). Studies at Sacred Lake have shown that bulk $\delta^{13}C$ values were up to 17 per mille higher in glacial times than today and that the composition of the bulk organic matter (TOC) was dominated by plants (including algae) possessing CO_2 concentrating mechanisms (Street-Perrott et al. 1997). The inference from isotopic values of terrestrial biomarkers that C_4 grasses were present has been confirmed by grass cuticle analysis (Wooller et al. 2000; Ficken et al. 2002) and further evidence for reduced CO_2 is shown by increased stomatal density of grasses at the LGM (Wooller and Agnew 2002). The shift toward grasses and sedges utilising the more efficient C_4 photosynthetic pathway would be consistent with lower CO_2, greater aridity and increased fire frequency. All three variables probably contributed to the lowering of vegetation belts and would tend to moderate the more extreme estimates of temperature lowering during the LGM in the tropics based on the simplistic application of modern lapse rates. Time-series analysis reveals that the precessional cycle and its harmonics dominate the frequency spectrum of the Sacred Lake $\delta^{13}C$ values (Olago et al. 2000), a further demonstration of the tight coupling between the tropical monsoons, earth surface processes and orbital forcing.

These long Late Quaternary palaeoenvironmental records complement the much larger number of studies from tropical Africa that provide continuous data from before the LGM to the present. The number of sites now investigated has enabled the regional significance of localised records to be established and enable key periods to be reconstructed with confidence (Pinot et al. 1999). A wide range of proxies from different archives shows that intertropical Africa was both drier and cooler than the present day at the LGM (Gasse 2000). Quantitative estimates from pollen transfer functions confirm a reduction of 32% in rainfall (Bonnefille and Chalié 2000) and a temperature fall of 2–5 °C in the Burundi highlands (Bonnefille et al. 1990) (Fig. 3). Few pollen records are available from the lowland tropics although offshore pollen data confirm a reduction in rainforest elements of the flora (Marret et al. 2001).

Lake-level data agree with this picture of conditions at least as dry as present at the LGM. New records from Lake Malawi and Lake Rukwa extend the pattern of negative water balance established in northern and equatorial Africa to the southeast quadrant of this study region (Fig. 3). Diatom data from Lake Rukwa indicate that the basin was occupied by a swamp-like environment in clear contrast to the high water levels of the early Holocene (Barker et al. 2002). Lake Malawi has previously been regarded as an outlier by indicating water level fluctuations in antiphase with most other tropical African lakes. However, recent work on well-dated deepwater (363 m) cores from the Northern Basin has now shown that Malawi was low at the LGM (Johnson et al. 2002; this volume; Gasse et al. 2002). The evidence for this interpretation comes from the abundance of diatom periphyton during the LGM indicating that the coring site was much closer to the lake margin than today. This assertion is supported by other data from these cores including evidence for a reduced silica supply to the lake (Johnson et al. 2002; this volume) and increased bulk $\delta^{13}C$ values suggesting less C_3 vegetation in the catchment and/or a higher contribution of algal detritus. The contrast with earlier studies arises from the more robust chronology and greater stratigraphical continuity of the northern basin cores.

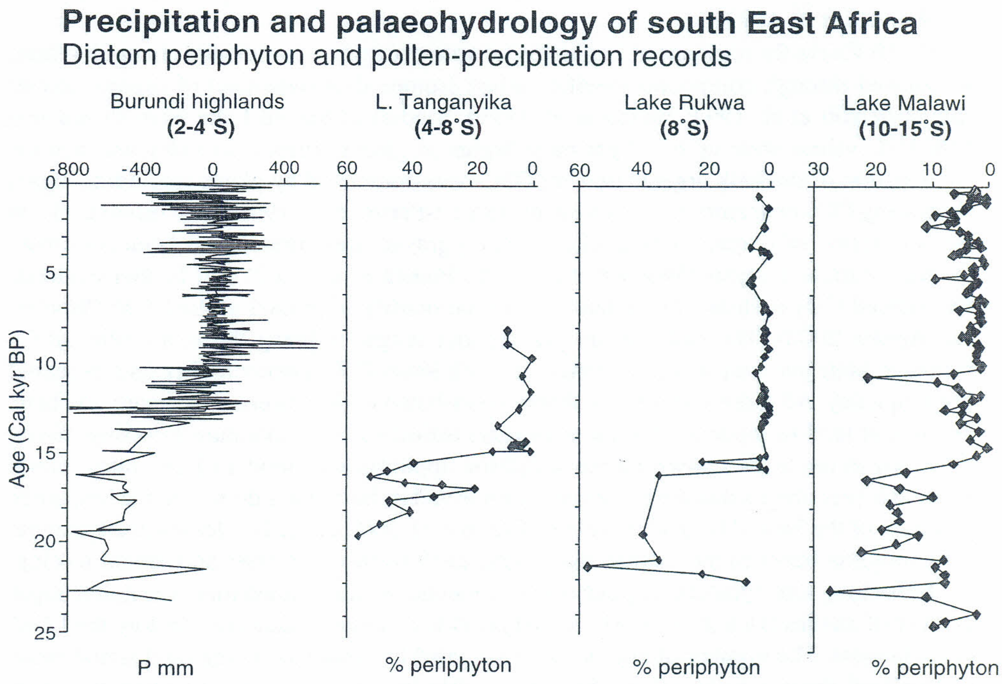

Figure 3. Precipitation and palaeohydrological records of the LGM from East Africa south of the equator. Precipitation in Burundi was calculated using pollen transfer functions by Bonnefille and Chalié (2000). Diatom periphyton is used as a surrogate for relative lake level change (note reversed scales). Data from Gasse et al. (1989), Barker et al. (2002) and Gasse et al. (2002).

The mechanisms responsible for relative dry glacial climates are revealed in the comparison of General Circulation Model (GCM) simulations by PMIP (Paleoclimate Modelling Intercomparison Project) (Pinot et al. 1999). All those model runs that used computed SSTs simulate aridity across this region of the PEP III transect; however, those based on empirical (and higher) SST estimates by CLIMAP (Climate: Long-range Investigation, Mapping, and Prediction) suggested wetter conditions than today, particularly over East Africa (Kutzbach and Guetter 1986). It is clear that at the LGM the tropical African climate was strongly affected by the cooling of the surrounding oceans, which in turn fluctuated in line with the development of the polar ice sheets, as well as the reduction in atmospheric greenhouse gases (Kutzbach and Street-Perrott 1985; Indermühle et al. 1999).

Intertropical Africa since the LGM

Insolation in the Northern Hemisphere tropics rose from a minimum at 22 kyr to a maximum at 12 kyr (Berger and Loutre 1991). Insolation alone would lead to a gradual enhancement of monsoon rainfall by 35–45% in northern intertropical Africa (Prell and Kutzbach 1992).

Such a smooth, progressive transition is not shown by the data (Kutzbach and Street-Perrott 1985), rather the evidence reveals abrupt changes and irregular climate fluctuations. Recovery from the dry glacial maximum began early in many sites, especially in the southern-most part of the study region. At Lake Tritrivakely in Madagascar the lake began to rise after 17.5–17 kyr. In Lake Malawi a transitional phase can be inferred from the diatom data beginning as early as 17.3 kyr, whereas the Lake Tanganyika diatom record suggests an initial P-E increase between 21 and 15 kyr (Gasse et al. 1989). Lake Rukwa was saline between ca. 16 and 15 kyr but slightly deeper than at the LGM, which compares to a short-lived transgression in Lakes Albert (Beuning et al. 1997b) and Victoria (Talbot and Livingstone 1989; Johnson 1996). In these lakes, an early post-LGM humid period is recorded by lake sediments bracketed by two palaeosols (Talbot and Livingstone 1989). The brief wet phase thus took place between about 16 kyr and 15 kyr, but pre-dated the major transgression that began after 15 kyr (Talbot and Laerdal 2000). In the Congo Fan record, the first increase in Congo discharge after the LGM is registered between 16.5 kyr and 16 kyr, followed by a return to lower values (Marret et al. 2001) (Fig. 4).

In contrast to these relatively short and low-amplitude early transgressions, the lake level rise ca. 15 kyr was spectacular. Many equatorial lakes such as Victoria (Talbot and Laerdal 2000), Magadi (Roberts et al. 1993), Manyara (Holdship 1976) and Tanganyika (Gasse et al. 1989) rose substantially at this time. The abrupt onset of the so-called African humid period is thought to represent a non-linear response to insolation changes triggered (at least in North Africa at 20 °N) when insolation reached 470 W m^{-2} (or 4.2% above modern values; Berger and Loutre (1991)). The amplitude of the hydrological response to insolation forcing requires positive feedback from vegetation, surface water and sea-surface temperature changes (deMenocal et al. 2000).

The Congo Fan record (Marret et al. 2001) is a multi-proxy dataset consisting of oxygen isotopic, biomarker (long chain alkane/alkenone) and palynological data (Fig. 4). High Congo palaeo-discharge events are recorded by rapid increases in the fluxes of pollen, *Pediastrum* (a freshwater green alga) and charred grass cuticle fluxes, high ratios of long chain terrestrial *n*-alkanes to marine alkenones, an increase in the alkenone (U^{K}_{37}) SST index, decreased $\delta^{18}O$ ratios and an increase in the sediment accumulation rate of terrigenous material. These changes reflect flushes of terrigenous matter, including pene-contemporaneous pollen, to the fan and reduced salinity in the Congo plume. Contemporaneous increases in dinoflagellate cyst flux and changes in cyst-assemblage composition indicate that these events stimulated river-induced upwelling and associated productivity. A major discharge pulse at around 13.5 kyr marks the most significant event in this 30 kyr record. The rise in lowland rainforest taxa, which continues into the Holocene, begins at this point, coincident with a decline in dry grassland taxa. The surface-water salinity record off the Niger Delta closely matches the evidence for a major increase in discharge from the Congo. Here, isotopic evidence from planktonic foraminifera indicates an abrupt decline in salinity beginning at ca. 13.5 kyr due to a dramatic rise in freshwater outflow from the Niger (Pastouret et al. 1978).

The major part of the PEP III transect demonstrates the extent and influence of the Younger Dryas cold event (ca. 12.5–11.5 kyr) on surface systems. The influence of this episode in tropical Africa is profound and manifested through an abrupt switch to relative drought. Substantial regressions lasting about a thousand years are shown in Lake Bosumtwi (Talbot and Johannessen 1992), Lake Magadi (Roberts et al. 1993), the Ziway-Shala basin

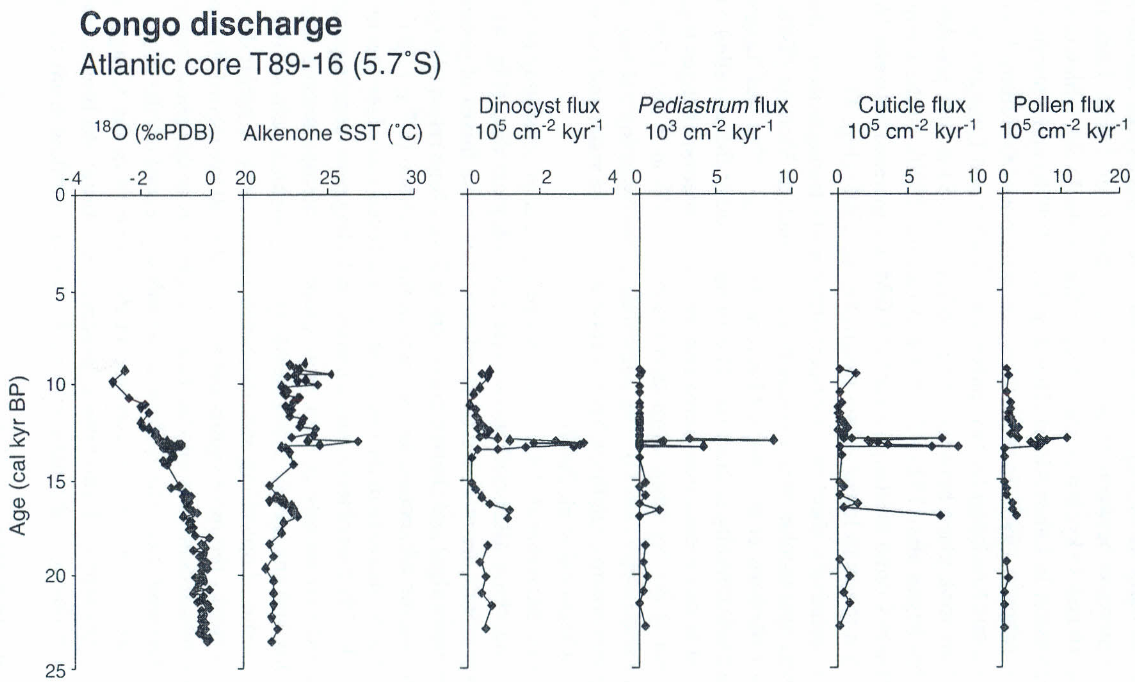

Figure 4. Evidence for changes in Congo discharge shown by fluxes of pollen, green algae (*Pediastrum*) and dinoflagellates recovered from marine core T89-16 (Marret et al. 2001).

(Gillespie et al. 1983), Lake Tanganyika (Gasse et al. 1989), Lake Victoria (Johnson et al. 2000), and Lake Albert (Beuning et al. 1997b). Further evidence for drought during the Younger Dryas comes from the cessation of peat growth in the Aberdare Mountains (Street-Perrott and Perrott 1990) and in a shift to grassland pollen in the Burundi highlands (Bonnefille et al. 1995). The response of lakes in the south-eastern tropics of Africa is less clear. The percentage of benthic diatoms in sediments from the northern basin of Lake Malawi is relatively high during the Younger Dryas although the increase begins 800 years before the inferred cooling in Greenland (Gasse et al. 2002). These changes are chronologically equivalent to the Antarctic Cold Reversal (Jouzel et al. 1995) and may reflect the southern de-glaciation rather than the break-up of the northern ice sheets (Johnson et al. 2002). Direct correlation between the Greenland and Congo Fan records is currently precluded by uncertainties in the ^{14}C age model for the latter record which is based on bulk carbonate (Marret et al. 2001). However, there is a clear "twin peak" palaeo-discharge event in the Congo record in which palaeo-discharge highs centred on 13.5 kyr and 13 kyr are separated by a drier phase with lower discharge. The current age model would suggest that these events led the Younger Dryas but it is equally plausible that the drier phase was coincident with the Younger Dryas.

Holocene events

Following the dry conditions of the Younger Dryas, the African humid phase became re-established in the intertropical region. Many of the major lakes overflowed and produced cascading systems that linked the lakes to the African continent's major drainage systems. New insights into the chronology of isolation and connection of the White Nile and its headwater lakes are provided by Sr-isotope analysis which can provide a sensitive tracer of water source as Sr isotopes are not fractionated in the hydrological cycle (Talbot et al. 2000; Talbot and Brendeland 2001). These studies indicate that flow from Lake Victoria via Lake Albert into the main Nile became re-established between 15 kyr and 14 kyr. The ensuing period of elevated discharge in the Nile (Adamson et al. 1980; Rossignol-Strick et al. 1982) coincides with the evidence for increased outflow from the Congo and Niger (see above), confirming a general increase in precipitation in the interior of the African continent at this time.

The general African humid phase came to an abrupt end ca. 5.5 kyr. According to deMenocal (2000), in at least the Northern Hemisphere, the mechanisms responsible may be similar to those that led to its onset. Insolation declined gradually but crossed the critical threshold of 4.2% greater than the present day at about this time triggering vegetation-albedo and surface-albedo feedback mechanisms and amplifying the orbital forcing (Claussen et al. 1999; Texier et al. 2000). Lake levels at many sites in tropical Africa show a series of century to millennial-scale arid events throughout the Holocene (Gasse and Van Campo 1994) (Fig. 5). These abrupt events have strong links to changes in Atlantic SSTs and the thermohaline circulation that influenced both tropical and extra-tropical regions of Africa (Street-Perrott and Perrott 1990; Lamb et al. 1995; Gasse 2000). However, the coincidence of these periods with similar short-lived events in Tibet also implies a connection to the Indian Ocean monsoon (Gasse and Van Campo 1994). Better ways of describing and explaining the abrupt hydrological changes within the Holocene are important if we are to understand these decadal-scale transitions.

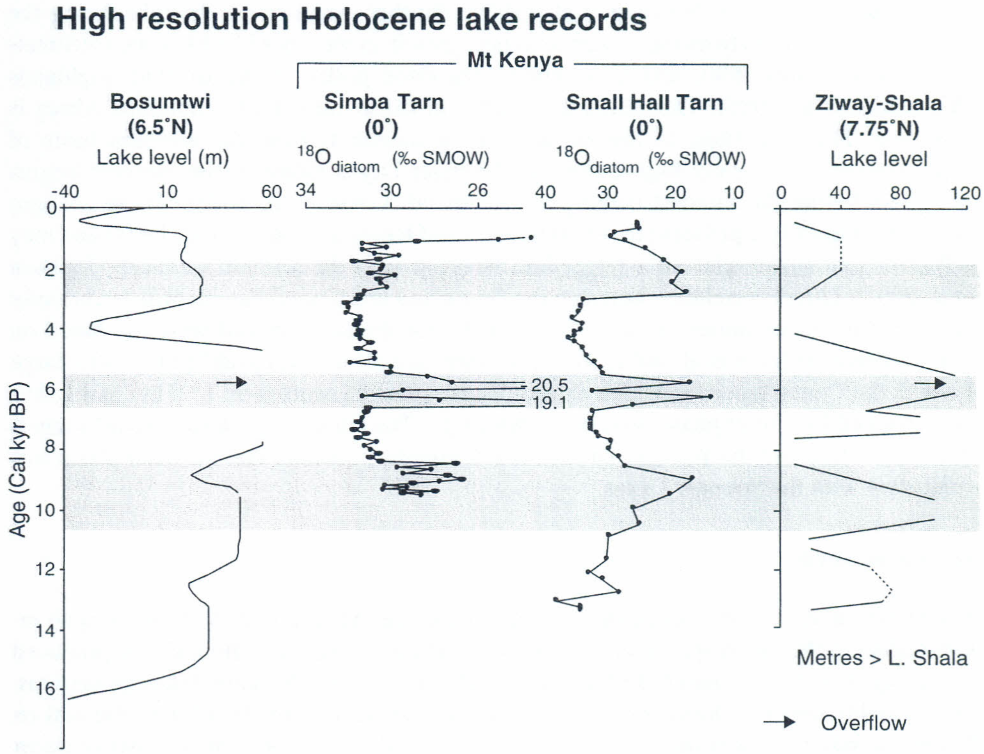

Figure 5. Comparison of high resolution Holocene lake level records from Bosumtwi (Talbot and Johansson 1992) and Ziway-Shala (Gillespie et al. 1983) with oxygen isotope records from high altitude tarns on Mt Kenya (Barker et al. 2001b). Note reversed scales. The grey shading represents periods of high P-E on Mt Kenya.

A recent study of oxygen isotope variations in diatom silica from alpine tarns on Mt Kenya has revealed a series of drier intervals corresponding to these abrupt Holocene events (Barker et al. 2001b). Whereas the levels of lakes at lower elevations record dry events lasting several centuries, the equivalent periods on Mt Kenya were apparently millennial in duration (Fig. 5). It seems that at extreme altitude lake- water isotopes are very sensitive to variation in convective intensity, cloud height and changes in evaporation. Therefore, high altitude lake isotope records give great precision in the delimitation of extreme wet periods but are less sensitive to drought; an inverse response to that of lake level, where the record is truncated once a drainage sill is reached.

Defining the duration and chronology of centennial-to-millennial scale climatic events is difficult given the imprecision of most ^{14}C chronologies and the heterogeneous nature of palaeoenvironmental archives. Nevertheless, two major dry periods can be identified after the Younger Dryas event. The first (8.4–8 kyr) coincides with the 8.2 kyr event found in the Greenland ice sheet (Alley et al. 1997), European lakes (von Grafenstein et al. 1998; Barber et al., this volume) and oceanic records (Barber et al. 1999). In Lake Victoria diatom production declined between 9.8 kyr and 7.5 kyr (Johnson et al. 2000), a period much longer than the duration of the 8.2 kyr event. However, shorter regressions ca. 8.4–8 kyr (Gasse and van Campo 1994; Gasse 2000) were found in Lake Abhé (Gasse 1977), the Ziway-Shala system (Gillespie et al. 1983), and Lake Bosumtwi (Talbot et al. 1984).

The second widespread regression was centred on 4.2–4 kyr (Gasse 2000). This period is important because of its relation to the collapse of the Old Kingdom in the Nile valley (Hassan 1997). Sedimentological and Sr-isotopic evidence for a regression and a period of probable isolation of Lake Albert at this time (Talbot and Brendeland 2001) suggests that the collapse must in part have been due to a drastic decline in the base-flow of the White Nile. In East Africa this event corresponds to a decline in moist rainforest and its replacement by dry forest types (Street-Perrott and Perrott 1993). In west equatorial Africa, this period is also recorded in a number of terrestrial and marine sites (Maley 1997; Marret et al. 1999).

Conclusions

Deciphering the imprint of environmental change has resulted in the application of novel proxies in palaeolimnological studies of tropical Africa. New techniques have been used to overcome limitations and exploit opportunities. Stable isotope proxies have played an important part in revealing the palaeoclimatic time-line summarised above. As in other parts of the PEP III transect, oxygen isotopes have been used to trace the hydrological cycle using sedimentary carbonate (e.g., Lamb et al. (2000), Ricketts and Johnson (1996)). Unfortunately carbonate is absent in many key sites in tropical Africa and other host materials have had to be investigated. Diatom silica and sponge spicules offer the opportunity to exploit lake sediment rich in biogenic silica; these have significant potential if methodological and interpretative difficulties can be addressed (Rietti-Shati et al. 1998; Barker et al. 2001b). Studies of oxygen isotopes in plant cellulose can also be used as in Lake Victoria (Beuning et al. 1997a) and in peat bogs of the Burundi highlands (Aucour et al. 1996). In all these studies interpretation of $\delta^{18}O$ has to be coupled with studies of the modern environment.

Limnological nutrient cycles may well be coupled to broader atmospheric changes and in part reflect climate changes. For example, in shallow lakes the relative importance of autochthonous carbon has created a sedimentary archive of shifts in the regional biota that reflect variations in climate, fire and atmospheric CO_2 (Street-Perrott et al. 1997; Wooller et al. 2000; 2002; Barker et al. 2001a; Ficken et al. 2002). In deep lakes the connection between bulk $\delta^{13}C$ values and atmospheric processes is more indirect, due to the dominance of aquatic productivity and the lower amplitude of change in $\delta^{13}C$. The glacial-interglacial range of $\delta^{13}C$ in Lake Bosumtwi is 26 per mille and in Sacred Lake is 17 per mille, whereas equivalent values for Lakes Victoria, Tanganyika and Malawi are 7, 9 and 4 per mille respectively (Fig. 6). Additional insights into the relative roles of climatic versus atmospheric CO_2 variations in forcing tropical vegetation change may be provided by coupled morphological-carbon isotope studies of charred grass cuticle preserved in the $>180\,\mu m$ fraction of lake and bog sediments. Many African grasses are ecologically sensitive and studies of palaeo-grassland assemblages have the potential to yield refined palaeoenvironmental reconstructions (Collatz et al. 1998; Wooller et al. 2000; 2002; Ficken et al. 2002; Beuning and Scott 2002). Nitrogen isotopes are also important in reconstructing nutrient cycling although the $\delta^{15}N$ signal is not a direct proxy of regional changes. A comparison of $\delta\,^{15}N$ values in lakes Victoria, Tanganyika and Bosumtwi illustrates the site-specific character of this isotope signal (Fig. 7). Nitrogen isotopes contribute to the functional understanding of lakes (e.g., N-fixation and limitation, NH_3 volatilization under high pH, flushing rates of soil N, dissolved inorganic N abundance) but regional synergy is harder to demonstrate.

The development, refinement and application of new methods of palaeoenvironmental reconstruction in the last decade have produced considerable progress in the testing of forcing factors controlling the African climate system and the identification of teleconnections between tropical Africa and other regions. Meridional linkages have been proposed between lake levels and the records from the polar ice cores and the surrounding oceans (Street-Perrott and Perrott 1990; Stager and Mayewski 1997; Johnson et al. 2002). Teleconnections have often assumed a passive role for the terrestrial tropics and have viewed the records in responsive mode. It is interesting to reverse this argument and to consider the extent to which changes in the terrestrial tropics and the surrounding oceans have generated some of these higher latitude changes (cf., Leuschner and Sirocko 2000). For example, Lake Victoria and lakes on Mt Kenya show a dry event beginning before the 8.2 kyr cold spell recorded in the Greenland ice sheet (Alley et al. 1997) and at glacial termination two tropical lakes rose before significant insolation changes at 65 °N (Trauth et al. 2001). The mechanisms by which the tropics could lead high latitude climate change at the millennial scale will differ with respect to particular events. One particularly important process involves methane emission from tropical wetlands formed during the initial phase of rising P-E that contributes to warming that leads Northern Hemisphere deglaciation (Petit-Maire 1990; Petit-Maire et al. 1991; Street-Perrott 1992; 1994). Other mechanisms that could drive or amplify changes at higher latitudes include changes in latent heat transport (Street and Grove 1976), albedo (Street-Perrott et al. 1990), SST (Bard et al. 1997; Henderson and Slowey 2000) and ENSO (Beaufort et al. 2001). The tropics are therefore central to our understanding of global climate change and further work is essential to understand the part played by different processes on specific events of various durations.

This synthesis has attempted to demonstrate that palaeoenvironmental records from tropical Africa are both coherent between the continent and its surrounding oceans, and linked to meridional changes along the PEP III transect. Terrestrial and oceanic data indicate that insolation forcing is integral to our understanding of African climates on multi-millennial time-scales, although it may be overridden during periods of full glaciation. The palaeoenvironmental record from tropical Africa also reveals rapid swings between wet and dry climates in just a few decades that have enormous implications for human societies, yet these are poorly understood and remain an important target for future research (cf. Olago and Odada (this volume)). In the tropics, as elsewhere, the prediction of future changes will be achieved by the continued development of new ways of revealing past climate signatures and mechanisms.

Summary

Classical techniques and newly developed environmental proxies inform this synthesis of recently published palaeoclimate data from intertropical Africa. Particular advances have been made in the application of oxygen isotope techniques to climate reconstruction from silica and organic hosts, as well as using carbon isotopes and compound specific analysis

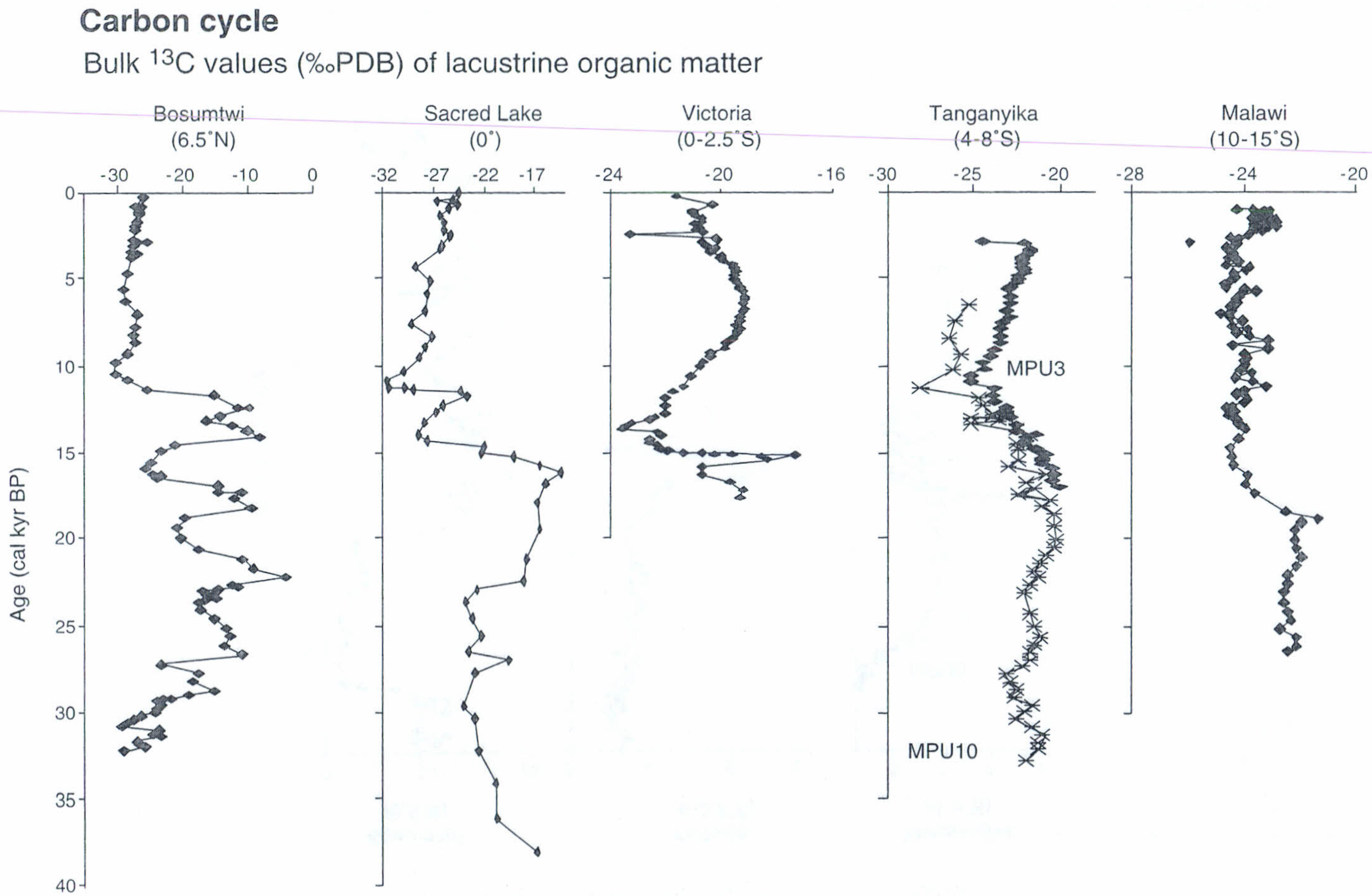

Figure 6. Changes in the carbon cycle recorded by bulk $\delta^{13}C$ values in crater lakes Bosumtwi (Talbot and Johannessen 1992) and Sacred Lake (Street-Perrott et al. 1997), together with records from Lake Victoria (Talbot and Laerdal 2000), Lake Tanganyika (Talbot and Jensen, unpub.) and Lake Malawi (Filippi and Talbot, unpub.).

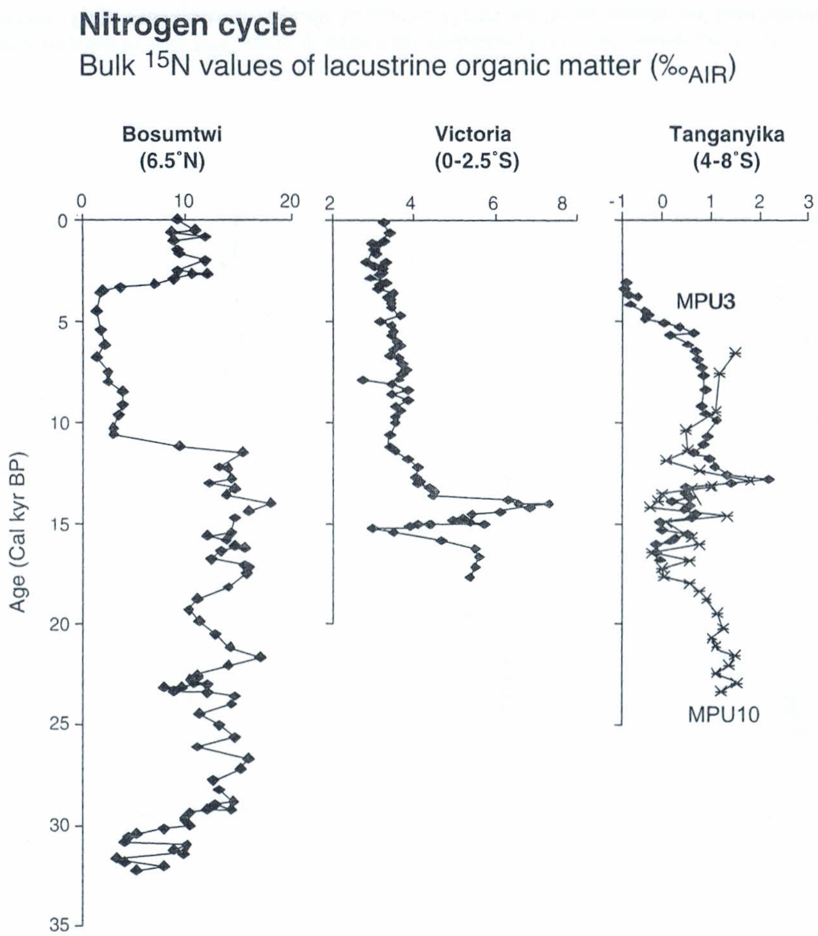

Figure 7. The nitrogen cycle in Lakes Bosumtwi (Talbot and Johannessen 1992), Victoria (Talbot and Laerdal 2000) and Tanganyika (Talbot and Jensen, unpub).

of carbon cycle dynamics. Nitrogen isotopes are closely linked to localised ecosystem processes and show less regional correlation. The close interaction between continental African climate and conditions in the surrounding oceans is clear in the examples discussed. We have also considered lacustrine and offshore sequences that give an insight into tropical African climate from marine isotope stage 6, the more numerous records available for the last 25 kyr, and abrupt climate shifts revealed by high-resolution records since the LGM. Long lake-level records from East Africa and marine cores from the Congo fan show the importance of orbital forcing in generating multi-millennial scale climate change. Nevertheless, recent studies from the southern African tropics indicate that the effects of insolation can be overridden under full glacial conditions. Forcing factors promoting millennial scale changes in the tropics are explored and the role of the tropics in driving changes at higher latitudes is briefly discussed. We note that at glacial termination two, tropical lake levels rose before insolation increased, and that methane emissions from greatly expanded tropical lakes during the deglacial periods is an important feedback process in global climate readjustment.

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