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Holocene environmental changes in Bangong Co basin (Western Tibet). Part 4: Discussion and conclusions

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Abstract

A 12.4 m core taken in Lake Bangong provides a continuous Holocene climatic record. We summarize information on changes in stable isotope and radiocarbon balances in the lake, hydrobiology and vegetal cover in the catchment, deduced from detailed analytical results given in the three preceding papers.

The Bangong record is then compared with the environmental history of the neighbouring Lake Sumxi also constructed from multidisciplinary analyses. The two records show a major environmental change at ≈10–9.5 ka B.P., attributed to a rapid strengthening of the summer monsoonal circulation which led to wet-warm conditions. This event was followed by a long-term trend toward aridity which culminated around 4–3 ka B.P.. In Western Tibet, maximum monsoon rainfall seems to have occurred from ≈9.5 to 8.7 ka B.P. and from ≈7.2 to 6.3 ka B.P., as two wet pulses separated by a reversal event centered on 8.0–7.7 ka B.P. Our results broadly agree with the records from Lake Seling in Central Tibet, and Lake Qinghai at the plateau's northeastern margin, and with palaeoclimatic studies in western China which document conditions wetter and warmer than those of today during the early–middle Holocene.

The environmental fluctuations recorded in western Tibet appear in phase with climatic changes recognized in tropical North Africa, suggesting that the 8.0–7.7 ka B.P. and the 4.0–3.0 ka B.P. dry events were caused by abrupt disequilibrium in the climatic system.

1. Introduction

Investigations of lakes on the Tibet–Qinghai plateau are of major interest as the region is important in influencing the atmospheric circulation of the Northern Hemisphere, and especially the Indian monsoon (Flohn, 1981; Clemens and Prell, 1991). The 1989 Sino-French expedition (Academia Sinica, Centre National de la Recherche Scientifique) investigated lakes in western Tibet, the coldest and the driest part of the plateau, where no continuous, well-dated climatic record was available. A 13 ka record was constructed from the Sumxi-Longmu Co basin

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(34°30′N; 80°23′E) from both lake-core and shoreline multidisciplinary studies (Gasse et al., 1991; Van Campo et al., 1993; Fontes et al., 1994; Liu, 1993; Avouac et al., this volume). A 12.4 m core taken in Lake Bangong (33°40′N, 79°E, 4241 m.a.s.l.), the largest lake of western Tibet, permits a reconstruction of the Holocene environmental changes, and provides the second continuous record derived from the 1989 expedition.

Detailed results of the multidisciplinary study conducted on the Bangong core have been presented in three parts as the three preceding papers of this volume. Fontes et al. (Part 1) present the hydrological and climatic setting of Lake Bangong, and discuss the chronology and stable isotope contents of carbonates. The second part (Van Campo et al., this volume) provides the detailed pollen record. Part 3 (Fan et al., this volume) deals with the study of organic matter and aquatic biological remains contained in the sediments.

This paper puts forward a cross-disciplinary synthetic view of the major hydrological and climatic changes deduced from the different categories of indicators analyzed along the Bangong core, and interpreted independently in the three preceding papers. The Bangong core study complements and confirms the palaeoclimatic interpretation of the Sumxi-Longmu Co record. We show that the long-term climatic trends observed in Western Tibet correlate well with the evolution of other Tibetan lakes (Fig. 1), and are broadly consistent with the palaeoclimatic story of Western China, Northeastern India, and tropical North Africa. Fluctuations in summer insolation in the Northern Hemisphere may account for major environmental fluctuations. However, attention is focussed on the abrupt returns to dry conditions, the major ones being centred around 8.0–7.7 and 3–4 ka B.P. These cannot be directly explained by the smooth changes in orbital parameters.

2. Major Holocene environmental changes in the Bangong Co basin

The study of the Bangong core provides information on changes in hydrological and hydrobiological conditions in Lake Bangong, and changes in vegetation cover and erosional rates over its catchment area over the past ≈10 kyrs. We refer to Fontes et al., Van Campo et al., and Fan et al. (this volume) for specific references and discussion on the significance of individal indicators. We adopt here the radiocarbon chronology established by Fontes et al. (this volume), and based on ^{14}C dates corrected for the effects of aging due to the admixture of old carbon in the lake water. This chronology appears in excellent agreement with the palynostratigraphy established from the comparison between the Bangong and the Sumxi pollen records, independently of the Bangong radiocarbon data (Van Campo et al., this volume).

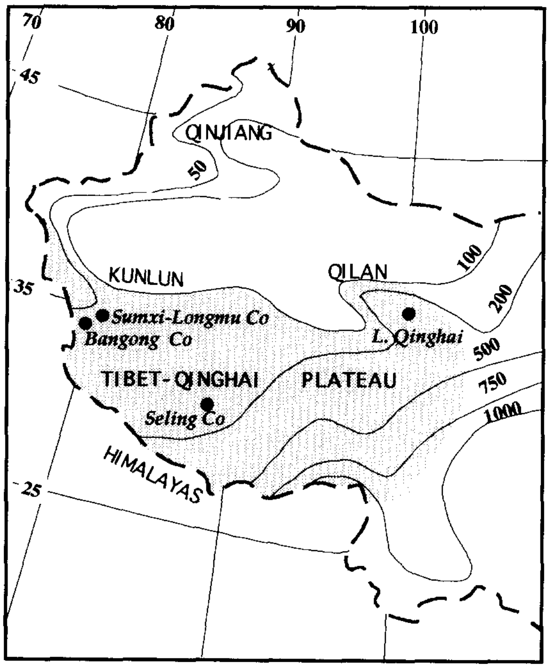

Fig. 1. Location map of the four core sites from the Qinghai–Tibet plateau discussed in this paper. Results are plotted as a function of age, according the radiocarbon chronology proposed by Fontes et al. (this volume).

Results obtained from analyses of the mineralogical and organic composition of the sediments, stable isotope contents of authigenic carbonates, pollen, and biogenic aquatic remains appear extremely consistent. Furthermore, the combination of different types of proxy data leads to a better understanding of the Bangong basin evolution, as underlined below by a few examples.

—The hypothesis of tectonics as responsible for hydrological changes cannot be totally rulled out from our studies of mineral or biogenic material of aquatic origin. The sill of the Shyok river, which is the potential outflow of the Bangong system, may have fluctuated in altitude in response to the Karakorum fault activity, inducing the opening (≈9.6 ka B.P.) or closure (after 2.1 kyr B.P.) of the lake. Nevertheless, it is conspicuous that terrestrial vegetation was independent of tectonics at the time scale considered. The excellent agreement between our hydrological, hydrobiological data and the pollen record (Van Campo et al., this volume) definitely demonstrates that climate has been the major driving factor in the hydrological evolution of Lake Bangong during the Holocene.

—The abrupt negative shift in ^{13}C content of authigenic carbonates (Fig. 2c) from about 3.9 to 3.2 ka B.P. cannot be fully understood without the palaeobiological record. When combined with an increase of desert plants (e.g. *Ephedra*, Fig. 2a), the local development of a Cyperaceae swamp (Fig. 2b), an increase in detrital organic input (Fig. 2d) mainly composed of altered lignocellulosic debris, this negative shift in δ^{13}C values can be attributed to the sudden establishment of sedges at the core site and to an enhanced flux of soil-derived CO$_2$, under a climate-induced low stand of the lake.

—The Lake Bangong catchment area includes large valleys occupied by salty marshes and soils. Changes in the drainage of these valleys may have modified the salt budget of the lake. However, around 6.2–6.0 and 1.3 ka B.P., diatom-inferred increases in water salinity (Fig. 3b) occur in phase with positive shifts in ^{18}0 content of carbonates (Fig. 3a). Thus, these increases in salinity are

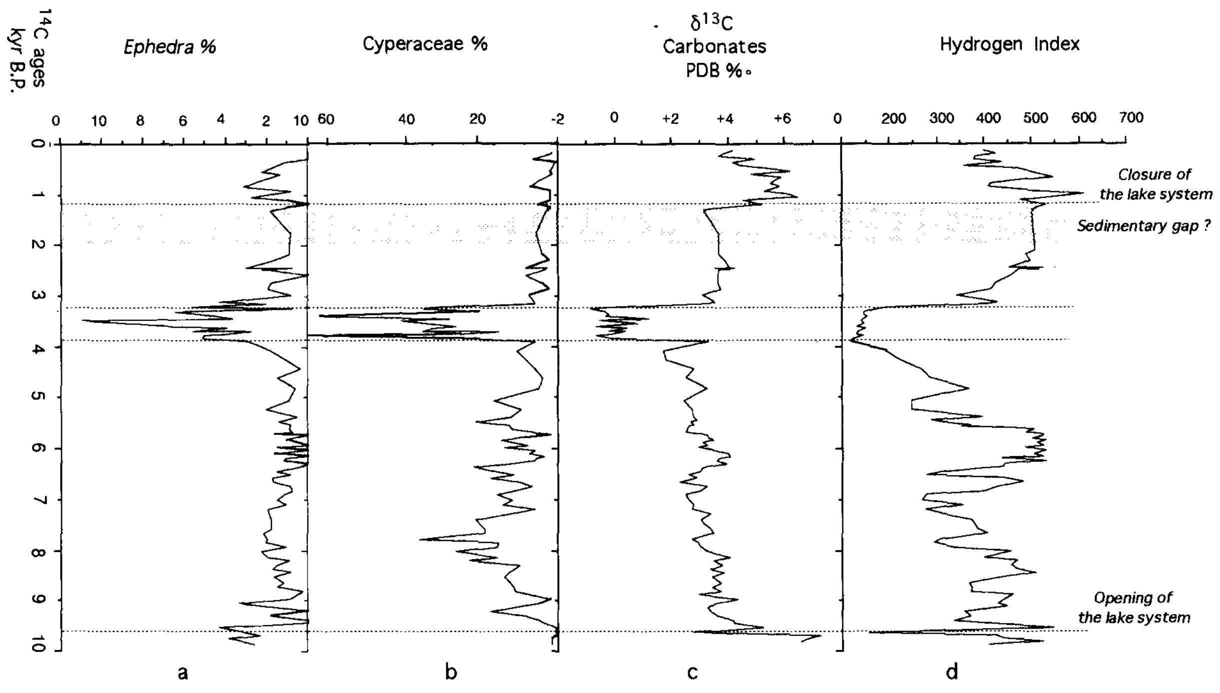

Fig. 2. Summary results for the Bangong Co core. Multi-disciplinary interpretation of the 3.9–3.2 kyr B.P. abrupt environmental event. a. Relative frequency of *Ephedra* pollen, a desert plant; b. Cyperaceae pollen, a palustral plant; c. ^{13}C content of authigenic carbonates; very low values ($< +1$‰) are primarily attributed to the rapid establishment of sedges at the core site, combined with an influx of soil-derived CO$_2$. Very high values ($> +4.5$‰) correspond to episodes of closure of the lake system, with long residence time and possible methanogenesis; d. Hydrogen Index, expressed as mg hydrocarbures per g Total Organic Carbon. Low values suggest influx of oxidized, detrital organic matter. (a and b, after Van Campo et al.; c, after Fontes et al.; d, after Fan et al., this volume. See texts for explanation).

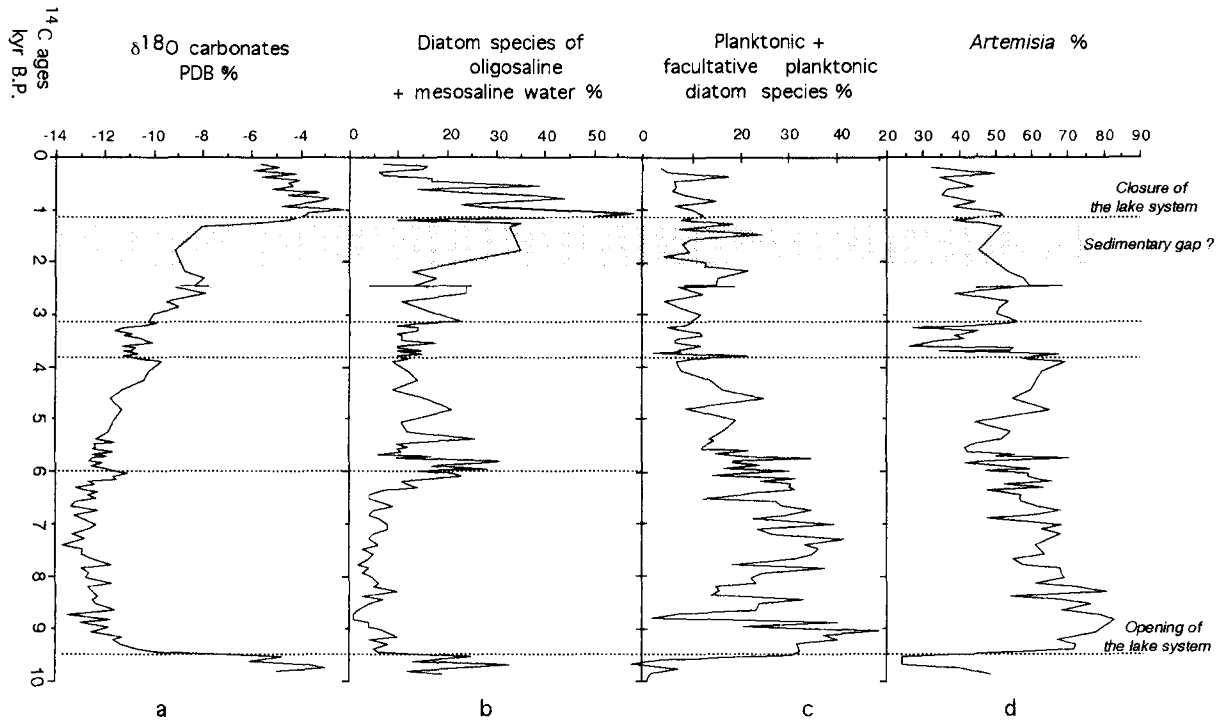

Fig. 3. Summary results for the Bangong Co core. Results are plotted as a function of age, according the radiocarbon chronology proposed by Fontes et al. (this volume). a. ^{18}O content of authigenic carbonates. Very high values (> −6‰) correspond to episodes of closure of the lake system. Extremely low values (< 12.5‰) are attributed to heavy monsoon precipitation in an open lake with rapid throughflow. b. Total percentage of saline water diatom species. The positive correlation between this salinity index and the δ^{18}O values suggests that salinity is due to evaporative concentration, rather than weathering of salty soils from the catchment area. c. Total percentage of planktonic (*Cyclotella* spp. mainly)+facultative planktonic (*Fragilaria* spp. mainly) diatom species, a rough indicator of water depth. d. Relative frequency of *Artemisia* pollen, an indicator of steppe vegetation. (a, after Fontes et al.; b and c, after Fan et al.; d, after Van Campo et al., this volume; see texts for explanation).

attributed primarily to evaporative concentration reflecting reduced Precipitation/Evaporation ratios, rather than to the weathering of salty soils from the drainage area.

Minor lags between environmental events as deduced from different proxies may be due to different response times of individual indicators. However, all results converge to define major successive stages in the Lake Bangong evolution.

2.1. *Arid conditions before ≈9.6 ka B.P.*

From ≈9.9 to ≈9.6 ka B.P., East Bangong was closed, in response to regional arid climatic conditions. The pollen record indicates a poor local and regional vegetal cover under a dry climate. The core site was occupied by a slightly saline marsh rich in charophytes. Diatom-inferred salinity is compatible with the predominance of aragonite in the mineral fraction. Oligo- to mesosaline conditions are attributed to evaporative concentration in a waterbody with long residence time, as indicated by high ^{18}0 contents of the water. High ^{13}C contents are linked to intense aquatic photosynthesis and/or to methanogenesis within bottom sediments. Reducing bottom conditions are compatible with the high content of well preserved vegetal cuticles and membranes in the sediments.

2.2. *Conditions generally wetter and warmer than those of today from ≈9.6 to ≈6.3 ka B.P.*

An extremely abrupt environmental change from arid to wet conditions is recorded at ≈9.6

ka B.P. A steppe vegetation rapidly established over the region. A freshwater, oligotrophic, planktonic diatom flora developed in the lake, implying a sudden influx of dilute, nutrient poor water. Content in total organic carbon decreased, and algal-derived material prevailed in the organic fraction. The disappearance of aragonite also reflects dilution of the lake water. The drastic decrease in stable isotope contents indicates the establishment of a positive water balance associated with enhanced regional precipitation strongly depleted in ^{18}O. The lake rose, and overflowed when the water level reached the sill of the Shyok river. Climatic-induced changes in lake hydrology, especially in salt and stable isotope balances, were considerably amplified by the sudden decrease in residence time when the lake overflowed. However, the abruptness of changes observed in the terrestrial pollen spectra attests to an extremely rapid transition from dry to wet climatic conditions.

From ≈9.6 to 6.3 ka B.P., the persistence of a freshwater lake with rapid throughflow is documented by the diatom flora and the stable isotope record. In agreement with detailed surveys of isotope content in precipitation in monsoon regions (Rozanski et al., 1993; Wei and Lin, 1994), extremely low $^{18}0$ contents are primarily attributed to an increase in summer monsoon precipitation, whereas ground temperature was high. An increase in temperature of calcite crystallization in the lake water may also have enhanced the negative shift in $\delta^{18}O$ values.

Proxy data indicate, however, short-term changes during this interval. The lowest $\delta^{18}O$ values, regarded as reflecting minimum water residence time in the lake and maximum monsoon rainfall, are observed between 9.0 and 8.7 ka B.P., and between 7.5–7.2 and 6.3 ka B.P..

The first wet pulse (9.0–8.7 ka B.P.) led to maximum depth and dilution of the lake water, as shown by the percentage of planktonic diatoms (Fig. 3c) and the total disappearance of saline water diatoms (Fig. 3b). The highest frequencies of the steppic *Artemisia* in the pollen assemblages is observed during this period.

From 8.6 to 7.5–7.2 ka B.P., climate instability and a return to drier conditions are suggested by several indicators. Percentages of littoral and saline water diatom species increase and peak around 8.2 ka B.P. (Fig. 3b,c). The diatom content shows a minimum around 7.7 ka B.P. Fluctuations in $\delta^{18}O$ values reaching ≈2‰ in magnitude are observed, with maxima at ≈8.6, 8.1 and 7.7 ka B.P. (Fig. 3a). The development of a local palustral flora (Cyperaceae) which peaked at 7.7 ka B.P. (Fig. 2b) is interpreted as a lake regression. The first wet pulse of the early Holocene age was thus followed by drier conditions, especially around 8.2–7.7 ka B.P.

The second humid pulse, from 7.5–7.2 to 6.3 ka B.P., corresponds to optimal conditions for biological activity, in the catchment area and in the lake itself. This is documented by the pollen record, which shows maximum pollen content around 7.0 kyr B.P. Diatom data also suggest intense algal productivity in the lake which was of the mesotrophic type. This interval is interpreted as the period of maximum moisture availability and maximum temperature recorded for the whole Holocene.

2.3. A non-linear return to aridity from ≈6.2 to 5.7 ka B.P.

Pollen data do not show significant changes in vegetal cover during this interval. However, a short-term but significant deficit in the Precipitation–Evaporation balance is recorded from ≈6.2 to ≈5.7 ka B.P. by an abrupt increase in ^{18}O contents, in phase with an increase in salinity deduced from the diatom flora. This dry spell underlines the end of the Holocene hydrological and climatic "optimum". The following periods do not show the extremely low $\delta^{18}O$ values characteristic of the intervals 9.0–8.7 ka B.P., and 7.2–6.3 ka B.P. This suggests that the Bangong basin experienced a persistent deficit in the Precipitation–Evaporation balance, and/or no longer received heavy monsoon rainfall so much as convective rains less depleted in heavy isotopes. This hypothesis will be discussed elsewhere (Wei Keqin and Gasse, in prep.).

From ≈5.7 to ≈3.8 ka B.P., steppe and alpine meadow cover regressed in two steps, at around 5.5 and 3.9 ka B.P., in phase with rapid drops in diatom content and the development of littoral diatoms. Influxes of detrital material increased in response to the lowering of the lake level, and/or enhanced erosional processes on the catchment area under conditions drier than those of the preceding stage. Content of ^{18}O reflects a net increase in the excess of Evaporation over Precipitation until $\approx$3.9 ka B.P.

2.4. A dry episode from ≈3.8 to ≈3.2 ka B.P.

The pollen record indicates arid conditions. *Ephedra*, characteristic of desertic environments, exceeds 10% of the pollen spectrum (Fig. 2a). A Cyperaceae swamp became established within the Bangong complex (Fig. 2b) with a substantial major drop in water level. A remarkable correlation is observed between the sudden increase in the Cyperaceae frequency, decrease in ^{13}C content (Fig. 2c), influx of detrital organic matter, and decrease in the Hydrogen Index values (Fig. 2d) which reflects both the change in the origin and in preservation conditions of organic matter in the sediments. The abrupt negative shift in $\delta^{13}C$ values is attributed to the rapid establishment of sedges at the core site and to a sudden influx of soil-derived CO_2 into the lake. Low diatom-inferred salinity, the diversity of littoral diatom species absent from any other level, the predominance of detrital minerals in the sediments, the sudden influx of detrital organic matter, and relatively low ^{18}O content suggest that the core site was directly subject to a river influence, and corresponded to a deltaic zone during a phase of very low water level. The interval 3.8–3.2 ka B.P. is thus interpreted as an arid episode.

2.5. A wet episode of minor amplitude from ≈3.2 to ≈2.1 ka B.P.

A wet pulse of minor amplitude is documented by both the pollen and the diatom records. The water level remained lower, however, than during the early–middle Holocene lacustrine episode, as documented by the abundance of littoral organisms including diatoms (Fig. 3c), ostracods, charophytes and sponge spicules. Calcite became again the predominant mineral in the sediments. Increasing ^{18}O content (Fig. 3a) is attributed to evaporative enrichment under increasing residence time of the water in the lake.

2.6. The interval 2.1–1.3 ka B.P.

No characteristic feature of emergence has been observed in the core material. However, the chronology of the upper part of the core has to be considered with caution. Our radiocarbon chronology suggests an extremely low sedimentation rate or a sedimentary gap between 2.1 and 1.3 ka B.P. This would imply very dry conditions during this interval, followed by a wet pulse shortly before 1.3 ka B.P.

2.7. The establishment of modern conditions (≈1.3?–0 ka B.P.)

The uppermost two metres of the core show close similarities with the base of the core. The sudden positive shift in stable isotope content (Figs. 2c, 3a) and in diatom-inferred salinity (Fig. 3b) is attributed to the closure of the lake system in response to the establishment of arid climatic conditions documented by pollen data. Short-term environmental changes are, however, recorded during this interval. Maximum contents of aragonite, heavy isotope and saline waters diatoms suggest a maximum in aridity at 1.2–1.0 ka B.P., followed by a trend toward moister conditions upward. A dry pulse, documented by the pollen record, may have occurred around 700 yr B.P.

3. Comparison between the Bangong and the Sumxi-Longmu Co records.

Sumxi Co (5058 m, 24.5 km^2) and Longmu Co (5008 m, 98.7 km^2) are two closed lakes lying in a small tectonic basin situated about 120 km northwards of Lake Bangong, and 800 m higher in elevation, on the northern flank of the Mawang Kangri massif. Climate is colder and drier than at Bangong, and the lakes are surrounded by an alpine desert. Like Lake Bangong, Sumxi Co is a freshwater lake mainly supplied by the meltwaters of the Mawang Kangri glaciers. The low salinity

(0.5 g/l) is attributed to infiltration through the lake floor. Sumxi Co is separated from Longmu Co by a threshold at 5100 m. Longmu Co is mainly supplied by spring water (0.8 g/l) emerging from a normal fault along the northwestern margin of the lake and possibly resurging from Sumxi Co. Longmu Co is hypersaline (172 g/l, sodium-chloride waters) due to evaporative concentration.

Hydrological and climatic changes in the Sumxi-Longmu Co basin were deduced from the study of a 13 ka lacustrine core (10.5 m) taken at Sumxi, shorelines, and outcropping sediments. Summary data on the Sumxi core ^{14}C chronology, mineralogy, stable isotope contents of calcite, and biological remains are given in Gasse et al. (1991). The detailed pollen and diatom records are discussed in Van Campo and Gasse (1993). Liu (1993) presented the mineralogical and stable isotope analyses of the outcropping sediments. Fontes et al. (1994) discussed the salt, radiocarbon, and stable isotope balances of the two lakes, and revised the Late Holocene chronology. Avouac et al. (this volume) proposed a climatic interpretation of the geomorphic study of regressive shorelines surrounding the lakes. A comparison between the Sumxi and the Bangong pollen records was conducted by Van Campo et al. (this volume). Summary results are given in Fig. 4.

The Sumxi-Longmu Co record differs from the Bangong record in several features. When compared with Lake Bangong, which was open during most of the Holocene, it is clear that the closed Sumxi-Longmu lake system has experienced very large changes in water level. The two lakes were connected during the early–middle Holocene to form a single water body lake more than 160 m deep. The hydrological regime of the two lake systems, induced by local topographical factors, also explain the differences in the general shape of the stable isotope records. In the closed Sumxi-Longmu lake system, the major factor controlling the variations in both ^{18}O and ^{13}O contents of authigenic carbonates is the residence time of the water and Total Dissolved Inorganic Carbon in the lake (see Fontes et al., this volume, and Fontes et al., 1994, for discussion). The ^{18}O and ^{13}O contents thus covary. Low stable isotope contents correspond to periods of short residence time, i.e. low lake level, and vice versa. The Sumxi record is characterized by a very low biological diversity and productivity and detrital material commonly predominates in the mineral fraction. In contrast to Bangong where the local flora is an important component of the pollen assemblages, fossil pollen grains preserved in the sediments are mainly of aeolian origin. *Artemisia* and Chenopodiaceae are the two prevalent pollen types in the record. As *Artemisia* pollen (A) come from the steppe and Chenopodiaceae pollen reflect primarily the montane desert, the A/C ratio is considered as a bioclimatic indicator of increase in available atmospheric and/or soil moisture (see Van Campo and Gasse for discussion). Diatoms are absent from the base of the core, suggesting extreme oligotrophy, and/or poor preservation. Their appearance at ≈9.0 ka B.P. may have resulted from a sudden increase in the total dissolved solid content, while the water rose above the threshold, inducing mixing of the Sumxi Co freshwater with the Longmu Co brines. Diatom content remains low and the diatom flora is of the oligotrophic type throughout the core.

Despite the differences between the Bangong and the Sumxi-Longmu lake systems, regional climatic changes inferred from the two independent records correlate remarkably well, the differences in timing fitting within the uncertainties in ^{14}C chronologies. As at Bangong, the Sumxi-Longmu record shows clear relationships between changes in regional vegetal cover, mineralogical compounds of the sediments, aquatic biological communities, and concentrations in salt stable isotope contents in the lake water

3.1. Generally dry conditions from ≈12.5 to ≈10.0 ka B.P.

Before 10.0 ka B.P., the rare pollen of desertic plants (dominated by *Ephedra* and Chenopodiaceae) in the Sumxi core indicates arid conditions. The A/C ratio is at a minimum (Fig. 4a,b). Aridity is also documented by the dominance of the detrital phase in the sediments (Fig. 4c). This precludes accurate stable isotope studies, because. the proportion of authigenic calcite is too low to be estimated (Fig. 4d). Little

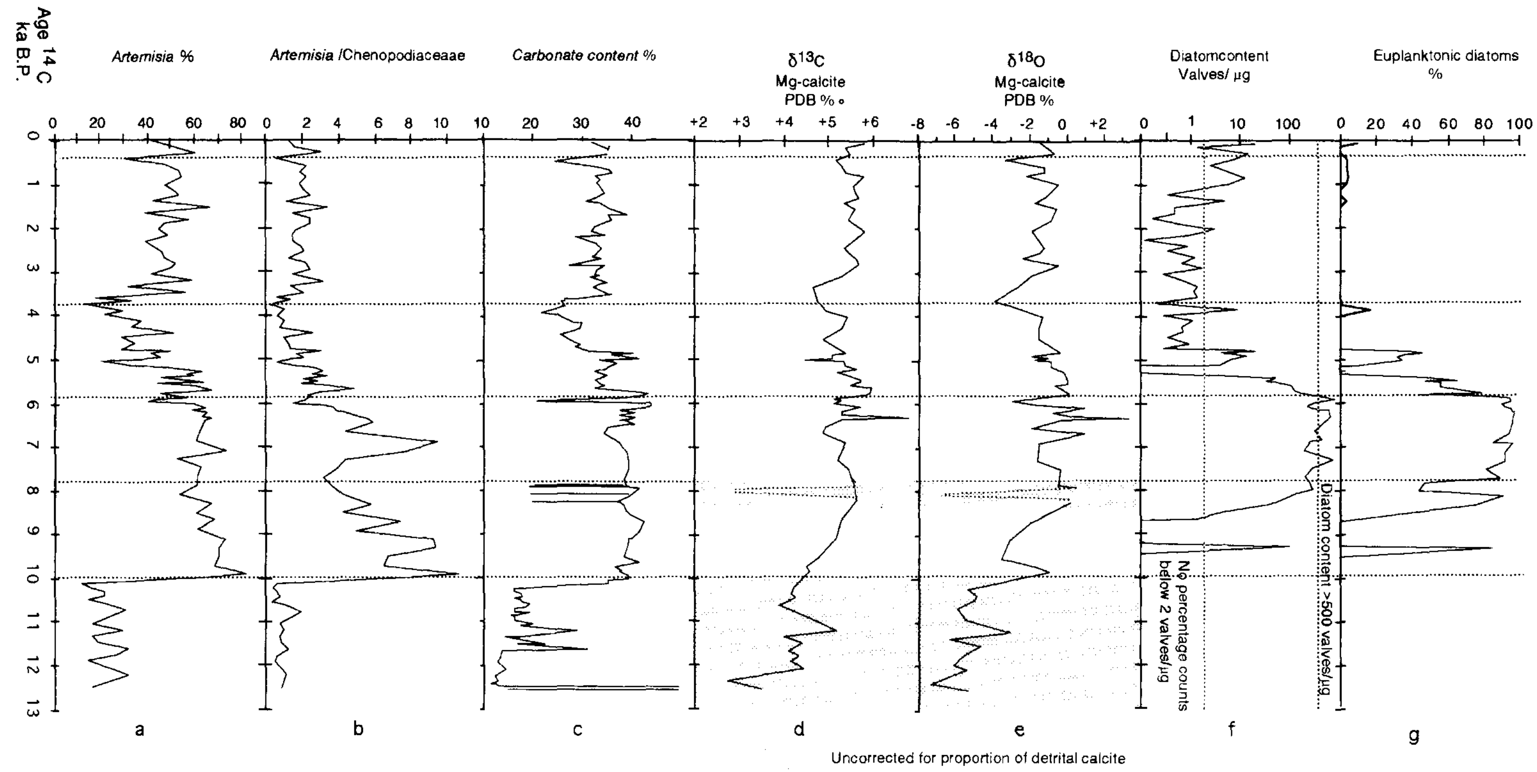

Fig. 4. Summary results for the Sumxi Co core. Results are plotted as a function of ^{14}C ages, according to Fontes et al. (1994). a. Relative frequency of *Artemisia* pollen, an indicator of steppe vegetation. b. *Artemisia*/Chenopodiaceae pollen ratio, a bioclimatic index of air/soil moisture. c. Total carbonate content (% bulk sediment; authigenic calcite mainly). Content in authigenic calcite is associated with inputs of pedogenetic CO_2 in the lake waters, and is thus regarded as an indicator of intense pedogenesis (implying soil moisture and development of a vegetal cover in the catchment area). d, e. Stable isotope contents (^{13}C, ^{18}O) of authigenic carbonates (Mg-calcite). Before 10 ka and around 8 ka B.P., the proportion of detrital calcite is too high to provide significant stable isotope values. f. Diatom content, an indicator of productivity in the lake. g. Percentage of planktonic diatoms (*Cyclotella* spp. mainly), a rough indicator of water depth. (a, b, f, g, after Van Campo and Gasse, 1993; c, d, e, after Fontes et al., 1994).

changes appears in the regional vegetation from 12.5 to 10.0 ka B.P. However, the appearance of authigenic calcite from periods of lake filling at ≈12.5 ka B.P. and at ≈11.5–11.0 ka B.P. (Fig. 2c) reflects inputs of pedogenetic CO_2 in the lake waters, and related brief increases in humidity and temperature in the catchment. A reversal event toward dry, cold conditions is then recorded by the total disappearance of both authigenic calcite and biological remains in the sediments, the lowest pollen content and the lowest A/C ratios observed for the whole record (Fig. 4b). This event was centred around 10.5 ka B.P. and ended at ≈9.9 ka B.P., and thus appears to be synchronous with the European Younger Dryas chronozone.

3.2. Conditions generally wetter and warmer than those of today from ≈9.9 to 6.0 ka B.P.

A major environmental change, as brief as a few centuries, occurred around 9.9 ka B.P. An abrupt increase in authigenic calcite content (Fig. 4c), which implies enhanced pedogenesis, is observed in phase with the sudden development of aquatic life. Ostracods are abundant around 9.9–9.5 ka B.P. and diatoms appear at ≈9.0–8.5 ka B.P. During the lake refilling, the low $^{18}0$ content (Fig. 4e) suggests enhanced rainfall and/or meltwater supplies strongly depleted in heavy isotopes. The rapid expansion of the *Artemisia* steppe (Fig. 4a) to the detriment of the montane desert vegetation is reflected in the sudden increase of the A/C ratio (Fig. 4b). This implies a net increase in the excess of precipitation over evaporation, at least at the seasonal scale, attributed to wet and warm summers.

A recessional event is recorded by a major negative shift in the A/C ratio which culminates around 8.0–7.7 ka B.P. (Fig. 4b). This episode of decreased air and/or soil moisture coincides with a drop in diatom content and in the percentage of planktonic diatoms (Fig. 4f,g) indicating a lake regression. Fine sand layers (Fig. 4c) reflect shallow conditions and/or enhanced erosion in the catchment area. Influx of detrital carbonates reduced the significance of the stable isotope signals during this short-term arid phase.

A second wet-warm pulse led to the maximum in lake volume which was reached from ≈7.5 to ≈6.2 ka B.P., when the two lakes, Sumxi Co and Longmu Co, were connected in a single, deep (⩾160 m) closed lake. The high residence time in this large lake is shown by the highest $\delta^{18}0$ and $\delta^{13}C$ values of the lake waters. This high stand coincides with a period of dense vegetal cover in the catchment area and intense pedogenesis. Maximum diatom content suggests optimal conditions for plankton growth in the lake.

This episode ended with a short-term dry event around 6.0 ka B.P. This is documented by synchronous negative shifts of the the A/C ratio, calcite content, stable isotope contents of authigenic carbonate, diatom content and planktonic diatom frequency. On the basis of equations developed to calculated the $\delta^{18}O$-values of the lake water in terminal lakes, Lin et al. (1994) suggested that this return towards lower $\delta^{18}O$-values fingerprints the end of the summer monsoon influence in the Sumxi catchment area.

3.3. A trend towards aridity from ≈6.0 to ≈3.7 ka B.P.

From ≈6.0 to ≈3.7 ka B.P., all environmental indicators reveal a general trend toward aridity. The general decrease in water supply induced the bipartition of the two lakes at ≈5.5 ka B.P., and in increase in detrital input. Sumxi Co, supplied by meltwater, remained fresh, as documented by relatively low ^{18}O content (Fig. 4e) and the diatom flora, while Longmu Co became rapidly became hypersaline. Pollen data indicate a maximum in aridity at ≈3.8 ka B.P.. The A/C ratio minimum (Fig. 4b) occurs in phase with a minimum in carbonate content (Fig. 4c) and in $\delta^{13}C$ and $\delta^{18}0$ values (Fig. 4d,e). Planktonic diatoms disappeared.

3.4. The establishment of modern conditions during the late Holocene

A minor wet pulse is registered by the pollen spectra between about 3.5 and 2.5 ka B.P. (Fig. 4a,b). However, sedimentary disturbances and diatom flora (Fig. 4f,g) suggest the persistence of very shallow conditions until ≈1.3 ka B.P. A very short-term dry event is documented at ≈0.4 ka B.P. by the pollen, mineralogical and stable isotope records.

3.5. *Similarities between the Sumxi and Bangong records*

Both records document the rapid establishment of wet–warm conditions at 9.9–9.6 ka B.P., and a recessional event centred around 8.0–7.7 ka B.P. A second wet-warm pulse culminated from 7.5–7.0 to 6.3–6.2 ka B.P., and ended with a dry spell around 6.2–6.0 ka B.P. Stable isotope studies suggest that Western Tibet no longer received heavy monsoon rainfall. However, this hypothesis needs to be confirmed by further investigations of the isotopic composition of modern precipitation in the region and by the study of other sedimentary records. A general trend towards dry conditions is then recorded from ≈6.0–5.5 ka B.P., leading to maximum aridity between about 3.9 and 3.2 ka B.P.. This short-term dry episode was followed by minor climatic oscillations. The late Holocene chronologies remain to be refined, in order to confirm the synchronism of the short-term dry events observed in both lakes during the last millenium and to postulate possible correlations with the "Little Ice Age" cold spell.

4. Comparison with the continuous Seling Co and Qinghai Lake records

Although several studies were carried out on outcropping sediments, few continuous records are available to date for the Tibet–Qinghai plateau. Core studies were recently performed for two large closed saline lakes: Seling Co, in Central Tibet (Gu et al., 1993), and Lake Qinghai, near the northwest corner of the plateau (Lister et al., 1991). In both cases, the palaeoclimatic interpretation is mainly derived from $\delta^{18}0$ profiles established for authigenic carbonates (Fig. 5). The two isotopic curves show clear similarities in their general shape. The climatic interpretation of the long-term and progressive increase in $\delta^{18}0$ values during the early and middle Holocene slightly differs depending on the authors. Detailed discussion of these isotope curves is beyond the scope of this paper and will be presented elsewhere (Wei Keqin and Gasse, in prep.). Here, we will discuss only on the major features which definitely document changes in the monsoon strenght during the post glacial period.

4.1. *Seling Co*

Seling Co (31°34′–31°57′N, 88°31′–89°21′E; 4530 m) is one of the largest lakes of the Tibet plateau (lake area: 1640 km^2; catchment area: ≈45,530 km^2). It is a closed, saline lake (18 g/l) with waters of the sodium-sulphate type. The region, semi-arid today, is under the influence of the summer monsoon. The lake is supplied mainly by precipitation in the catchment area. Gu et al. (1993) provided a ≈12 ka climate record deduced from a 3.08 m core taken under 27 m of water in the southern part of the lake. The chronology is based on five ^{14}C dates on carbonates, and one ^{14}C date on total organic matter. Some ageing, by dissolution of old limestones or the presence of some of detrital carbonates in the sediments, is suspected. However, no dating of modern waters or modern sediments are available. Radiocarbon ages on carbonates were empirically corrected for ageing (of about 1000 a) on the basis of the single age obtained on organic matter for the core base, and on mean sedimentation rate. The climatic interpretation proposed by Gu et al. (1993) is reported below. It is based on mineralogical analyses and on stable isotope contents (^{13}C, ^{18}0) of carbonates (Fig. 4a).

From ≈12.2 to 10.0 ka B.P., cold–dry conditions predominated. Dolomite was abundant in the carbonate fraction. High ^{18}O contents indicate extensive evaporation. Low ^{13}C contents are attributed to a long period of freezing limiting exchange with atmospheric CO_2. The interval ≈10.8–10.0 ka B.P. shows minimum (calcite+aragonite)/dolomite ratios, and maximum δ^{18}O-values. It is regarded as a period of decreased temperature and humidity, and is tentatively correlated with the Younger Dryas cold/dry spell.

A rapid and large change from dry–cold to wet–warm conditions occurred around 10.0 ka B.P. Calcite and aragonite became the predomi-

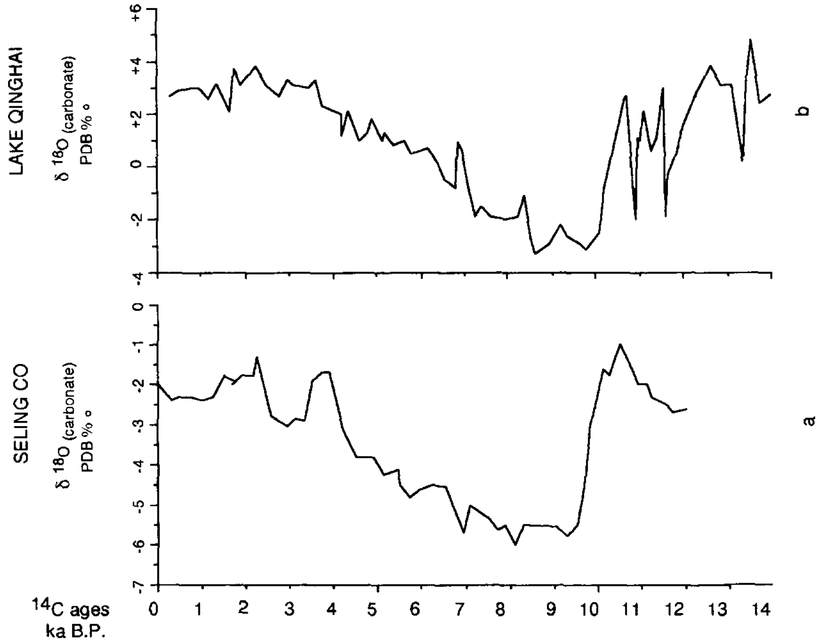

Fig. 5. Variations in ^{18}O content of: a. total carbonate fraction in a core from Seling Co (after Gu et al., 1993); b. ostracod valves in a core from Lake Qinghai (after Lister et al., 1991) (see text for discussion).

nant minerals in the sediments, reflecting water dilution. The $\delta^{18}O$-values decreased drastically. This is attributed to the strenghtening of monsoonal circulation, associated with increased precipitation, relative humidity, and temperature.

Conditions wetter than those of today prevailed from about 10.0 to 4.2 ka B.P. The interval 10.0–8.4 ka B.P. was a period of expansion of the water body. The highest water level and maximum water dilution may have occurred from 8.4 to 5.5 ka B.P. A progressive increase in $\delta^{18}O$ values from 5.5 to 4.2 kyr B.P. is regarded as indicating a general trend towards aridity associated with cooling.

Dry climatic conditions prevailed during the late Holocene. Two aridity maxima are recorded from ≈4.2 to ≈3.3 ka B.P., and from ≈2.4 to 1.4 ka B.P.. This is documented by high $\delta^{18}O$ values and high proportion of dolomite in the sediments. These two dry events alternated with moister periods, from ≈3.3 to 2.4 ka B.P. and from ≈1.4 ka B.P. to present.

4.2. The Qinghai Lake record

Lake Qinghai is a closed lake, 26.5 m deep, which extends over 4278 km^2 at 3194 m above sea level. Mean annual precipitation in the catchment area, due to summer monsoon mainly, is about 400 mm a^{-1}. The lake is fed by surface runoff (46%) from the catchment area (30,000 km^2), direct rainfall (42%), and groundwater inflow (12%). The lake output is essentially by evaporation loss (Lister et al., 1991). The alkaline, magnesium-sulphate rich waters have a total salinity of 14 g/l. Lake Qinghai has experienced large fluctuations in water level, salinity and stable isotope contents in response to climate changes.

A 5.6 m core, taken in the deepest part of the basin, was analyzed in detail for sedimentology, and for ^{18}O content of fossil ostracod valves that can be related to the precipitation/evaporation budgets which have controlled the palaeo-levels of the lake (Lister et al., 1991). The chronology is based on 3 AMS radiocarbon dates measured on vegetal remains of aquatic origin (*Ruppia*) and ranging between 10.9 and 8.4 ka B.P. No measurement of ^{14}C activity was conducted on modern waters. The precise timing of environmental events younger than 8.4 ka B.P. cannot be ascertained. The age of the core base is estimated at 14.3 ka B.P. by extrapolation. We discuss below the interpretation proposed by Lister et al. (1991).

The record suggests that the regional climate remained arid until at least 12.5 ka B.P., when an incipient monsoon was possibly initiated, inducing a first rise of minor amplitude in lake level. Sedimentary evidence then documents a further period of aridity after 10.8 ka B.P., synchronous with the Younger Dryas event, and which is tentatively attributed to a monsoonal weakening. At ≈10.2 ka B.P., the basin began filling in response to a permanent strengthening of the Asian monsoon, as shown by a rapid decrease in $\delta^{18}O$ values. The overall positive shift for $\delta^{18}O$ values through the early–middle Holocene is interpreted as being due to steady evaporative enrichment of ^{18}O in the lake-water reservoir, essentially independently of the lake level, and as reflecting long-term stable climatic and hydrological regimes. Negative deviations from that trend suggest, however, lake-level rises around 10.0 ka B.P., from ≈9.5 to 8.5, and 8.2 to 7.2 ka B.P. Short-term positive deviations are observed around 8.2 and 6.8 ka B.P. Uncertainties on the core chronology after 8.4 ka B.P. make it difficult to correlate these aburpt changes with the short-term dry events deduced from the multi-proxy records from Sumxi and Bangong. A stranded shoreline terrace at +12 m may represent the highest Holocene lake-level and may be dated at about 7–6 ka B.P.

After ≈3 ka B.P., a possible overall weak negative $\delta^{18}O$ shift may represent a naturally changing isotopic steady state (Lister et al., 1991). We note, however, that the highest $\delta^{18}O$ values for the whole Holocene period are observed around 3.7 ka B.P., and from about 2.4 to 1.5 ka B.P., as at Seling Co.

5. Discussion

On the basis of a carefull survey of the Chinese literature, Fang (1991) suggested that, during the post Glacial period, lakes from Tibet have experienced their highest levels between 15 and 12 ka B.P. in central and western Tibet, and during the middle Holocene in southern Tibet and in the Qinghai basin. Such regional differences are not confirmed by our data. The absence of chronological control in Fang's investigation may explain these apparent discrepancies, as numerous causes may bias the radiocarbon records. This was clearly illustrated by the discussion of radiocarbon chronology of the Sumxi-Longmu Co (Fontes et al., 1994) and Bangong Co (Fontes et al., this volume).

The four continuous lacustrine records available for the Qinghai–Tibet plateau (Bangong Co, Sumxi Co, Seling Co and Lake Qinghai) show consistent trends in past changes in climate, from the Qinghai plateau to western Tibet. The most characteristic features of these records are the sudden establishment of wet conditions around 10 ka B.P., and the maximum aridity around 4–3 ka B.P. This implies that the climate evolution at the four sites has been driven by the same factors. Lags of a few centuries appear in the timing of the abrupt event observed around 10 ka B.P. This may be due to the different qualities of dated materials, standard errors on the ^{14}C ages, the validity of age interpolation, and large uncertainties affecting any radiocarbon age around 10 ka B.P. because of the ^{14}C plateau at the Late Pleistocene–Holocene boundary (Stuiver et al., 1993).

In all cases, $\delta^{18}O_{(carbonate)}$ values are extremely low during the early Holocene, and reflect enhanced supplies of rainfall strongly depleted in heavy isotopes. This is attributed, by all authors, to the strenghthening of the Indian monsoon. At Lake Bangong, where the ^{18}O content of the waters can be regarded as reflecting the mean ^{18}O composition of catchment precipitation because of a rapid throughflow during most of the Holocene, the stable isotope record suggests that heavy monsoon rains reached Western Tibet at least from ≈9.6 to 8.7, and from ≈7.2 to ≈6.3 ka B.P.. After ≈6.3 ka B.P., the overall positive $\delta^{18}O$ gradient indicates a general trend toward aridity. It also suggests an increase in $\delta^{18}O$-values of precipitation which may be due to a change in the precipitation regime, from monsoon precipitation to convective rains. This is in excellent agreement with the climatic evolution deduced from the detailed pollen analyses from both the Bangong and Sumxi cores. The two pollen records clearly shown that wet conditions were established in two steps, at ≈10.0 and 7.5–7.0 ka B.P., as well as a step-wise return toward aridity from ≈6.3 to ≈3.8 ka B.P..

Our reconstruction is broadly consistent with palaeoclimatic studies in northwestern China. Several authors have attempted to synthetize the great amount of informations based on different types of proxy data (palaeoglaciology, loess/palaeosol profiles, pollen, lake-level fluctuations, archaeology, historical and instrumental data) published in the Chinese literature (Zhou et al., 1991; Fang, 1991; Zhaodong, 1993; Shi, 1993, among others). In conflict with the Li's (1990) hypothesis proposing wet-cold conditions during the Late Glacial Maximum and a warm-dry climate during the Holocene in Xinjiang, all these others authors conclude that conditions warmer and wetter than today prevailed during the early–middle Holocene period. Lake Manas in northern Xinjiang (Rhodes et al., this volume) experienced a two step change from dry to wet conditions during the last deglaciation, with the major step being dated at ≈10 ka B.P. This suggests that Indian and Asian monsoons have fluctuated in phase and penetrated inland during the early–middle Holocene. Our results also agree with climatic reconstructions from northwestern India. The sedimentological and palynological record of Lake Didwana (Bryson and Swain, 1981; Swain et al., 1983; Singh et al., 1990) suggests a rise in precipitation leading to the intermittent filling of the lake after 13 ka B.P. The establishment of a permanent lake is attributed to the onset of significant monsoon rains at ≈10 ka B.P.. The early–middle Holocene wet episode is interrupted by a period of reduced rainfall around 8.0 ka B.P., and maximum available moisture is recorded between 7.5 and 6.2 ka B.P. Long intervals of drought have occurred since ≈3.8 ka B.P.. There is thus good consistency in the evolution of sites influenced by the Indian monsoon, which supports the prediction of general circulation models for an orbitally-induced increase in monsoonal precipitation at ≈9000 yr B.P. (COHMAP Members, 1988).

However, the smooth variations of the orbital parameters do not account for the short-term dry periods recorded at Sumxi and at Bangong, the two major ones occurring in the intervals ≈8.0–7.7 and ≈3.9–3.2 ka B.P. As previously discussed by Van Campo and Gasse, 1993), these two dry events appear in phase with rapid climatic changes observed at northwestern India, and with dry spells already recognized in tropical North Africa (Gillespie et al., 1983; Gasse et al., 1977; Servant and Servant-Vildary, 1980; Talbot et al., 1984; Gasse and Fontes, 1992). Although a more precise timing of the rapid changes registered in tropical lakes is still needed, our results emphasize synchronous variations in the monsoon strength in both the Indian and African monsoon domains. We suggest that these large amplitude abrupt reversions to dry conditions in the tropics may have been caused by rapid changes in energy redistribution in the ocean–atmosphere–land system, at least in the northern hemisphere.

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