

Water resources variability in tropical and subtropical Africa in the past

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Abstract Hydrological fluctuations of spectacular amplitude took place in Africa during the past millennia. Changes in precipitation result from changes in the Earth's orbit and from complex interactions between the different climate subsystems, the atmosphere, the ocean and the vegetation. The paper successively presents: (a) a brief overview of the long-term hydrological changes that have occurred over the past 21 thousands of years at the time scale of 10^3 years; (b) some Holocene palaeohydrological records from North Africa which illustrate short-term (10^2 years), abrupt changes superimposed on the general trends; and (c) changes in water quality through space and time in palaeolakes from the Sahara and the Sahel.

INTRODUCTION

Africa has experienced dramatic changes in water resources during the late Quaternary. Generating famines, migrations, civilization foundations and collapses, their consequences for human populations were of utmost importance. This is evidenced by a huge amount of data derived from a large variety of archives, i.e. historical and archaeological records, studies in hydrology and hydrogeology, geology, palynology, macro- and microfossils.

In the tropics and subtropics, the primary cause of hydrological changes is their fundamental dependability on the monsoon that sets the yearly rhythm of life in both the African monsoon domain and a large part of East Africa influenced by the Indian monsoon. The monsoons follow the seasonal latitudinal migration of the Intertropical Convergence Zone (ITCZ). In summer, monsoon winds are driven by the differential land-ocean heating responsible for an atmospheric pressure gradient which draws the monsoonal air flow inland. Past monsoon fluctuations may thus be related to (a) changes in seasonal distribution of solar radiation, (b) changes in the sea surface conditions of the subtropical oceans, and to (c) changes in tropical land surface conditions. Solar radiation distribution follows the cyclic variations in the Earth's orbital parameters (Berger, 1978). The precession of the equinoxes (23 000 and 19 000 year cycles) changes the season of perihelion and thereby the season of maximum and minimum solar radiation. Increased summer solar radiation results in enhanced land-sea contrast and thus in monsoon strengthening, expected to have occurred every 23 000–19 000 years, but out of phase in the northern and southern hemispheres. Tropical sea surface conditions are closely related to high-latitude boundary conditions, i.e. polar ice sheets and sea ice extent, intensity of the oceanic thermohaline circulation. Vegetation on land depends on climate, but is also a

climate factor through feedbacks to the atmosphere. Hydrological fluctuations in Africa thus result from orbital forcing and from complex interactions between atmosphere, ocean and vegetation.

Much of the available palaeohydrological records are based on ^{14}C dates. In the sections below, we thus used the radiocarbon chronology. Ages are given in kyears BP (10^3 ^{14}C years before present).

LONG-TERM HYDROLOGICAL CHANGES OVER THE PAST 20 kyears BP

The past 20 kyears encompass extreme climatic conditions, including the last glacial maximum (LGM) around 18 kyears BP ago and the early-mid Holocene (10–4.5 kyears BP) when monsoon rainfall in the northern tropics was considerably reinforced in response to orbital forcing.

It is now well established that climate was cooler and drier than today in tropical and subtropical Africa during the LGM. The tropical sea surface (e.g. Bard *et al.*, 1997) and ground surface temperatures (Bonnefille *et al.*, 1992; Stute *et al.*, 1997) were lower than at present, and the monsoon circulation was attenuated. A tendency towards aridity is observed even in the southern hemisphere despite high summer insolation (Gasse & Van Campo, 1998). Sedimentological studies from the Pretoria Saltpan (South Africa) suggest a decrease in precipitation of about 17% compared to modern times (Partridge *et al.*, 1997). In equatorial East Africa, pollen-inferred precipitation was 11% lower than today (Bonnefille *et al.*, 1992). Lake Tanganyika was at least 300 m below its present level. Precipitation in its basin was estimated at about –11 to –15% (compared to modern times) using a water and balance energy model (Bergonzini *et al.*, 1997). Many lakes from equatorial and northern Africa were dry, e.g. Lake Victoria, or much lower than today (Street-Perrott *et al.*, 1989; Johnson & Odada, 1996). The Sahara was hyperarid and sand dunes advanced along its northern and southern margins (Talbot, 1981).

Post-glacial warming was associated with monsoon reactivation. From about 15–13 kyears BP till now, the general envelope of changes in precipitation (and/or in the precipitation minus evaporation balance) can be primarily accounted for by changes in summer insolation which reached its maximum at 10–9 kyears BP in the Northern Hemisphere, while it was weaker than at present in the southern Hemisphere. A detailed review of Holocene vegetation, lake levels and climate of Africa is given by Street-Perrott & Perrott (1993). Closed rift lakes lying north of the July ITCZ in East Africa underwent water-level rises as high as 100–200 m above their present-day level, that culminated between about 9 to 6 or 4.5 kyears BP (Fig. 1(a), 1(b)). Early Holocene increases in precipitation, derived from palaeolake data in East Africa using water and energy balance models, were estimated at +15 to +25% (compared to modern times) in Kenya (Hastenrath & Kutzbach, 1983). An estimate of +86% was proposed for the Lake Chad basin (Kutzbach, 1980). In the Sahara, a multitude of shallow freshwater lakes occupied interdunal depressions; a grass cover developed and grazing herbivores migrated (Petit-Maire *et al.*, 1997). Human migrations into the Sahara occurred successfully. Mortars and grinders, rock engravings and pottery artefacts show that Saharan Neolithic civilizations flourished in an environment with accessible water and substantial food.

The early-mid Holocene was also a period of intensive recharge of the aquifers in the Sahara and the Sahel. The reconstructed initial heavy isotope content of Holocene precipitation which recharged the aquifers is very low ($\delta^{18}\text{O} = -10$ to 11‰ vs SMOW; Fontes *et al.*, 1993; Edmunds & Wright, 1979; SMOW means standard mean ocean water). In the northern Niger and northern Mali, these low values were attributed to convective showers generated by squall lines that develop along the ITCZ, implying an ITCZ northwards movement of about 500 km. Groundwaters recharged during the Holocene contained up to 45 mg kg^{-1} of nitrate, indicating biologically active soils. This confirms that typical Sahelian environments occurred during the Holocene up to 500 km north of the present limit (Fontes *et al.*, 1993).

After 6–4.5 kyears BP, an overall trend towards aridity is observed to the north of the ITCZ (July position), while the interior of South Africa became wetter after 6 kyears BP. The Saharan-Sahelian aquifers progressively shrank, trapping the early-mid Holocene groundwater as a mining resource tens of metres below the ground surface. A renewed expansion of the Sahara took place, generating human migrations out of the desert which reached its present-day limit between 3 and 2 kyears BP (Petit-Maire *et al.*, 1997). In Ancient Egypt, the collapse of centralized government in about 2200 BC coincided with the reduced Nile flood discharge and the invasion of the Nile Valley by sand dunes (Hassan, 1997). The Egyptian civilization decline was thus linked with the decrease in precipitation in Ethiopia and Equatorial Africa, the sources of Nile floodwater.

ABRUPT POST-GLACIAL HYDROLOGICAL EVENTS IN NORTH AFRICA

The general climatic trends observed over the post glacial period were punctuated by several sudden shifts towards aridity. This is illustrated through some lake-level records selected from east to west across northern Africa (Fig. 1). Detailed information on individual lake records and selection criteria are given in Gasse & Van Campo (1994). The lake-level curves were derived from detailed geomorphological observations, and from the sedimentological, palaeobiological and/or geochemical study of numerous natural exposures and/or, in some cases, from cores taken from the modern lakes.

In northern East Africa, the records (Fig. 1(a), 1(b)) derive from lakes which depend, hydrologically, on the Ethiopian highlands: Lake Abhé in the desertic Afar depression and the Ziway-Shala lake system in the semiarid Ethiopian Rift (Gasse & Street, 1978; Gillespie *et al.*, 1983). Both lake systems are mainly supplied by surface runoff. The two records show remarkable similarities, although signals of larger amplitude were observed from Lake Abhé which received the overflow of the Ziway-Shala lake during moist Holocene periods.

In the western Sahara and the Sahel, numerous studies conducted by different authors (Servant & Servant-Vildary, 1980; Hillaire-Marcel *et al.*, 1983; Gasse *et al.*, 1990; Baumhauer, 1991; Fontes & Gasse, 1991) provide consistent information on the climatic evolution over the region, illustrated by the examples of the Bilma and Termit palaeolakes (Servant & Servant-Vildary, 1980; Fig. 1(c), 1(d)). 85% of the flow in to Lake Chad (282 m a.s.l.) is supplied by the Chari River which drains the

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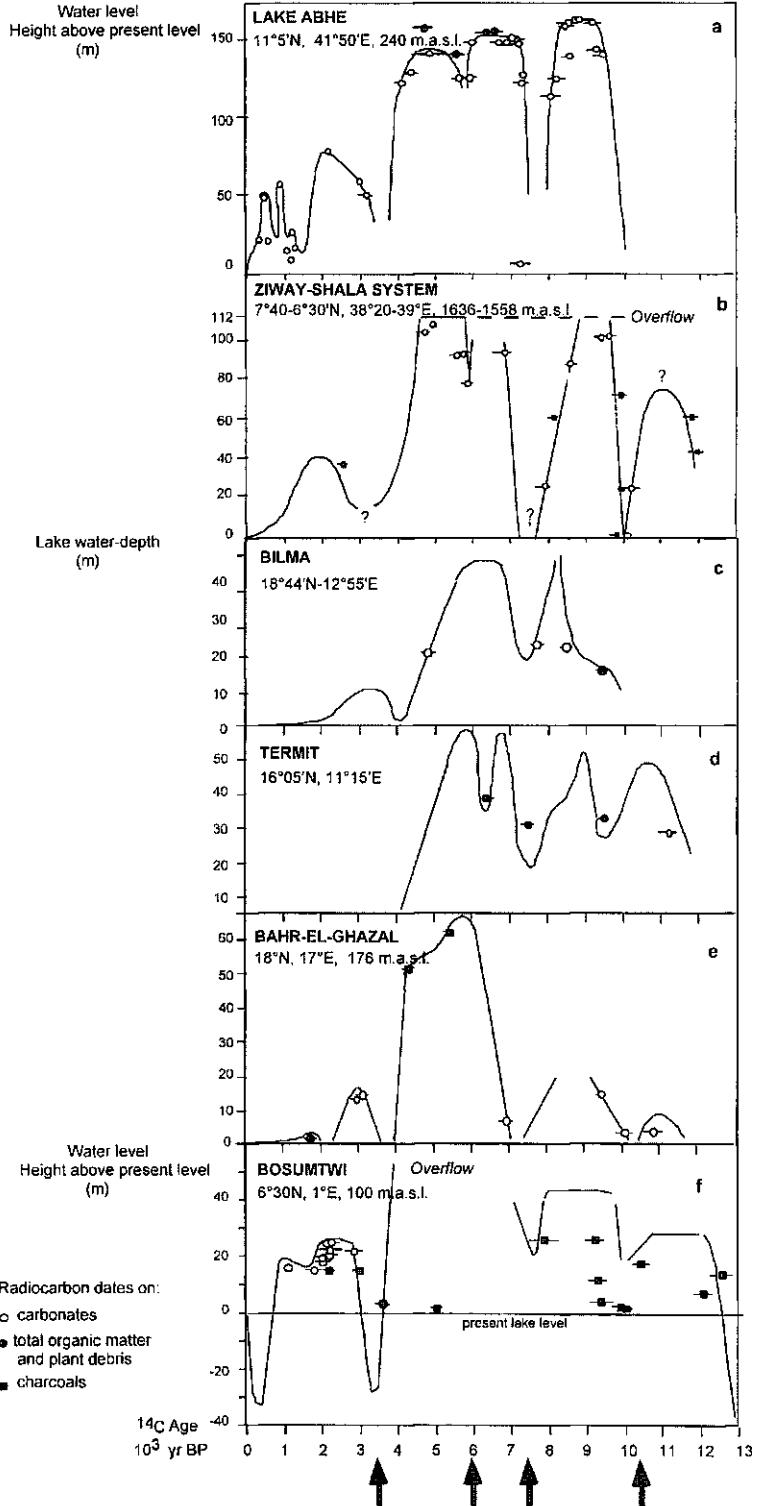


Fig. 1 Water-level fluctuations of some lakes in the northern tropics of Africa. After Gasse & Van Campo (1994). See text for original references.

Sudanian and Sudano-Guinean zones. Thus it depends mainly on southern climatic zones. The large endoreic depression of the Pays-Bas receives the overflow of lake Chad through the Bahr-el-Ghazal River when the lake level rises to 283 m a.s.l. Water-level changes in the Bahr-el-Ghazal (Fig. 1(e)) thus register changes in the water ($P - E$) balance of the entire Lake Chad basin (Servant & Servant-Vildary, 1980).

In Ghana, Lake Bosumtwi occupies a meteorite impact crater in the semi-deciduous rain forest zone, with 1500 mm of annual precipitation. Multi-proxy analysis of sediment cores allowed lake-level changes to be inferred (Talbot *et al.*, 1984; Fig. 1(f)).

Lake data show substantial evidence of several short-term dry periods from 13 kyears BP to present in Africa, the major ones occurring during the following intervals 11–9.5 kyears BP, 8–7 kyears BP, 6 kyears BP, and 4–3 kyears BP. The pre-10 kyears event broke off the re-establishment of wet conditions following the arid LGM, and fitted in with the Younger Dryas which is a sudden cooling event well recorded in high latitudes (Bard & Broecker, 1992). The 8–7 kyears dry spell interrupted a generally humid episode, while the youngest one fingerprinted the overall return towards aridity. Apparently synchronous dry spells were also identified in the Tibet Plateau, suggesting causes acting at large geographical scale (Gasse & Van Campo, 1994). However, although several hypotheses were proposed, these small-scale fluctuations may be caused by several mechanisms and are not understood yet.

TEMPORAL AND SPATIAL CHANGES IN WATER QUALITY IN THE SAHARA-SAHTEL

Lacustrine sediments may preserve a record of past water chemistry through their mineralogy and biological remains. Transfer functions, established from a data set of about 300 modern diatom and water samples from North Africa (Gasse *et al.*, 1995) allow past water conductivity, pH, and major ion ratios to be inferred from fossil diatom assemblages. They were applied to 12 Holocene groundwater-fed palaeolakes lying along a meridian transect from Nigeria to south Algeria (PALHYDAF sites, Fontes & Gasse, 1991; and samples kindly provided by Street-Perrott for Nigeria and by A. M. Aucour for Mali). The spatial distribution of chemical facies (Fig. 2) clearly reflects a latitudinal gradient: from the carbonate–bicarbonate/alkaline type in the Sahel to the chloride–sulphate/alkaline earth type in northern Sahara. This may be due to the geological nature of rocks weathered by rain waters, and/or to the source of water vapour leading to various contents in chloride of marine origin in the precipitation that supplied the aquifers.

Along individual profiles (Fig. 3; Gasse *et al.*, 1997 and unpub.), conductivity can be interpreted in terms of evaporative concentration, provided that neither weathering of salt crusts nor seepage of heavy brines through a permeable lake bottom, had occurred. The chemical profiles were compared with changes in the relative frequency in planktonic diatoms which roughly reflects water depth, and with changes in the $\delta^{18}\text{O}$ content of carbonates. Negative $\delta^{18}\text{O}$ shifts indicate rises of the supplying aquifers depleted in heavy isotopes, while increasing values reflect a

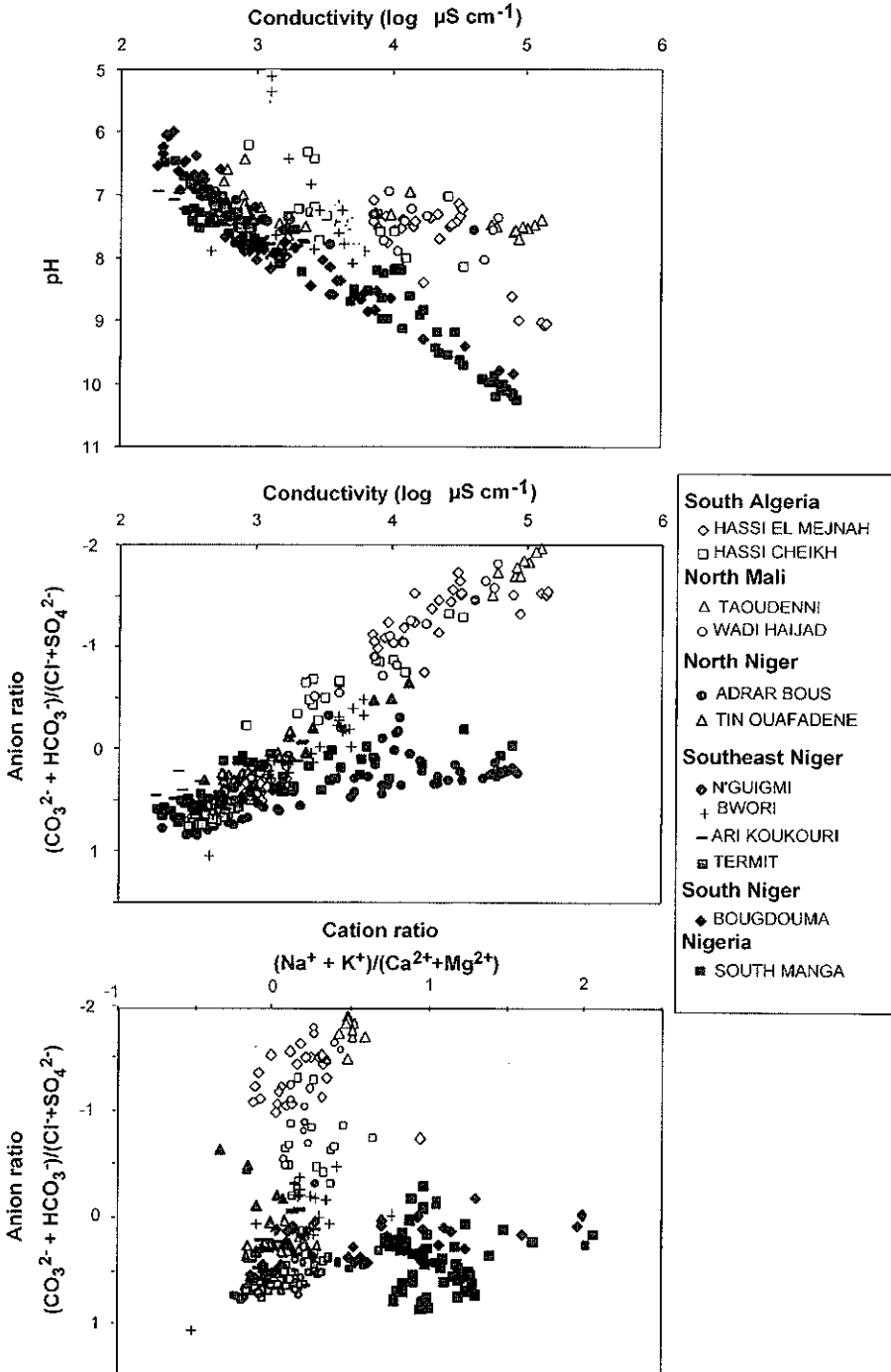


Fig. 2 Diatom-inferred water chemistry of 12 groundwater-fed lakes lying along a transect from south Algeria to Nigeria, illustrating the latitudinal gradient in chemical facies. The ages of the samples range from 13 to 0 kyears BP.

decrease in the freshwater input/evaporation ratio. The profiles show: (a) enormous changes in water quality, from fresh water during stages of aquifer rise, to hypersaline conditions during the short-term dry intervals identified above, and after 4.5–4 kyears BP; (b) in the Sahel, increases in conductivity are accompanied by changes in the chemical facies associated with the precipitation of trona and natron in desiccating ponds; (c) extremely low $\delta^{18}\text{O}$ values, e.g. at Tin Ouaffadene around 9–8

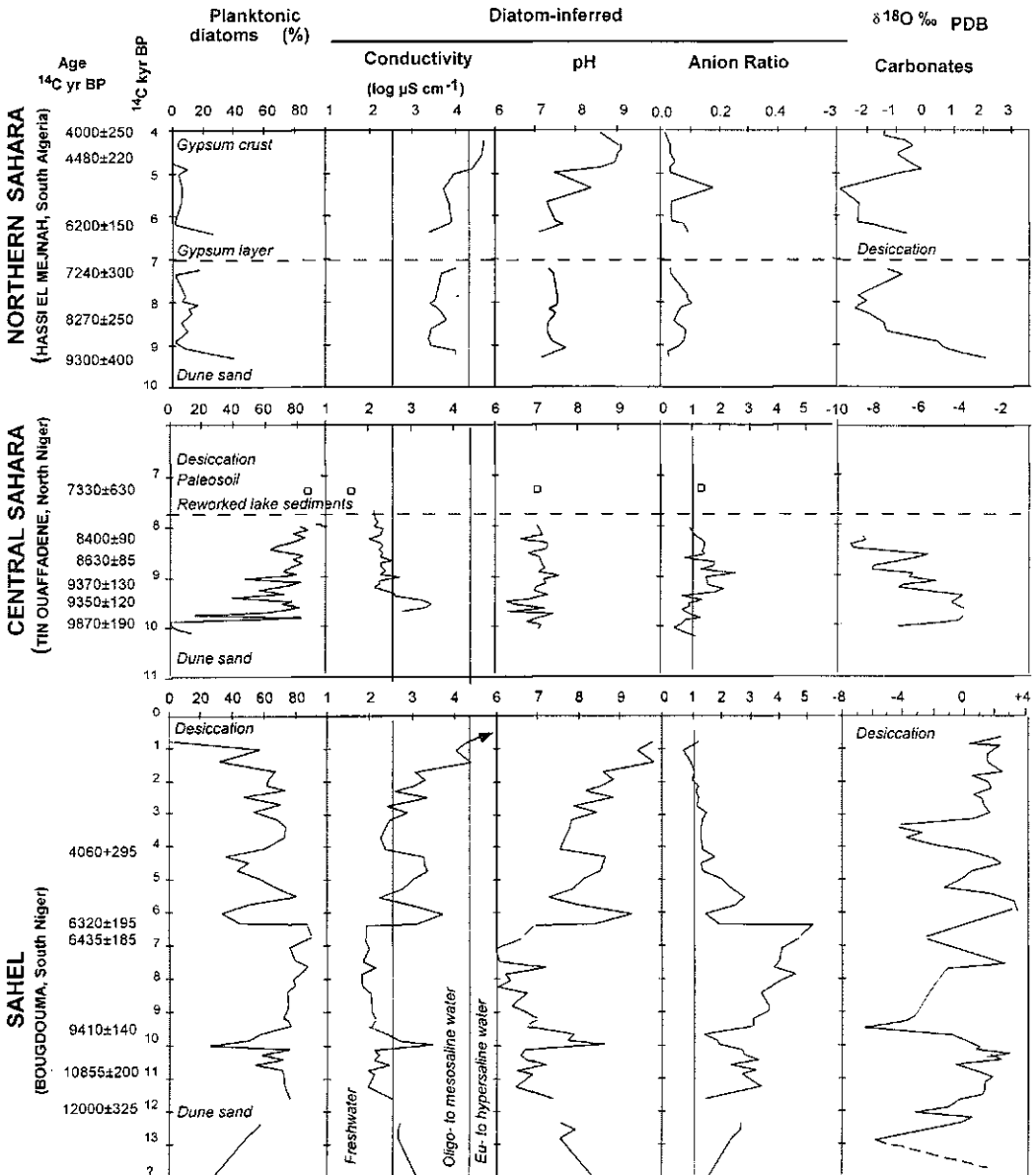


Fig. 3 Changes in diatom-inferred water chemistry along three Holocene lake profiles from the Sahel, central Sahara, and northern Sahara, respectively. Comparison with changes in the relative percentages of planktonic diatoms, and with changes in $\delta^{18}\text{O}$ content of carbonates.

kyears BP suggest that precipitation supplying the aquifers was strongly depleted in heavy isotopes and fell as squall showers, in agreement with groundwater data.

CONCLUDING REMARKS

Climate models have been used to examine how the changes in Earth's orbit result in the differences between the climate of today and that of the past. One of the most spectacular palaeohydrological change in Africa was the development of a wet and green Sahara during the early-mid Holocene. Atmospheric models (i.e. Kutzbach *et al.*, 1993) underestimated observed climatic differences. Coupled atmosphere-vegetation models (Texier *et al.*, 1997) supported the hypothesis of positive feedbacks between climate and vegetation, and coupled ocean-atmosphere models (Kutzbach & Liu, 1997) demonstrated that some of the differences might be explained by changes in ocean temperatures. However, simulations from these models show only partial agreement with palaeodata. Recently, a coupled atmosphere-ocean-vegetation model (Ganopolski *et al.*, 1998) revealed strong synergetic effects between the different climate subsystems and provided results in better agreement with palaeoclimatic data. However, further work is urgently needed for a better understanding of the mechanisms of water storage and losses in the surface and groundwater reservoirs, and for obtaining more detailed pictures of climatic changes in Africa through more high resolution well dated records, and through development of climate-system model with finer spatial and temporal scales.

REFERENCES

- Bard, E. & Broecker, W. S. (eds) (1992) *The Last Deglaciation: Absolute and Radiocarbon Chronologies*. NATO ASI Series I: Global Environmental Change 2, Dordrecht, The Netherlands.
- Bard, E., Rostek, F. & Sonzogni, C. (1997) Interhemispheric synchrony of the last deglaciation inferred from alkenone palaeothermometry. *Nature* **385**, 707-710.
- Baumhauer, R. (1991) Palaeolakes of the south central Sahara—problems of palaeoclimatological interpretation. *Hydrobiologia* **214**, 347-357.
- Berger, A. L. (1978) Long-term variations of caloric solar radiation resulting from the earth's orbital elements. *Quatern. Res.* **9**, 139-167.
- Bergonzini, L., Chalié, F. & Gasse, F. (1997) Paleoevaporation and paleoprecipitation in the Tanganyika Basin at 18,000 years BP inferred from hydrologic and vegetation proxies. *Quatern. Res.* **47**, 295-305.
- Bonnefille, R., Chalié, F., Guiot, J. & Vincens, A. (1992) Quantitative estimates of full glacial temperatures in equatorial Africa from palynological data. *Clim. Dyn.* **6**, 251-257.
- Edmunds, W. M. & Wright, E. P. (1979) Groundwater recharge and palaeoclimate in the Sirte and Kufra basins, Libya. *J. Hydrol.* **40**, 215.
- Fontes J. Ch. & Gasse, F. (1991) PALHYDAF (Paleohydrology in Africa) Program (1991): Objectives, Methods, Results. *Palaeogeogr. Palaeoclim. Palaeoecol.* **84**, 191-215.
- Fontes, J. Ch., Gasse, F. & Andrews, J. N. (1993) Climatic conditions of Holocene groundwater recharge in the Sahel zone of Africa. In: *Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmosphere* (Proc. Vienna Symp., 1993), 231-248. IAEA-SM-329/59, Vienna, Austria.
- Ganopolski, A., Kubatzki, C., Claussen, M., Brovkin, V. & Petoukhov, V. (1998) The influence of vegetation-atmosphere-ocean interaction on climate during the mid-Holocene. *Science* **280**, 1916-1919.
- Gasse, F., Téthet, R., Durand, A., Gibert, E. & Fontes, J. Ch. (1990) The arid-humid transition in the Sahara and the Sahel during the last deglaciation. *Nature* **346**, 141-156.
- Gasse, F., Juggins, S. & Ben Khelifa, L. (1995) Diatom-based transfer-functions for inferring past hydrochemical characteristics of African lakes. *Palaeogeogr. Palaeoclim. Palaeoecol.* **117**, 31-54.
- Gasse, F. & Van Campo, E. (1994) Abrupt post-glacial climate events in West Asia and North Africa monsoon domains. *Earth. Plan. Sci. Lett.* **126**, 435-456.

- Gasse, F. & Van Campo, E. (1998) A 40,000 yrs pollen and diatom record from the southern tropics (Lake Tritrivakely, Madagascar Plateaux). *Quatern. Res.* **49**, 299–311.
- Gasse, F. & Street, F. A. (1978) Late Quaternary lake-level fluctuations and environments of the northern rift valley and Afar region (Ethiopia and Djibouti). *Palaeogeogr. Palaeoclim. Palaeoecol.* **25**, 145–150.
- Gasse, F., Barker, Ph., Gell, P. A., Fritz, S. C. & Chalié, F. (1997) Diatom-inferred salinity in palaeolakes, an indirect tracer of climate change. *Quatern. Sci. Rev.* **16**, 547–563.
- Gillespie, R., Street-Perrott, F. A. & Switzer, R. (1983) Post-glacial arid episodes in Ethiopia have implications for climate prediction. *Nature* **306**, 680–683.
- Hassan, F. A. (1997) Nile floods and political disorder in Early Egypt. In: *Third Millennium BC Climate Change and Old World Collapse*. NATO ASI Series. Series I, **49**, 1–24.
- Hastenrath, S. L. & Kutzbach, J. E. (1983) Paleoclimate and water budget of East African lakes. *Quatern. Res.* **19**, 141–153.
- Hillaire-Marcel, C., Riser, C., Rognon, P., Petit-Maire, N., Rosso, J. C. & Soulié-Marsche, I. (1983) Radiocarbon chronology of Holocene hydrologic changes in northeastern Mali. *Quatern. Res.* **20**, 145–164.
- Johnson, T. C. & Odada, E. O. (1996) *The Limnology, Climatology and Paleoclimatology of the East African Lakes*. Gordon & Breach, Amsterdam, The Netherlands.
- Kutzbach, J. E. (1980) Estimate of past climate at paleolake Chad, North Africa, based on a hydrological and energy balance model. *Quatern. Res.* **14**, 210–223.
- Kutzbach, J. E. & Liu, Z. (1997) Response of the African monsoon to orbital forcing and ocean feedbacks in the Middle Holocene. *Science* **278**, 440–443.
- Kutzbach, J. E., Guetter, P. J., Behling, P. J. & Delin, R. (1993) Simulated climatic changes: results of the COHMAP climate-model experiments. In: *Global Climates Since the Late Glacial Maximum*, 5–11. University of Minnesota Press, Minneapolis, USA.
- Partridge, T. C., de Menocal, P. B., Lorentz, S. A., Paiker, M. J. & Vogel, J. C. (1997) Orbital forcing of climate over South Africa: a 200 000-year rainfall record from the Pretoria Saltpan. *Quatern. Sci. Rev.* **16**, 1–9.
- Petit-Maire, N., Beaufort, L. & Page, N. (1997) Holocene climate change and man in the present day Sahara desert. In: *Third Millennium BC Climate Change and Old World Collapse*. NATO ASI Series. Series I, **49**, 297–308.
- Servant, M. & Servant-Vildary, S. (1980) L'environnement quaternaire du bassin du Tchad. In: *The Sahara and the Nile* (ed. by M. A. J. Williams & H. Faure), 133–162. Balkema, Rotterdam, The Netherlands.
- Street-Perrott, F. A. & Perrott, R. A. (1993) Holocene vegetation, lake levels and climate in Africa. In: *Global Climates Since the Last Glacial Maximum*, 318–356. University of Minnesota Press, Minneapolis, USA.
- Street-Perrott, F. A., Marchand, D. S., Roberts, N. & Harrison, S. P. (1989) *Global Lake-level Variations from 18,000 to 0 Years Ago: A Palaeoclimatic Analysis*, 1–213. United States Department of Energy, Washington, USA, no. DOE/ER/60304-III.
- Stute, M., & Talma, S. (1997) Glacial temperatures and moisture transport regimes reconstructed from noble gas and $d^{18}O$, Stampriet aquifer, Namibia. In: *Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmosphere* (Proc. Vienna Symp. 1997), SM-349. IAEA, Vienna, Austria.
- Talbot, M. R. (1981) Holocene changes in tropical wind intensity and rainfall: evidence from southeast Ghana. *Quatern. Res.* **16**, 201–220.
- Talbot, M. R., Livingstone, D. A., Palmer, D. G., Maley, J., Melack, J. M., Delibrias, G. & Gulliksen, J. (1984) Preliminary results from sediment cores from lake Bosumtwi, Ghana. *Palaeoecol. of Africa* **16**, 173–192.
- Texier, D., de Noblet, N., Harrison, S. P., Haxeltine, A., Jolly, D., Laarif, F. I. C. P., Tarasov, P. & Joussaume, S. (1997) Quantifying the role of biosphere-atmosphere feedbacks climate change: coupled model simulations for the 6000 years BP and comparison with paleodata for north Eurasia and northern Africa. *Clim. Dyn.* **13**, 865–875.