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Quantitative climate and vegetation trends since the late glacial on the northeastern Tibetan Plateau deduced from Koucha Lake pollen spectra

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ABSTRACT

Quantitative information on vegetation and climate history from the late glacial–Holocene on the Tibetan Plateau is extremely rare. Here, we present palynological results of a 4.30-m-long sediment record collected from Koucha Lake in the Bayan Har Mountains, northeastern Tibetan Plateau. Vegetation change has been traced by biomisation, ordination of pollen data, and calculation of pollen ratios. The application of a pollen–climate calibration set from the eastern Tibetan Plateau to Koucha Lake pollen spectra yielded quantitative climate information. The area was covered by alpine desert/steppe, characteristic of a cold and dry climate (with 50% less precipitation than today) between 16,700 and 14,600 cal yr BP. Steppe vegetation, warm (~1°C higher than today) and wet conditions prevailed between 14,600 and 6600 cal yr BP. These findings contradict evidence from other monsoon-influenced areas of Asia, where the early Holocene is thought to have been moist. Low effective moisture on the northeastern Tibetan Plateau was likely due to high temperature and evaporation, even though precipitation levels may have been similar to present-day values. The vegetation changed to tundra around 6600 cal yr BP, indicating that wet and cool climate conditions occurred on the northeastern Tibetan Plateau during the second half of the Holocene.

Introduction

Quantitative palaeoclimate and palaeovegetation data from the Tibetan Plateau for the late glacial and Holocene are extremely rare (cf. Shen et al., 2006a) but are necessary for evaluating the results of numerical modelling (e.g., Song et al., 2005). The influence of the climate of the Tibetan Plateau on northern hemisphere circulation is regarded as important and thus such information is particularly desirable (e.g., Yanai et al., 1992).

Qualitative information about climate change on the Tibetan Plateau for this interval has been deduced mainly from lake sediment records (e.g., Lister et al, 1991; Herzschuh et al., 2005; Mischke et al., 2005; Shen et al., 2005; Herzschuh et al., 2006a,b; Morrill et al., 2006; Wu et al., 2006; Zhao et al., 2007), and to a lesser extent from regional ice core and tree ring data (Thompson et al., 1990, 1997; Bräuning and Mantwill, 2004; Zhang et al., 2003). To date, it is assumed that the general climate trends on the Tibetan Plateau are similar to those of other areas influenced by the Asian summer monsoon (An et al., 2000; Morrill et al., 2003; An et al., 2006; Herzschuh, 2006). During the late glacial the circulation led to cold and dry conditions on the Tibetan Plateau. Warm, wet conditions, comparable to those of the Holocene, occurred during the Bølling/Allerød phase (~14,700–12,700 cal yr BP) while cold and dry climate conditions prevailed during the Heinrich 1 and Younger Dryas events around 16,000 cal yr BP and 12,000 cal yr BP. Maximum monsoonal strength resulting in wet and warm conditions on the Tibetan Plateau is assumed for the early Holocene, while continuous cooling and drying is thought to have occurred since ca. 6000 yr ago. A review by Herzschuh (2006) of proxy records exposed significant regional differences in climate history between the Tibetan Plateau and its northern foreland and also across different areas of monsoon-influenced Central Asia. One hypothesis stated within this synthesis is that climate history differs between areas of different precipitation/evaporation (P/E) ratios. Early Holocene climate was wetter than today in areas of present-day high P/E ratios such as the south-eastern Tibetan Plateau, while it was relatively dry in areas of present-day low P/E ratios such as the Alashan Plateau in Inner Mongolia.

Pollen analysis of lake sediments is commonly used to deduce palaeovegetation and palaeoclimatic changes. Quantitative reconstructions of temperature and precipitation using modern pollen–

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climate relationships have been a useful and common tool in palaeoclimatology for more than 25 yr (Seppä and Bennett, 2003; Birks and Seppä, 2004).

In this paper we present a late glacial–Holocene pollen record from Koucha Lake, a medium-sized lake on the semi-arid northeastern Tibetan Plateau. We reconstruct variations in vegetation and climate via qualitative assessment of pollen percentages, analysis of pollen ratios, application of the biome reconstruction method (Prentice et al., 1996), and the use of pollen–climate transfer functions (Birks and Seppä, 2004). Quantitative climate information from the northeastern Tibetan Plateau will help to track regional differences in climate history in Central Asia and to understand its causes.

Regional setting

Climate and vegetation of the Tibetan Plateau

The Tibetan Plateau, with an average altitude of more than 4000 m asl, is situated in the western part of China between 80–105°E and 27–37°N. Several NW–SE trending mountain ranges rise above the widespread plains: the most prominent are the Kunlunshan and the Tangulashan.

The Tibetan Plateau is a large summer heat source that greatly affects atmospheric circulation through its thermal effect (Murakami and Ding, 1982; Luo and Yanai, 1983; Yanai et al., 1992; Wu and Zhang, 1998). From May to September the Tibetan Plateau—like most areas in east, southeast and south Asia—is dominated by the Asian summer monsoon system. Only a small amount of the total annual moisture supply is brought by the westerlies. When the summer monsoon retreats at the beginning of September, the winter monsoon begins and occupies monsoonal Asia by mid-October. The pressure distribution at sea level in the Asia Pacific region for January shows a well-developed, intense high pressure cell over central Siberia and Mongolia and a strongly established low pressure cell over the northwestern Pacific Ocean. The resulting winds, which transport dry continental and cold polar air masses over Asia, originate mainly from northern areas and constitute the winter monsoonal system (Wang, 2006). There is a general gradation in conditions, from high summer temperatures (up to 19°C) and precipitation (>700 mm) on the southeastern plateau to low precipitation (<100 mm) and summer temperatures (~6°C) on the northwestern Tibetan Plateau (Sun, 1999).

The vegetation of the Tibetan Plateau is outlined in several overview works (e.g., Chang, 1981; Zhang, 1993; Zhou and Wang, 1987) and regional studies (e.g., Sun and Kong, 1992; Huai and Zhou, 1997; Wu, 1995, 2000; Kürschner et al., 2005); however, many of them are published only in Chinese. Montane conifer and broad leaf forests, dominated by *Pinus*, *Picea*, *Abies*, *Tsuga*, *Quercus* and *Betula* species, grow along the warm and wet southeastern and eastern margins of the Tibetan Plateau up to altitudes of ~3000 m in the north and ~4500 m in the south. Due to intensive logging, patches of forest are normally only preserved in remote areas and on steep slopes. Areas of the wet eastern plateau above the tree line are covered by sub-alpine shrubs (e.g., *Salix*, *Potentilla*, *Rhododendron*, *Lonicera*, *Caragana*, *Berberis*) intermixed with alpine meadows rich in Asteraceae, Polygonaceae, Rosaceae, and Gentianaceae at higher altitudes. Cold and wet areas on the eastern Tibetan Plateau above 4500 m are covered by high-alpine meadows mainly composed of different *Kobresia* species (e.g., *Kobresia pygmea*, *Kobresia capillifolia*). Ranunculaceae, *Polygonum*, Fabaceae, and Caryophyllaceae are common taxa found in these vegetational zones.

The warm and dry Qinghai Lake area in the northeastern Plateau is dominated by temperate steppe (mainly *Artemisia* and Poaceae such as *Artemisia scoparia*, *A. gmelinii*, *A. frigida*, *Achnatherum splendens*, *Stipa breviflora*, *S. krylovii*, *S. glareosa*, *S. bungeana*, *Koeleria cristata*, *Agropyron cristatum*) which becomes alpine steppe—a mixture of *Artemisia*, Cyperaceae (e.g., *Kobresia littledalei*, *K. royleana*, *Carex moorcroftii)* and Poaceae (*Stipa subsessiliflora*, *S. purpurea*)—above ~4000 m. This vegetation type, characterised by sparse vegetation cover, dominates large areas of the northeastern and central Tibetan Plateau. Only the dry north-central and westernmost regions of the Plateau and the western part of the Qilian Mountains are occupied by alpine deserts, where the dominant shrub Chenopodiaceae (e.g., *Ceratoides compacta*) is accompanied by *Artemisia*, Poaceae, *Ephedra*, and *Nitraria*.

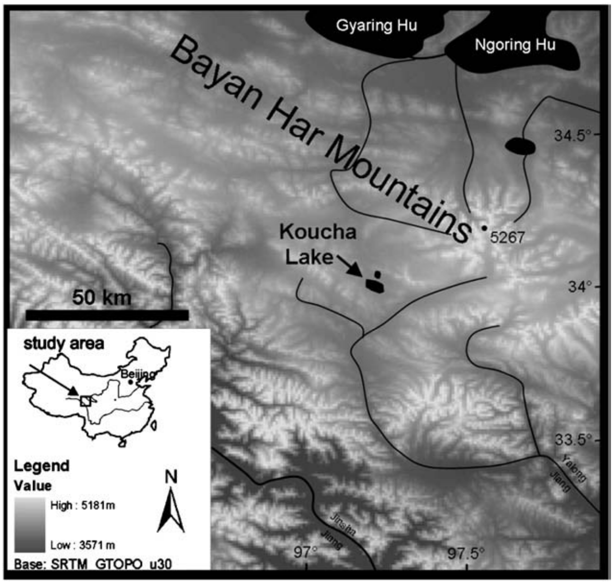

Figure 1. Koucha Lake area on the north-eastern Tibetan Plateau.

Setting of Koucha Lake and its vicinity

Koucha Lake (34.0°N; 97.2°E; 4540 m asl) is situated on the northeastern Tibetan Plateau, south of the Bayan Har Mountains, an eastern range of the Tangulashan (Fig. 1). The lake occupies a glacially eroded, wide depression in the southern foreland of the Bayan Har Mountains. According to Li et al. (1991) and Zhou and Li (1998), the region was covered by a local ice cap during the penultimate glaciation. The freshwater lake (lake size 4 km × 1 km) has a maximum depth of ~6 m and is fed by several small streams (catchment area ~88 km^2); a single outflowing stream is one of the upper tributaries of the Yellow River. The climate is dominated by the Asian monsoon system. Regional climate information from climate stations reveals cool temperatures during summer and precipitation mainly occurring between June and September (Maduo climate station at 98.22°E, 34.91°N, 4273 m asl, $T_{July}=8.1$°C, $P_{ann}=311$ mm; Chengduo climate station at 33.8°N, 97.13°E, 4418 m asl, $T_{July}=6.9$°C, $P_{ann}=469$ mm).

The vegetation around Koucha Lake is dominated by dense *Kobresia* meadows. At higher elevations in the nearby Bayan Har Mountains this grades into sparse alpine vegetation. Areas above ~5000 m are free of vegetation. Elevations below ~4400 m, which are characterised by higher temperature and lower levels of precipitation, are occupied by alpine steppes with vegetation coverage of ~50%. The whole area is grazed by yaks and sheep. A monastery lies several kilometres downstream of the lake.

Materials and methods

Coring, sediment material and age–depth model

A 560-cm-long core was drilled in the central part of the lake (water depth 4.12 m) in March 2003 using Livingstone coring equipment. The core consists of sandy marl in the lower section

Table 1
Radiocarbon dates

Depth (cm)	Dated material	$\delta^{13}C$ (‰)	^{14}C age (^{14}C yr BP)	Calibrated age (cal yr BP)
160–181	Pollen	−17.67	2320±30	2342±10
224–249	Pollen	−18.45	3685±35	4008±88
310–325	Pollen	−22.71	6795±35	7633±48
374–387	Pollen	−26.00	10,180±45	11,876±174
427	Alkali soluble fraction	−18.67	13,650±90	16,271±428

(560–423 cm) and organic-rich lake carbonate in the upper section (423–0 cm).

Five AMS radiocarbon dates, and the assumption that the uppermost sediments are contemporary, provide the chronological control for the core (Table 1). Four of the dates are based on extracted pollen grains. The sediment contained no terrestrial plant macrofossils that could have been used for dating. The lowermost date was performed on bulk organic matter due to low pollen concentrations. An age–depth model was developed using calibrated ages (Fig. 2). For this purpose, radiocarbon ages were transformed to calendar years using the Calib program (Stuiver and Reimer, 1993, online version 5.1.beta). The age–depth model was constructed by linear interpolation between date points.

Pollen sample treatment and analysis

In total, 66 pollen samples were analysed. Processing of the pollen samples in the laboratory included treatments with HCl (10%), KOH (10%) and HF (50%; 2 h boiling), followed by acetolysis, sieving (7 mm) in an ultrasonic bath, and mounting in glycerine. In total, at least 300 terrestrial pollen grains were counted for each level. Pollen identifications are based on the relevant literature (Moore et al., 1991; Wang et al., 1997; Beug, 2004) and on a pollen reference collection of more than 600 plant species from western China.

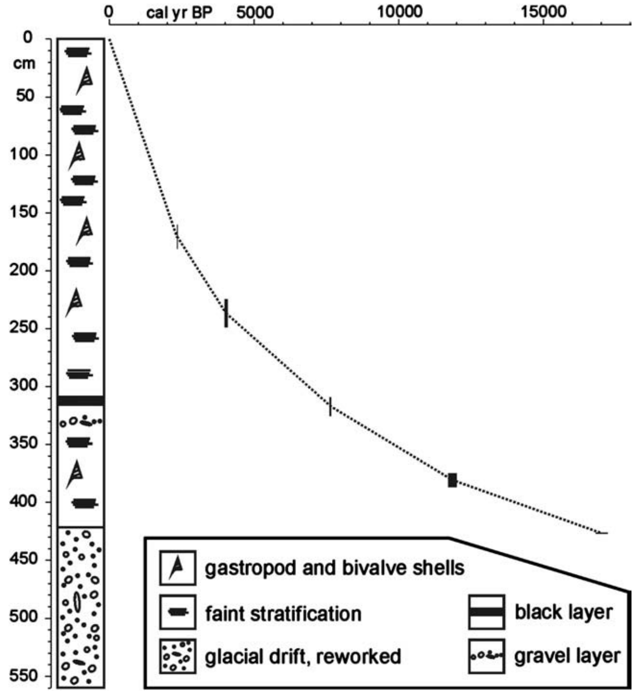

Figure 2. Age–depth model (based on linear interpolation between AMS dates) and sediment record from Koucha Lake (bar width indicates 1σ range and length indicates the sampled interval).

The total pollen count of arboreal and terrestrial non-arboreal taxa identified in each pollen spectrum was taken as 100% for the calculation of the pollen percentages. The resulting values were used for the construction of the pollen diagram and for numerical analyses. Only pollen taxa that occurred with a frequency of >0.5% in at least three samples were included in the numerical analyses and in the construction of the pollen diagram. The definition of the local pollen zone boundaries was based on the results of a Constrained Incremental Sum of Squares cluster analysis using ZONE software version 1.2.

Numerical analysis and interpretation methods

Multivariate analysis was used to assess trends in the data set and address two specific questions: Which taxa exhibit similar trends in the pollen record and which pollen zones have similar composition? Detrended correspondence analysis (DCA) and principal component analysis (PCA) were performed on the basis of the square root transformed pollen percentage data using CANOCO 4.5 for ordination and CANODRAW for Windows for plotting. DCA gave a compositional gradient of less than two standard deviation units, showing that the data set has a mainly linear structure which implies the usage of the linear-based PCA (ter Braak, 1987) would be more successful. Since the pollen taxa compositions were considered more important for our interpretation, the data were 'species-centred' and the distances between the samples in the species sample bi-plot do not correspond exactly. However, it was checked with a 'sample-centred' approach (not shown here), which yielded only a few differences.

Traditional interpretations of pollen records in terms of vegetation and climate reconstruction are often based on the presence and abundance of selected indicator taxa (e.g., Birks and Birks, 1980). For pollen records from arid regions in central Asia, this approach is hampered by limited pollen morphological knowledge and the lack of valuable indicator taxa. Herzschuh (2007) showed that pollen ratios are a valuable tool in gaining vegetation and climate information. Herzschuh et al. (2006b) introduced the *Artemisia*/Cyperaceae (A/Cy) ratio as a semi-quantitative measure for summer temperature changes on the central and eastern Tibetan Plateau, based on the observation that cold, high alpine environments (both alpine meadow and alpine steppe) on the eastern and central Tibetan Plateau are dominated by Cyperaceae (mostly *Kobresia*), while warmer areas at lower elevations on the southern and northeastern Tibetan Plateau are covered by temperate steppe vegetation with higher *Artemisa*. Herzschuh (2007) found a significant positive correlation between the A/Cy ratio of surface pollen spectra from the eastern Tibetan Plateau and mean July temperature, confirming the reliability of this ratio.

The qualitative interpretation of pollen spectra can be checked with a quantitative method for pollen-based biome reconstruction

Table 2
Assignment of pollen taxa to biomes used in the biomisation procedure

Biome	Pollen
Tundra	*Anthemis*-type, Apiaceae, *Aster*-type, Cichorioideae, Brassicaceae, Caryophyllaceae, Cyperaceae, Fabaceae, Gentianaceae, Koenigia, Lamiacaeae, Papaveraceae, Poaceae *Polygonum aviculare*-type, *Polygonum bistorta*-type, Ranunculaceae, *Rumex*/*Rheum*; *Saussurea*-type, Saxifragaceae, Scrophulariaceae, *Thalictrum*, *Veronica*
Steppe	*Alium*-type, *Anthemis*-type, Apiaceae, *Artemisia*, *Aster*-type, Chichorioidae, Brassicaceae, Caryophyllaceae, Fabaceae, Gentianaceae, Hippophaë, Koenigia, Lamiacaeae, Lonicera, Papaveraceae, Poaceae *Polygonum aviculare*-type, *Polygonum bistorta*-type, *Potentilla*-type, Ranunculaceae, Rosaceae, *Rumex*/*Rheum*; *Salix*, *Saussurea*-type, Saxifragaceae, Scrophulariaceae, *Thalictrum*, *Veronica*

All identified terrestrial pollen taxa are used in the biomisation. Taxa not assigned to the tundra or steppe biome were not shown.

Table 3
Model information and model performance statistics when assessed by leave-one-out cross-validation of the WA-PLS pollen–precipitation transfer functions in terms of RMSEP (root mean square error of prediction)

Pollen–climate calibration set for the eastern Tibetan Plateau		
	P_{ann}	T_{July}
Number of samples	113	113
Climate range	104–670 mm	4.0–17.4°C
Regression method	WA-PLS	WA-PLS
Number of component	1	2
r^2	0.79	0.5
Maximum bias	112 mm	5.18°C
RMSEP	62 mm	1.67°C
RMSEP as % of gradient length	11.1	12.5

r^2 = coefficient of determination between predicted and observed climate values and maximum bias.

(called biomisation; Prentice et al., 1996). Based on knowledge of the contemporary biogeography and ecology of modern plants, the pollen taxa are assigned to plant functional types and to main vegetation types (biomes). An affinity score for each single biome is then calculated according to Prentice et al. (1996). The pollen taxa-biome matrix applied in the present study (Table 2) is based on the biomisation procedure presented by Yu et al. (1998), but it was improved by information given in Yu et al. (2001).

In order to gain quantitative information on precipitation changes, pollen–climate transfer functions have been applied to the fossil pollen spectra from Lake Koucha. The modern pollen data set consists of 113 modern surface-sediment samples from the eastern Tibetan Plateau (Table 3). The pollen spectra cover a wide range of mean annual precipitation values (104–670 mm) and temperatures (4.0–17.4°C). Transfer functions were developed with weighted averaging partial least squares (WA-PLS) regression. Model performance was tested by leave-one-out cross-validation. The root mean square error of prediction (RMSEP) is 62.3 mm and 1.67°C, and the coefficient of determination (r^2) is 0.79 for precipitation and 0.5 for July temperature between the observed meteorological values and the model predicted values. The RMSEP, when expressed as percentages of the gradient length sampled is 11.1% for precipitation and 12.5% for July temperature, respectively, which can be considered low in comparison to similar studies.

Results

Results from the pollen analysis are shown in the pollen diagram (Fig. 3). The pollen concentration of the lower section of the core (560–430 cm) was too low to perform pollen analysis. All pollen spectra show high frequencies of Cyperaceae, *Artemisia*, and Poaceae (mostly > 10% for each taxon), which add up to more than 70% in most samples. Chenopodiaceae, Brassicaceae, *Aster*-type, *Ranunculus*-type, *Thalictrum*, and *Betula* occur with moderate-high frequencies (1–10% in most samples).

The different pollen assemblage zones (PAZ) vary significantly in their composition. PAZ 1 (430–408 cm; 16,400–14,600 cal yr BP) is characterised by high values of Chenopodiaceae (7–13%), Brassicaceae and Caryophyllaceae and Poaceae. The lowermost sample differs from the other samples with its high *Picea* and *Pinus* values (4% and 24%). *Artemisia*/Cyperaceae ratios are low (0.6–1.1) except for the lowermost sample (A/Cy: 2.1) (Fig. 5). PAZ 2 (408–296 cm; 14,600–6600 cal yr BP) shows high frequencies of *Artemisia* (27–51%) while Cyperaceae has low frequencies (<40%) resulting in high *Artemisia*/Cyperaceae ratios (mostly >3). The characteristic pollen taxa of PAZ 2 are *Salix* and *Betula*. Frequencies of Chenopodiaceae, Brassicaceae, Caryophyllaceae and Poaceae are significantly lower in comparison to PAZ 1. PAZ 3 (296–0 cm; 6600–0 cal yr BP) shows high Cyperaceae frequencies and low *Artemisia* frequencies and *Artemisia*/Cyperaceae ratios (mostly <1). Furthermore, PAZ 3 is characterised by relatively high *Ranunculus*-type and *Polygnonum bistorta*-type values.

A preliminary DCA yielded a gradient length of 0.87 standard units, which indicates that numerical methods based on linear response models are appropriate with our data set (Table 4). The first two PCA axes capture 45.4% (axis 1: 31.1%, axis 2: 14.3%) of the total variance in the data. The pollen taxa ordination separates the elements of sparse alpine vegetation and alpine deserts (Chenopodiaceae, Caryophyllaceae, Brassiceae, *Anthemis*-type, and *Saussurea*-type) at the positive end of the second axis and herbs, shrubs, and trees typical of steppe and forest-steppe vegetation (*Artemisia*, *Hippophaë*, *Salix*, and *Betula*) at the negative end (Fig. 4). Poaceae and *Ephedra fragilis* s.l.-type show intermediate scores. Taxa typical for high-cold meadows (Cyperaceae, *Ranunculus*-type, *Polygonum bistorta*-type) are located on the negative end of the first axis. Pollen samples for the different PAZ are clearly clustered in the bi-plot: samples of PAZ 1 exhibit high values on the second axis; PAZ 2-samples cluster at its negative end, and samples of PAZ 3 exhibit negative values on the first axis.

The biome reconstruction indicated that steppe and tundra biomes dominated throughout. In comparison to these, desert or different forest biomes had very low values and were therefore not shown. Steppe biome dominated in the area during PAZ 1 and 2 and tundra in PAZ 3. Steppe had its maximum extension during PAZ 2.

The quantitative precipitation reconstruction (Fig. 5), deduced from the application of a pollen–precipitation transfer function to the fossil Koucha pollen data, yielded values between 290 and 436 mm. The precipitation values estimated for PAZ 1 (430–408 cm; 16,400–14,600 cal yr BP) range between 290 and 318 mm (median: 299 mm). The precipitation reconstruction for the lowermost sample has been excluded as it contained an anomalously high content of coniferous pollen. The lowest precipitations of the profile (<300 mm) were reconstructed for the lower part of PAZ 1. The reconstruction of such low values is clearly connected to high amount of desertic elements such as Chenopodiaceae and Brassicaceae in the fossil pollen data. The estimated precipitation values rise rapidly at the transition to PAZ 2 as a result of the increase in steppe and shrubland taxa, such as *Artemisia* and *Salix*, in the pollen spectra at the expense of desert taxa. The precipitation values of PAZ 2 (408–296 cm; 14,600–6600 cal yr BP) range between 314 and 400 mm (median: 358 mm). Comparatively low precipitation values were reconstructed for 9700–7500 cal yr BP (depth: 348–314 cm). The precipitation values estimated for PAZ 3 (296–0 cm; 6600–0 cal yr BP) are similar or slightly higher than those of PAZ 2 (range: 329–436 mm, median: 380 mm). There is no clear trend in the precipitation data; maximum values reconstructed were for around 2000 cal yr BP and for the present day.

The quantitative July temperature reconstruction yielded values between 6.1 and 10.2°C. The median temperature of the four lowermost samples (PAZ 1) is 9.0°C. The median PAZ 2 (8.3°C) is slightly higher than the median of PAZ 3 (7.4°C).

Discussion

Critical assessment of the data

There are several limitations and potential problems with the pollen-stratigraphical data and resulting vegetation and climatic reconstructions from Koucha Lake on the northeastern Tibetan Plateau.

The pollen samples were evenly distributed throughout the profile, but due to changes in sedimentation rate, the temporal resolution decreases with depth. The resolution is very low during the late glacial (~600 yr), slightly higher during PAZ 2 (~400 yr) and highest during PAZ 3 (~150 yr).

The information on the pollen morphology of the Tibetan Plateau is still insufficient. Since it was not within the scope of this study to validate or establish new pollen types at the genus or species level, we

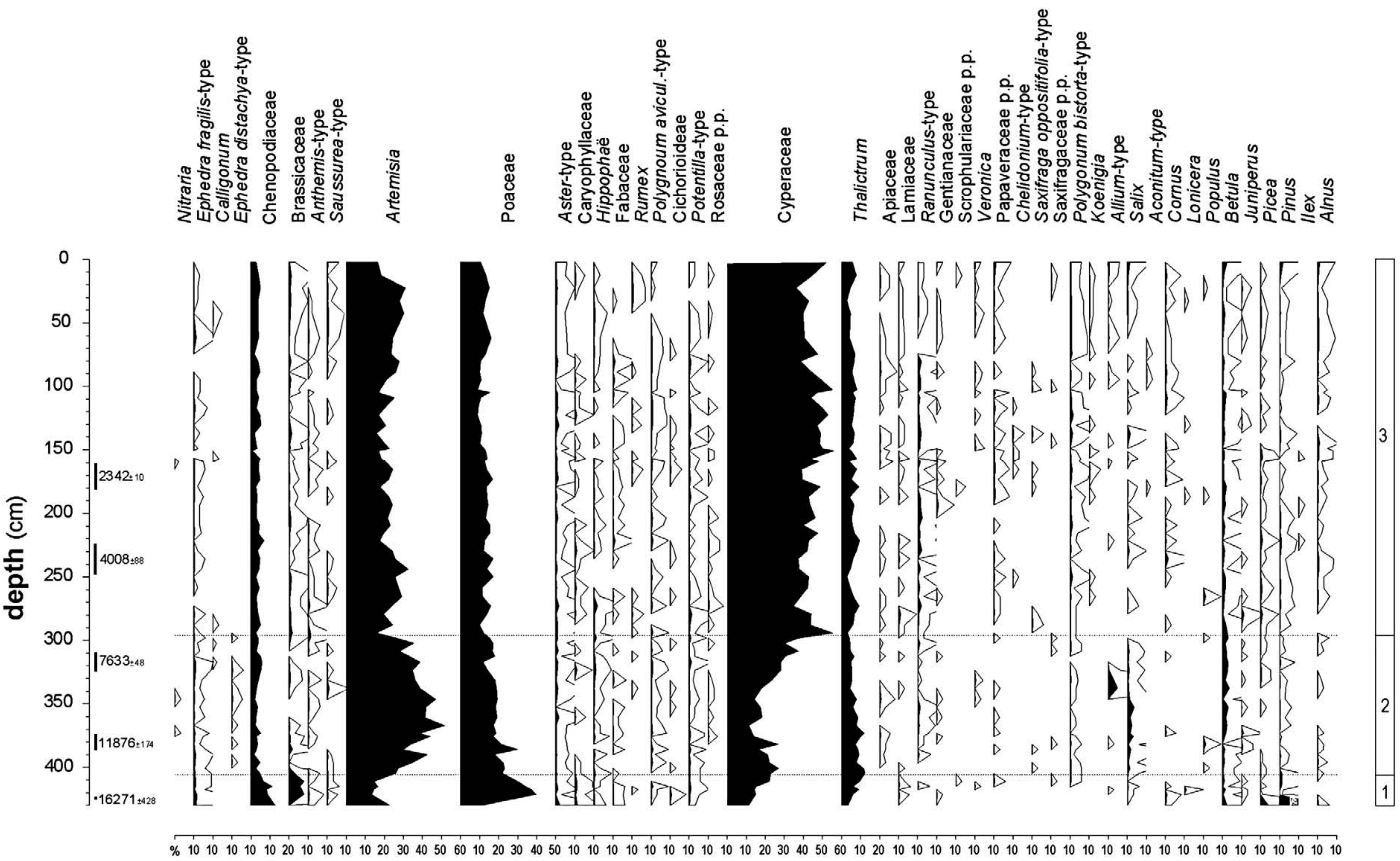

Figure 3. Pollen diagram of Koucha Lake showing all pollen types used in the numerical analyses. The species in the pollen diagram are arranged from low (left) to high (right) weighted average optima for P_{ann} as inferred from an unpublished regional modern pollen rain study.

Table 4
Results of detrended correspondence analysis (DCA) and principal component analysis (PCA) of Koucha Lake pollen spectra

	DCA		PCA	
	Axis 1	Axis 2	Axis 1	Axis 2
Eigenvalue	0.051	0.039	0.31	0.14
Gradient length (SD)	0.870	0.920	–	–
Cumulative % of variance	(9.4)	(16.6)	31.1	45.4

have presented some of our pollen data at the family level, which reduces the information content of the profile.

Information on the distribution of modern plant taxa on the Tibetan Plateau is also limited. The information necessary to draw up the taxa × biome matrix for the biome reconstruction has been partly adopted from other regions, which blurs the validity of our reconstruction.

The application of the pollen–climate transfer function to the Koucha Lake pollen records also yielded some problems:

> T_{July} deduced for the top of the profile is 1.8°C higher than present-day local T_{July} around Koucha Lake. This may be due to the fact that Koucha Lake is significantly larger than other lakes in the calibration set and therefore has a larger pollen source area that includes areas of lower elevation with vegetation corresponding to a warmer, drier climate. The pollen–temperature transfer function therefore overestimates the absolute values of T_{July}. This is the case for all samples in the profile. The relative temperature excursions within the profile should not be affected and absolute temperature can be estimated by subtracting 1.8°C from the deduced values.
>
> It is generally assumed that plant growth in arid and semi-arid areas is limited by moisture availability rather than by absolute precipitation. However, moisture availability is a function of both precipitation and evaporation, which is primarily driven by temperature and cloudiness. This relationship for pollen-based climate reconstructions implies that annual precipitation levels are overestimated during cold, cloudy phases and underestimated during warm, clear phases. The quantitative climate reconstruction for the Koucha Lake pollen spectra via WA-PLS modelling is also affected by these problems. The residuals of the calibration models show slight trends, indicating overestimation at dry and cold sites and underestimation at warm and wet sites. These biases are inherent to WA-PLS and result from the inverse deshrinking used in WA-PLS (Birks, 1995, 1998).

We believe that the T_{July} values estimated for the basal three samples of the profile are high and thus unreliable for two reasons.

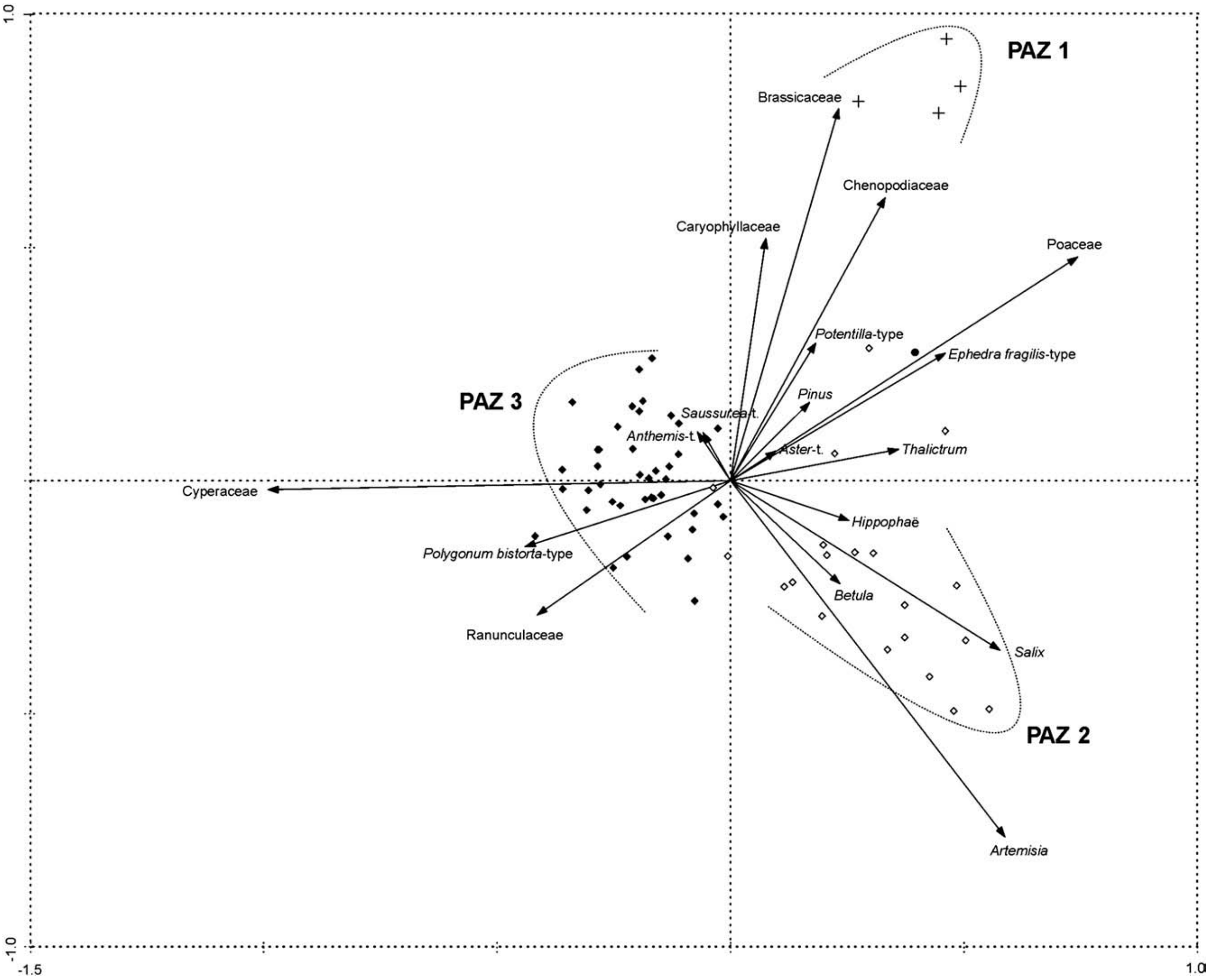

Figure 4. Diplot of the first two PCA axes. Samples from the same pollen zone are indicated by the same symbols. For better visualization only pollen taxa that have a frequency of more than 1% in at least 3 samples are indicated.

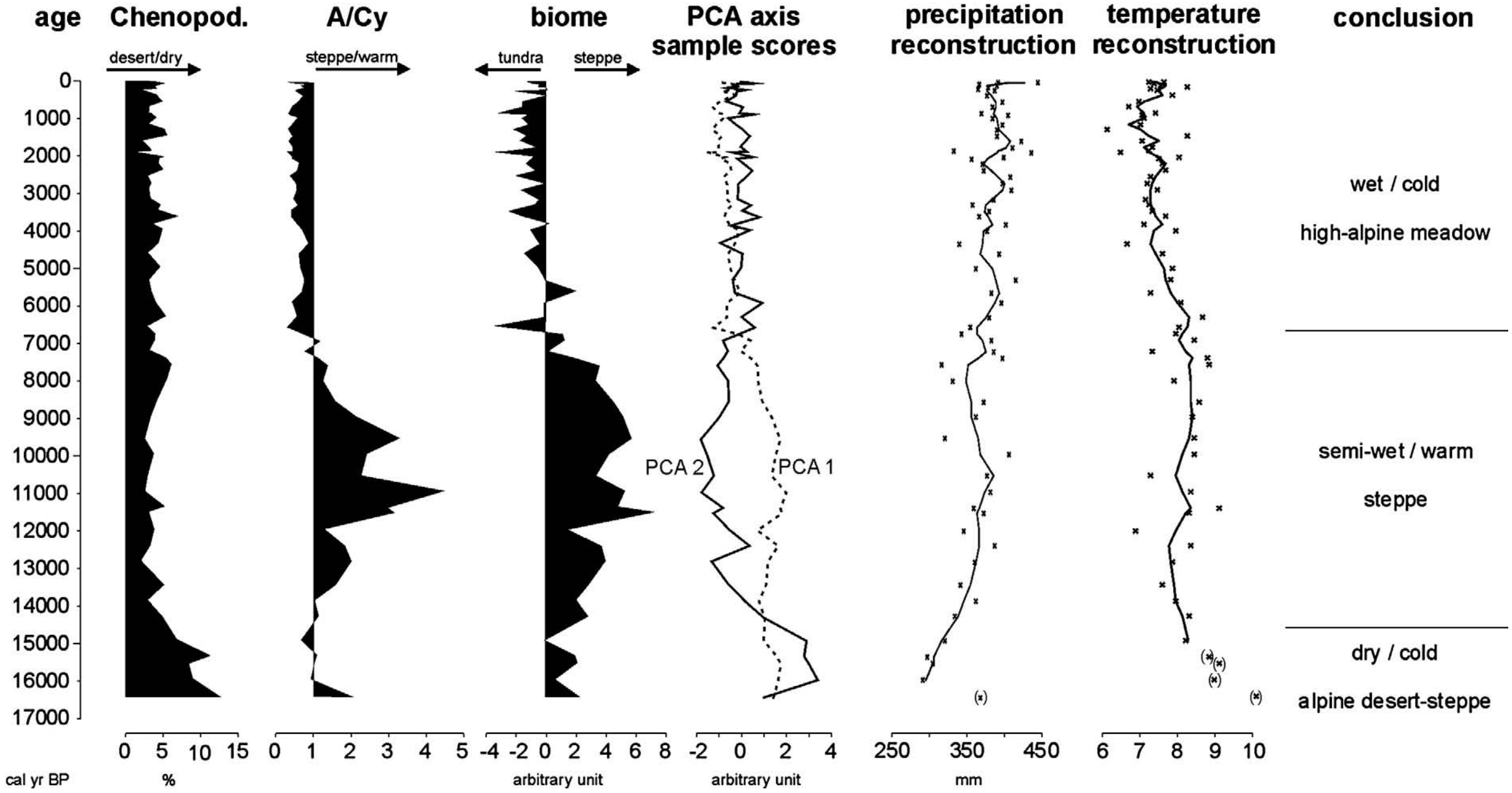

Figure 5. Summary of vegetation and climate reconstruction as inferred from the Koucha Lake pollen record (A/Cy: *Artemisia*/Cyperaceae ratio). For clarification, we did not show the calculated scores for each biome but rather the difference between steppe and tundra biomes.

Firstly, a high amount of coniferous pollen was found in the spectra, which leads to high T_{July} in the quantitative reconstruction. We assume that these pollen grains do not come from the surrounding vegetation of Koucha Lake, but instead either originate from reworked material that is supported by the sandy matrix in this part of core or represent a long-distance transport component which is especially high during periods of low regional pollen production. A second reason might be the high content of Chenopodiaceae, which originates from alpine desert, covering the surrounding of Koucha Lake during the sedimentation of PAZ 1. In the calibration set, only two samples ('modern analogues') come from this vegetation type. Here, Chenopodiaceae pollen grains are most abundant in samples from the warm temperate desert. High percentages of Chenopodiaceae (and other desert taxa) and coniferous trees might thus have caused the overestimation of T_{July} in PAZ 1.

Although the application of the transfer function contains some limitations, we assume that the general climatic trends portrayed by the reconstruction are reasonable due to a number of strengths:

(i) The profile location is located within the calibration set area.
(ii) The reconstructed precipitation and temperature values are within the range of the calibration set climate data.
(iii) The calibration set samples and the profile pollen samples were prepared and analysed by the same laboratory, insuring high taxonomic consistency within the data set.

Koucha Lake vegetation and climate data in comparison to other records

The following major climatic and vegetation trends can be deduced from the Koucha Lake pollen records. The reconstruction of alpine desert-steppe vegetation indicates that the area was dominated by cold and dry climate conditions before ca. 14,600 cal yr BP. The climate became warmer and wetter and the area was covered by steppe vegetation between ca. 14,600 and 6600 cal yr BP. Alpine meadows, indicating wet and cold conditions, dominated the latter part of the Holocene.

Although the semi-arid northeastern Tibetan Plateau provides a large area with many lakes (most of them are situated in the Yellow River source area), no pollen records exist that cover the late glacial and/or Holocene. The nearest palaeovegetation records come from the wet and tree-covered eastern margin of the Tibetan Plateau (Nianbaoyeze Mountains: Yang, 1996; Schlütz, 1999; Zoige Basin: Yan et al., 1999) and from the comparatively warm Qinghai Lake area at an elevation of ~3200 m (Shen et al., 2005; Herzschuh et al., 2006a). The early late glacial vegetation of these regions is similar to the Koucha Lake area during that time. It is characterised by alpine deserts and dry-steppes with high percentages of Chenopodiaceae, *Artemisia*, other Asteraceae, and *Ephedra*. Between the Bølling/Allerød and the mid-Holocene, these areas were covered by coniferous or mixed forests (mainly *Abies*, *Picea*, *Pinus*, *Betula*). The Qinghai Lake record reveals a continuous reduction of forest since ca. 6000 cal yr BP (Shen et al., 2005). Forest decline is evident in many records from the eastern and southern Tibetan Plateau (Herzschuh et al., 2006a,b; Shen et al., 2006b). Whether this was caused by a moisture decrease or by anthropogenic impact is still debated (Ren and Beug, 2002). The present-day vegetation of these areas is significantly different from the Koucha Lake area and so is vegetational development.

Conditions similar to the northeastern Tibetan Plateau do exist on the central Tibetan Plateau, but there are only a few pollen records from that area. Lake Zigetang pollen records cover almost the complete Holocene (Herzschuh et al., 2006b). As in the Koucha Lake area, the vegetation changed from an *Artemisia*-dominated steppe to a *Kobresia*-dominated alpine meadow. This change (from $A/Cy > 1$ to $A/Cy < 1$, change from steppe to tundra in the biome reconstruction) occurred slightly later on the central Tibetan Plateau (Lake Zigetang at 4400 cal yr BP: Lake Koucha at 6600 cal yr BP), possibly because the central Tibetan Plateau is generally slightly warmer and drier. An early Holocene run for the Tibetan Plateau of the BIOME4 biogeochemistry–biogeography model by Song et al. (2005) yielded a vegetation pattern slightly different from these results. In their biome reconstruction, the area of alpine meadow was extended during the early Holocene while desert vegetation disappeared and steppe area shifted towards to the western Tibetan Plateau.

Both climate modelling results and proxy records (see reviews in Morrill et al., 2003; Wang et al., 2005; Feng et al., 2006; Herzschuh, 2006) reveal that the Asian monsoon intensified from the Bølling/Allerød to the early mid-Holocene, causing higher temperature and increased precipitation in southern and eastern Asia. Accordingly, several records from the Tibetan Plateau suggest temperatures above the present-day level during that time, for example the Guliya ice core oxygen isotope record from the western Tibetan Plateau (ca. 15,000–7000 cal yr BP; Thompson et al., 1997). Our reconstruction and two other pollen-based quantitative temperature reconstructions from two lakes on the southern Tibetan Plateau by Tang et al. (1999) confirm this general trend. The absolute difference between early stages of the mid-Holocene and present-day values is higher in these records than in Koucha Lake (Koucha Lake: ca. 1°C; Hidden Lake and Ren Co Lake: ca. 2–3°).

In addition to temperature, an intensified monsoon climate is characterised by increases in summer precipitation. Palaeoclimatic information from monsoonal Central Asia does not absolutely show this pattern. Reviews by Herzschuh (2006) and An et al. (2006) exposed significant regional differences. Wet climate conditions during the early Holocene can be deduced from most records from the eastern margin of the Tibetan Plateau and the Chinese Loess Plateau. (e.g., Zhou et al., 2002; Hong et al., 2003). Furthermore, several lakes from the central and western Tibetan Plateau experienced lake levels above present day conditions (e.g., Sumxi Co, Van Campo and Gasse, 1993; Seling Co, Kashiwaya et al., 1995; Bangong Co, Fontes et al., 1996; Zabuye Lake, Wang et al., 2002; Ahung Co, Morrill et al., 2006). In contrast, several records from deserts in the northern Tibetan foreland and the Qaidam Basin indicate comparatively dry conditions during the early-mid Holocene (e.g., Zhao et al., 2007). Herzschuh (2006) proposed that for arid areas of central Asia, effective moisture might have decreased during the first half of the Holocene when moisture loss due to evaporation (as a result of higher temperature) was not compensated for by higher precipitation levels. Today the Koucha Lake area is situated in a semi-arid area (Sun, 1999). This suggestion might explain why the vegetation around Koucha Lake indicates lower effective moisture between 14,600 and 6600 cal yr BP compared to present-day conditions. Further evidence for dry conditions during that time comes from the ostracod-based quantitative salinity reconstruction from the same sediment core of Koucha Lake presented in Mischke et al. (2008). Higher salinities pointing to low lake levels occurred during the time when steppe vegetation was dominant around the lake. However, the assumption of low effective moisture levels around Koucha Lake contradicts the findings of high lake levels during the early Holocene in arid areas of the western Tibetan Plateau mentioned above.

Conclusion

Our findings on quantitative and qualitative climatic and vegetation change from the northeastern Tibetan Plateau, based on a pollen record from Koucha Lake in the Bayan Har Mountains, yielded the following conclusions:

(i) Vegetation changed significantly at the beginning of the Bølling/Allerød interstadial and during the early part of the mid-Holocene, while the changes at the late glacial/Holocene boundary were comparatively minor.

(ii) The early Holocene around Koucha Lake was characterised by warmer and drier conditions than today. This is in contradiction to some other palaeoclimate records from monsoon-influenced Asia, where reconstructions of warmer and wetter climate conditions have been generated. Our findings may be a further indication for a strong regionalisation of palaeoclimate change on the Tibetan Plateau.

(iii) Late Holocene vegetation changed very little in Koucha Lake area and there is no strong evidence for any human impact in our pollen record.

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