Moisture-advection feedback supports strong early-to-mid Holocene monsoon climate on the eastern Tibetan Plateau as inferred from a pollen-based reconstruction

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Highlights

- pollen record from a temperature- and precipitation-sensitive site
- abrupt 3°C temperature increase/decrease at 10.4/5.0 cal kyr
- warm/wet early/mid Holocene related to moisture-advection feedback

Abstract

(Paleo-)climatologists are challenged to identify mechanisms that cause the observed abrupt Holocene monsoon events despite the fact that monsoonal circulation is assumed to be driven by gradual insolation changes. Here we provide proxy and model evidence to show that moisture-advection feedback can lead to a non-linear relationship between sea-surface and continental temperatures and monsoonal precipitation. A pollen record from Lake Ximencuo (Nianbaoyeze Mountains) indicates that vegetation from the eastern margin of the Tibetan Plateau was characterized by alpine deserts and glacial flora after the Last Glacial Maximum (LGM) (21–15.5 cal kyr BP), by alpine meadows during the Late Glacial (15.5–10.4 cal kyr BP) and second half of the Holocene (5.0 cal kyr BP to present) and by mixed forests during the first half of the Holocene (10.4-5.0 cal kyr BP). The application of pollen-based transfer functions yields an abrupt temperature increase at 10.4 cal kyr BP and a decrease at 5.0 cal kyr BP of about 3°C. By applying endmember modeling to grain-size data from the same sediment core we infer that frequent fluvial events (probably originating from high-magnitude precipitation events) were more common in the early and mid Holocene. We assign the inferred exceptional strong monsoonal circulation to the initiation of moisture-advection feedback, a result supported by a simple model that reproduces this feedback pattern over the same time period.

Keywords

moisture-advection feedback, monsoon, Tibetan Plateau, Holocene, Last Glacial Maximum, pollen-climate calibration

1. Introduction

Precipitation and temperature changes in monsoonal Asia are assumed to generally portray insolation changes on orbital time-scales (Prell & Kutzbach, 1992; Wang et al., 2008). With respect to the last deglacial and Holocene, three proxy-based findings contradict the assumption of a strict linear relationship between monsoonal strength and insolation. First, though proxy-record amalgamation curves (Herzschuh, 2006; Wang et al., 2010) indicate that the postglacial moisture rise depicts the general shape of the insolation curve, the moisture optimum lags the insolation optimum by several thousand years. Second, various studies indicate that temperature and moisture changes since the last glacial may not be in parallel. For example, a pollen record from the south-eastern Tibetan Plateau indicates that glacial deserts were replaced by wet high-cold meadows from about 15 cal kyr BP while thermophile forests only started to expand at the beginning of the Holocene (Kramer et al., 2010a). Third, the gradual transition of insolation is not suitable to explain the observed abrupt climatic changes recorded, for example, on the Tibetan Plateau (Mischke & Zhang, 2010).

Moisture change in monsoonal Asia during the Late Glacial has been found to correlate well with temperature change in the northern high-latitudes (Wang et al., 2001; Herzschuh, 2006) where the post-LGM warming trend was reversed by cold events originating from the fluctuation in the strength of the Atlantic Meridional Overturning Circulation (AMOC) (Shakun & Carlson, 2010). In contrast, low-latitude marine records show these cold reversals with much weaker amplitude and abruptness (Shakun & Carlson, 2010). Two alternative hypotheses that could explain the features of the AMOC events are preserved in remote Asian monsoon areas. First, AMOC events directly drive monsoonal circulation via hemispheric-wide teleconnection patterns such as the transition of the westerlies (Sun et al., 2012). Second, the temperature event in the North Atlantic region has, due to its remoteness, only minimal direct temperature effects but triggers a feedback mechanism in monsoonal Asia which in turn amplifies temperature and precipitation. The self-amplifying moisture-advection feedback introduced by Zickfeld et al. (2005), elaborated by Levermann et al. (2009) and applied to past monsoon transitions by Schewe et al. (2012) may be a candidate to cause non-linear behavior with respect to changes in the system´s energy budget. It is based on the idea that, regardless of the many other complex aspects of monsoon circulation, a fundamental dynamical feature, the so-called moisture-advection feedback, is required for monsoon rainfall to extend substantially into the continental interior throughout the summer season. An atmospheric temperature gradient between a relatively cool ocean area and a relatively warm continental atmosphere is necessary to drive the monsoon winds. In spring, at the onset of the summer monsoon, this gradient is established due to the differential heating of the land and ocean surfaces. However, during the monsoon rains, the land surface cools down again, and the atmospheric temperature gradient cannot be maintained through sensible heating from the ground, but only through latent heating from precipitation. The monsoon winds therefore carry their own "fuel" in the form of moisture which condenses over land and releases latent heat, reinforcing the temperature gradient and thus the monsoon winds. This self-amplifying feedback leads to a non-linear response of the monsoon strength to changes in the parameters that govern the availability of energy to the circulation.

One such parameter is the near-surface humidity over the ocean area that acts as the moisture source for the monsoon circulation. When it falls short of a critical value the moisture supply (and thus the latent heating) becomes insufficient to maintain a deep circulation, and an abrupt transition can occur from a conventional monsoon climate to a much drier summer climate.

Suitable records that provide quantitative estimates of both temperature and precipitation changes from the Asian interior, necessary to understand climate mechanisms better, are rare but are needed to avoid problems that arise from the correlation of independent chronologies. Here we present quantitative climate estimates from the application of pollen-climate transfer functions to a record from Lake Ximencuo on the eastern Tibetan Plateau. We consider this site to be sensitive to both temperature and precipitation change due to its location at the thermally dependent treeline and its intermediate position along the southeast–northwest moisture gradient on the eastern Tibetan Plateau. To minimize taphonomic effects on the reconstruction we applied a transfer function that was solely constructed on modern pollen records from lake surface-sediments. As pollen records reflect plant-relevant climate variables (a combination of air humidity, precipitation, evaporation, growing season length, etc.) rather than monsoon rain strength and air temperature, we verify the mean annual precipitation reconstruction with a fluvial input proxy and the mean annual temperature reconstruction with a temperature-dependent weathering proxy from the same core.

Specifically, we want (1) to extract the regional vegetation changes on the eastern Tibetan Plateau since the last glacial maximum, (2) to reconstruct mean annual temperature, annual precipitation and monsoon-rain events and (3) to examine the validity of existing conceptual models concerning non-linear monsoon behavior by a proxy-data set.

2. Regional setting

Lake Ximencuo is located in the Nianbaoyeze Mountains on the northeastern Tibetan Plateau in the administrative districts of Jiuzhi county (Qinghai Province) and Aba Tibetan Autonomous Prefecture (Sichuan Province) (Fig. 1). The mountains mainly consist of a granitic dome (Lehmkuhl & Liu, 1994) that rises from the surrounding plateau surface of ~4000 m a.s.l. to peaks that exceed 5000 m a.s.l. Only the main peak (Nianbaoyeze, 5369 m a.s.l) is presently covered by a small ice cap. The distribution of lateral and terminal moraines in the valleys radiate from the main summit. They have been found to indicate several Pleistocene glaciation phases and Holocene glacier highstands (Lehmkuhl & Liu, 1994; Lehmkuhl, 1995; Owen, 2003).

The climate on the eastern Tibetan Plateau is dominated by the Asian monsoon circulation characterized by warm and wet summers and cold and dry winters. About 80% of precipitation falls between May and October. Lehmkuhl (1995) collected information from regional climate stations in Jiuzhi (located ~40 km northeast of Lake Ximencuo at 3629 m a.s.l.) and Aba (~60 km southeast at 3277 m a.s.l.). Mean annual temperature at these stations is 0.1°C and 3.3°C, and annual precipitation reaches 765 mm and 711 mm, respectively. According to the station-based climate model of Böhner et al. (2006), mean annual temperature at 4000 m a.s.l. is -1.6°C and annual precipitation in the Nianbaoyeze Mountains decreases from south (~1000 mm/year) to north (~600 mm/year) and increases with elevation.

No detailed investigation of the vegetation in the Nianbaoyeze Mountains is available. Information on vegetation composition and distribution on the eastern margin of the Tibetan Plateau is given in Huang (1987), Hou (2001), Kürschner et al. (2005) and Wang et al., (2006). The Nianbaoyeze Mountains are situated at the northwestern and upper limit of coniferous forests of the eastern Tibetan Plateau. The nearest closed montane forests, mostly composed of *Picea* (*P. purpurea*, *P. likiangensis* var.

balfouriana, *P. asperata)* and *Abies* (e.g. *A. faxoniana)*, intermixed with a few broadleaf elements such as *Betula,* are distributed to the south and east of the Nianbaoyeze Mountains at elevations between 2500 and ~4000 m, about 40 km away from Lake Ximencuo. In the Nianbaoyeze Mountains themselves, only very few trees are presently found. A few relict stands of *Picea purpurea* occur on the wet northern slopes in the Lake Magencuo valley up to 4250 m (Lehmkuhl, 1995), about 10 km away from Lake Ximencuo. Some tree-like and shrubby *Juniperus* are found on southern slopes. Shrubby vegetation composed of *Artemisia, Sibiraea, Spiraea, Lonicera*, *Salix*, *Rhododendron, Potentilla* and *Caragana* grow well on shady northern slopes up to 4400 m. High-alpine meadows are widely distributed covering a wide elevation range from 3500 to 4500 m a.s.l., and are mainly composed of *Kobresia*, *Polygonum* and Poaceae. The diversity of alpine meadows on the eastern Tibetan Plateau decreases with increasing elevation (Wang et al., 2006) which often leads to a strong dominance of *Kobresia pygmaea* at higher elevations*.* Sparse alpine vegetation covers the mountain debris slopes composed of several species of the genera *Saussurea*, *Saxifraga*, *Aconitum*, *Androsace,* and of the families Caryophyllaceae, Fabaceae and Cyperaceae.

The valleys in the Nianbaoyeze Mountains are traditional settlement areas of Tibetan nomads (Ryavec, 1999). Herders have practiced a ‘semi-nomadic’ lifestyle since the mid-1990s: from May to September they live in traditional Tibetan black tents in the mountains close to the summer pastures (up to 4500 m a.s.l.). From autumn to spring, they live in permanent houses in the valleys (around 3700 m a.s.l.) with fenced winter pastures. The herds in this region are mainly composed of yak (63%), sheep (31%) and some horses (6%) (Miller, 1999).

Lake Ximencuo lies at the northern margin of the Nianbaoyeze Mountains at 4030 m a.s.l. (Fig. 1). It has an open water area of 3.6 km^2 and a small catchment area of ~50 km^2 (Zhang & Mischke, 2009). The lake fills a deep (maximum lake depth: 63 m), glacially-eroded basin surrounded by prominent moraines to the north. The moraines in the immediate vicinity of the northern half of Lake Ximencuo have been dated to 20.2 ka BP whereas granitic boulders near the southern margin of the lake were exposed by 16.5 ka BP (Owen et al., 2003), corresponding with a multiproxy-based interpretation of the lake record (Zhang & Mischke, 2009).

3. Material and methods

3.1 Sediment core and chronology

In February 2004, a core of 12.81 m length was obtained from the center of Lake Ximencuo (33.3792°N/101.1035°E; 4000 m a.s.l.) at a water depth of 56.2 m using an UWITEC piston corer. Sediment properties including grain-size analysis, X-ray florescence spectroscopy, magnetic susceptibility and total organic and inorganic carbon yielded three main sediment units (Zhang & Mischke, 2009). The lower part of the core (1281–710 cm) is characterized by high minerogenic content. Intermediate minerogenic and organic contents characterize the middle part of the core (710–350 cm), and the upper part of the core (350–0 cm) is characterized by high organic content particularly between 350–171 cm.

Radiocarbon dating of 18 stratigraphic levels was performed on bulk organic matter due to the lack of any macroscopic remains. The alkali soluble and insoluble fractions were dated separately, though not for all horizons for the former. Within dating errors, the alkali insoluble and alkali soluble fraction yielded similar results for the Holocene, however, the ages of the alkali soluble fraction were significantly older than the ages of the insoluble fraction for the period before, a result also known from other sites of comparable lake sediments from the Tibetan Plateau (Kramer et al., 2010a). The radiocarbon age of 869 ^{14}C years BP for the core-top sample was regarded as a 'lake reservoir effect' (see reasoning in Zhang & Mischke, 2009) and subtracted from all other ^{14}C ages. Relevant information on all radiocarbon dates are presented in Zhang & Mischke (2009) and Mischke & Zhang (2010). For this study the age-depth model (Fig. 2) was newly constructed using the Bacon package (Blaauw & Christen, 2011) in R software (R Core Team, 2012) including all dated horizons (using the alkali soluble fraction for the lower part of the core and the alkali insoluble fraction for the upper part). We *a priori* assumed an accumulation shape of 2, a mean accumulation rate of 100 yr/cm, memory strength of 20 and step-rate of 20 cm. Due to the obvious glacier-related high sediment flux, a sedimentation rate of 10 yr/cm was assumed for the core part below 450 cm.

3.2 Pollen data

Pollen analyses were performed on 109 core samples. Processing of pollen samples (2 ml of sediment) 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. At least 300 terrestrial pollen grains were counted, except for some samples accumulated prior to 15 cal kyr BP when pollen content relative to the non-soluble minerogenic remains was extremely low. Pollen identifications are based on the relevant literature (Moore et al., 1991; Wang et al., 1997; Beug, 2004) and on a type slide collection of more than 600 plant species from western China. The total pollen sum of arboreal and terrestrial non-arboreal taxa identified in each pollen spectrum is taken as 100% for the calculation of the pollen percentages. Non-pollen palynomorphs were counted from the pollen slides and their abundances are expressed relative to the terrestrial pollen sum. Identification of non-pollen palynomorphs is based on Kramer et al. (2010b). Only pollen taxa which occur in at least five core samples are included in the numerical analyses and in the construction of the pollen diagram.

3.3 Pollen-based ordination, clustering and climate reconstruction

Pollen zonation was based on the results of depth constrained clustering (Birks & Gordon, 1985) using squared chord distance as a dissimilarity measure and the broken-stick model for the identification of the zone number (Bennett, 1996) implemented in the rioja package (Juggins, 2009) for R. Pollen percentages were square-root transformed prior to further computations. Ordinations were performed to identify the major groupings in pollen samples and to portray relationships among pollen taxa. A preliminary detrended correspondence analysis yielded a gradient length of 1.5 standard deviation units, indicating that numerical methods based on linear response models are appropriate with our dataset. Accordingly, a principal component analysis (PCA) was performed (setup: focusing on species correlation, centering of species data). Ordinations were implemented using CANOCO software, version 4.5 (ter Braak & Šmilauer, 2002).

To quantify annual precipitation (P_{ann}) and annual temperature (T_{ann}), we applied a pollen-precipitation transfer function (based on 55 pollen taxa) to the fossil pollen spectra. For that purpose the original lake sediment-based transfer function presented in Herzschuh et al. (2010a) was extended by the lake surface-sediment pollen spectra from the southeastern Tibetan Plateau presented in Kramer et al. (2010c) and from the Qaidam Basin presented in Zhao & Herzschuh (2008). Samples from sites below 3000 m a.s.l. on the southeastern plateau were excluded from the dataset due to intensive anthropogenic disturbance of the vegetation. Finally, our modern pollen-climate calibration dataset is based on 132 lake surface-sediments from the southern, eastern and northeastern Tibetan Plateau covering a wide range for P_{ann} (31–1780 mm) and T_{ann}.(-6.52–5.00°C). Pollen-climate transfer functions were derived using weighted-averaging partial least squares (WA-PLS) (ter Braak & Juggins, 1993). Model performance was assessed by leave-one-out crossvalidation (Birks, 1998). A two-component WA-PLS model for P_{ann} and a three-component WA-PLS model for T_{ann} were chosen to be the most parsimonious models on the basis of model performance statistics (Birks, 1998). Root mean square error of prediction (RMSEP) is 108 mm for P_{ann} and 1.56°C for T_{ann}, and the coefficient of determination (r^2) is 0.92 and 0.64 between observed and model-predicted values. RMSEP, when expressed as a percentage of the climate variable gradient, is 6.2% and 13.5% for P_{ann} and T_{ann}, respectively, illustrating the good performance of the models. The tree pollen content of the lower part of the core (before 15 cal kyr BP) is interpreted as originating from far distances (similar to near-by Lake Nalengcuo; Kramer et al, 2010a), which reaches high values at times of low regional pollen productivity. For that reason, models without tree taxa were applied to these samples (P_{ann}-no tree model 1st component: RMSEP of 133 mm and r^2 of 0.87; T_{ann}-no tree model 2nd component: RMSEP of 1.61°C and r^2 of 0.63).

3.4 Grain-size data and endmember modeling

Grain-size analysis was performed at 8-cm intervals between the core base and 6.1 m core depth, at 4-cm intervals between 6.1 and 4.1 m, and at 2-cm intervals above 4.1 m. A Malvern Mastersizer 2000 laser granulometer was used (size range: 0.02–2000 µm). Sample pretreatment included (1) adding H_2O_2 to remove organic matter and soluble salts, (2) using diluted 1 M HCl to remove carbonate, and (3) using Na-hexametaphosphate to disperse aggregates. General parameters obtained from grain-size analyses (skewness, mean, kurtosis, sorting, grain-size fraction for sand, silt and clay) are presented in Zhang & Mischke (2009). Here we present the reanalyses of these grain-size data using the End-Member Modeling Algorithm (EMMA) developed by Weltje (1997). This was applied in order to identify robust end-members (EMs) and estimate their proportional contribution to the sediments. To avoid a fixed single outcome and extract reliable robust EM(s), models were run considering different numbers of end-members (between the minimum and maximum numbers of potential EMs) and flexible weight transformations. The minimum number of potential EMs was determined by the cumulative explained variance reaching at least 95%; the maximum number of EMs was determined by the maximum value of the mean coefficient of determination. We tested the robustness of the EMs and then extracted the final robust EM(s) and residual member(s). All these computations were made using MATLAB software. A detailed description of the EMMA method applied can be found in Dietze et al. (2012).

3.5 Modeling approach

We construct a simple conceptual model of the summer monsoon circulation (Levermann et al., 2009; Schewe et al., 2012) in which a characteristic relation between monsoon precipitation and humidity over the ocean follows from the self-amplifying moisture-advection feedback: below the critical threshold precipitation is zero; above the threshold, precipitation increases with humidity over the ocean the functional form becoming approximately linear at some distance from the threshold. In order to obtain quantitative results, a number of parameters has to be known: the slopes of the relations between (a) monsoon winds and atmospheric temperature gradient and (b) precipitation and the terrestrial atmospheric humidity; and (c) the threshold. Here, we merely intend to demonstrate that the timing and abruptness of the transitions into and out of a strong monsoon phase in the first half of the Holocene can be reproduced with this model. Quantitative rainfall estimates for the study period would require more data and are beyond the scope of this study. Therefore, we set parameters (a) and (b) to values estimated previously for the East Asian region on the basis of reanalysis data (Schewe et al., 2012). The humidity threshold is assumed to correspond to a sea-surface temperature (SST) threshold, which is deliberately chosen to be at 26.35°C. The Mg/Ca-inferred SST time-series reported by Rashid et al. (2011) for the Bay of Bengal, which is likely to have been a major source of moisture for our study region, is then translated by the conceptual model into a monsoon rainfall time-series.

4. Results

4.1 Vegetation changes at Lake Ximencuo

Overall, the non-arboreal taxa Cyperaceae, Poaceae, *Artemisia* and Chenopodiaceae and the arboreal taxa *Betula*, *Picea* and *Pinus* are the most abundant taxa in the fossil pollen spectra from Lake Ximencuo, summing up to >85% in most samples (Fig. 3). The first two PCA axes capture 45.8% (axis 1: 30.2%, axis 2: 15.6%) of the total variance in the data. The correlation biplot of the first two axes (Fig. 4) separates samples characterized by elements of sparse alpine vegetation and alpine deserts at the positive end of the first axis and those with high values for shrubs and meadow-elements at the negative end. The second axis separates samples dominated by Cyperaceae and Poaceae from those rich in tree pollen and *Artemisia*. In accordance with the results from depth-constrained cluster analyses and from the broken-stick model the pollen diagram can be separated into five pollen assemblage zones (PAZ).

PAZ 1 (12.74–6.30m; 20.9–15.3 cal kyr BP) is characterized by high values of Chenopodiaceae, Caryophyllaceae, Brassicaceae, *Aster*-type, *Anthemis*-type, *Saussurea*-type, Papaveraceae and *Hippophaë* as well as by high values of tree taxa such as *Pinus*, *Picea* and *Betula* summing up to 10–20%. A decrease of tree taxa and a rise of Cyperaceae to mostly >45% mark the transition to PAZ 2 (6.30–4.78m; 15.3–13.8 cal kyr BP). The transition to PAZ 3 represents the strongest turnover in the pollen assemblage. In contrast to previous zones, PAZ 3 (4.78–3.64m; 13.8–10.4 cal kyr BP) has comparatively low percentages of desertic and glacial elements as well as a low tree pollen fraction. It is characterized by meadow and shrubland taxa such as Poaceae, *Thalictrum* and *Salix* and has in comparison to the other zones intermediate values for Cyperaceae and *Artemisia*. The steep rise of tree taxa particularly of *Betula* marks the transition to PAZ 4 (3.64–2.65m; 10.4–5.0 cal kyr BP) which, aside from a high arboreal pollen portion, is characterized by the highest *Artemisia* and lowest Cyperaceae values of the whole record. PAZ 5 (2.65–0 m; 5.0–0 cal kyr BP) displays again higher values for typical meadow taxa such as Poaceae and *Thalictrum*, lower *Artemisia* and tree values and higher Cyperaceae values than in PAZ 4. While the samples of PAZ 1 and PAZ 3 are loosely scattered in the lower right and upper central part of the PCA plot, PAZ 2 and particularly PAZ 4 and PAZ 5 form well-defined clouds in the upper right, lower left and upper left quadrant, respectively.

Glomus, a fungal spore, is present in several samples from the lower part of the core (before 14.5 cal kyr BP) and in a few late Holocene samples. *Botryococcus* and *Pediastrum* are absent in PAZ 1, have low values in PAZ 2 and have high values in PAZs 3, 4 and 5. The highest values are recorded after about 7.0 cal kyr BP, which however, may originate from changes in the pollen influx rather than from changes in algae productivity. Volvocaceae are present during the last 6.5 cal kyr and show highest values during the last 2.4 cal kyr.

4.2 Pollen-based quantitative climate reconstructions

The total reconstructed range is between 316 and 883 mm for P_{ann} and 0.90 and -4.57°C for T_{ann}, which is covered by the modern climate range of pollen analogues (Fig. 5). Transfer function-based reconstructions for the upper part of the core of 759 mm for P_{ann} and -1.80°C for T_{ann} (mean of the upper two samples) resemble well the climate station-based values of 791 mm and -1.62°C, indicating the general applicability of the transfer function to this record.

Reconstructed mean annual temperature is mostly below -3°C during the Late Glacial with slightly higher values between 14.7 and 12.6 cal kyr BP. A sharp increase of about 3.5°C occurs during the earliest part of the Holocene and the thermal optimum lasts until ~5 cal kyr BP when temperature suddenly drops by about 2.5° towards an overall Holocene minimum around 4 cal kyr BP.

Reconstructed annual precipitation is low for the lower part of the core, mostly less than 500 mm, even below 400 mm for most samples from the period 17.8 and 15.1 cal kyr BP. Reconstructed precipitation is above average between 15.3 and 6 cal kyr (mostly >800 mm), with strong increases occurring around 14 cal kyr BP and 10.5 cal kyr BP. Around 4 cal kyr BP reconstructed precipitation shows a Holocene minimum. It ranges around 700 mm for the late Holocene part of the core.

4.3 Grain-size endmembers and their changes through time

The grain-size spectra are dominated by the silt fractions (62.1–81.9%), with the clay (13.4–25.8%) and sand (0–24.0%) fractions only accounting for a small part of the total. We obtained three robust and one residual endmember when running the models with different weight transformations (the percentile range of P_1-P_{99}, P_2-P_{98}, P_3-P_{97}, P_4-P_{96}) and EMs from 5 and 6 endmembers (Fig. 6). The robust endmember 1 is dominated by a clay fraction peaking at 2 µm. It constitutes a high portion throughout (Fig. 7) and it dominates during the lower part of the record between 21.0 and 15.3 cal yr BP. Robust endmember 2 has a bimodal frequency distribution peaking at 16 µm and 125 µm. This endmember is almost absent from the lower part of the record until 15.3 cal kyr BP, it sporadically appears between 15.3 and 13.8 cal kyr BP and obtains its highest portion during the early-to-mid Holocene. Robust endmember 3 is unimodal and dominated by silt-size grains with a peak at 62 μm; it dominates the spectrum between 15.3 and 6.0 cal kyr BP. The residual member is high in the upper part of the core. Robustness analyses yielded a mean value of r^2=0.68±0.22 for grain-size scale and r^2=0.86±0.09 for ages.

4.4 Modeling results

The translation of the SST record of Rashid et al. (2011) into monsoon strength according to the simple conceptual model of the summer monsoon circulation (Schewe et al., 2012) exhibits an abrupt increase around 11 cal kyr BP and an abrupt decrease around 5 cal kyr BP (Fig. 5).

5. Discussion

5.1 Vegetation changes at Lake Ximencuo in comparison to other Tibetan records

The pollen record from Lake Ximencuo indicates that a dry glacial flora dominated the post-LGM vegetation which is in agreement with other records from the eastern Tibetan Plateau (e.g. Herzschuh et al., 2009, Kramer et al., 2010a). However, in comparison to other sites the amount of ruderal indicators and cushion plants such as Papaveraceae, Chenopodiaceae, Brassicaceae, *Saussurea*-type and Caryophyllaceae is particularly high at Lake Ximencuo. This indicates that fresh glacier-free soils dominated in the direct vicinity of the lake which fits with the finding that the glacier extended to the southern lake shore until about 16.5 ka (Owen et al., 2003; Zhang & Mischke, 2009).

We did not observe differences in the pollen grain preservation that would indicate the input of reworked pre-LGM material. Accordingly, we interpret the high amount of *Pinus*, *Picea* and *Quercus* as an extra-regional signal. This is in agreement with modern pollen deposition studies where sparse vegetation cover has been shown to cause a high reflection of long-distance transported pollen grains (Herzschuh, 2007). Our interpretation also fits with the finding that boreal forests survived at lower elevations in the Yunnan-part of the Tibetan Plateau throughout the glacial as revealed by high *Pinus* pollen values in Shudu Lake sediments (Cook et al., 2011).

Starting at about 15.5 cal kyr BP, the dry glacial flora is replaced by Cyperaceae-rich high-alpine meadow (probably dominated by *Kobresia,* analogous to modern vegetation) which turned into alpine meadow and shrubland roughly similar to the modern vegetation by about 14 ka. The composition and timing of these Late Glacial vegetation changes are in agreement with reconstructions based on the Naleng Lake pollen record (Kramer et al., 2010a), a glacial lake that is likewise located at the present-day treeline indicating that the Lake Ximencuo pollen record reflects typical regional signals. The re-expansion of ruderal taxa, particularly of Chenopodiaceae, between 12.5 and 11 cal kyr BP is, within dating errors, synchronous with the Younger Dryas event.

Starting at about 11 cal kyr BP , *Betula*-rich *Picea/Pinus* forest became established in the Nianbaoyeze Mountains and dominated the area until about 5.0 cal kyr BP without major vegetation changes. The expansion of boreal forests beyond their present-day western and northern limit during the early and mid Holocene is a phenomenon seen in most records from the eastern Tibetan Plateau margin (Herzschuh et al., 2010b; Zhao et al., 2011). In contrast to the Lake Naleng area (Kramer et al., 2010c), where alpine meadows re-occur between 8 and 7 cal kyr BP, only a minimal glacial flora re-expansion may have occurred at Lake Ximencuo as suggested by a slight increase in the Papaveraceae record.

The mixture of alpine meadows and shrublands broadly similar to modern conditions became established in the surroundings of Lake Ximencuo by about 4.8 cal kyr BP. However, secondary vegetation (indicated by higher *Potentilla*-type and *Quercus* values) reflecting human impact expanded from about 3 cal kyr BP onwards, similar to findings from the Naleng Lake record (Kramer et al., 2010c).

5.2 Pollen-based quantitative climate estimates and comparison to other records

Pollen-based climate reconstructions may be biased if human activities and CO_2 changes markedly affected the past vegetation composition. Hitherto archeological or paleoecological evidence that humans—although present since at least the mid Holocene (Altenderfer et al., 2006)—altered the vegetation beyond a local scale is lacking. This is obvious when comparing a Holocene low-resolution peat pollen record from the Ximencuo valley (Schlütz et al., 2009) to our pollen record from Lake Ximencuo which reveals that both records differ particularly in the abundance and trends of herbaceous plants. While local human impact is traceable by grazing indicators at the site of the peat record since 6 cal kyr BP, on a regional scale the abundance of these indicators during the Holocene does not vary in the lake pollen record with its much larger pollen source area. Accordingly, we assign the mid-Holocene decline of tree pollen largely to climate, as this feature is consistent with records of forest decrease from all over Inner Asia (Zhao & Yu, 2012). This supports the suitability of the record for quantitative climate reconstruction purposes. Nevertheless, the pollen-based reconstruction may underestimate Late Glacial and early Holocene precipitation as dryland vegetation is favored in times of low CO_2 particularly at high elevations (Herzschuh et al., 2011). Furthermore, long-term processes such as soil development in the direct vicinity of the lake may have caused vegetation-climate disequilibrium and thus reduce the quality of the climate reconstruction, while time-lags related to small migration rates are probably irrelevant in the mountainous terrain of eastern Tibet.

Quantitative climate estimates from Lake Ximencuo can be compared to other pollen-based reconstructions from the Tibetan Plateau, although it needs be taken into account that they have been derived using different reconstruction methods and/or modern calibration sets based on various sedimentary origins.

Available reconstructions from the Tibetan Plateau (Koucha Lake, Herzschuh et al., 2009; Luanhaizi, Herzschuh et al., 2010a; Kuhai Lake, Wischnewski et al., 2011; Donggi Cona, Wang et al., 2013) show, like those from Lake Ximencuo, ~50% of the present-day precipitation value for the pre-14 cal kyr BP Late Glacial period. In particular, those records from the northeastern Tibetan Plateau (Herzschuh et al., 2009, Wischnewski et al., 2011) indicate that a major increase in precipitation occurred at about 15 cal kyr BP while at Lake Ximencuo a two-step increase towards Holocene levels occurred (i.e. likewise about 15 cal kyr BP and at the beginning of the Holocene). All available records from the southern or eastern humid plateau margins (Tang et al., 1999; Lu et al., 2011, Herzschuh et al., 2010a) indicate that the early-to-mid Holocene was the wettest period of the entire post-LGM phase. However, absolute values and values relative to modern conditions vary markedly among these sites. At all these sites (but not Chen Co) a slightly wetter mid Holocene than early Holocene is recorded and all sites show a gradual reduction of reconstructed precipitation from about 6 cal kyr BP. However, the Lake Ximencuo precipitation pattern differs from those obtained from the arid upper northeastern Tibetan Plateau where the early Holocene seems to be slightly drier than present-day conditions (Herzschuh et al., 2009, Wischnewksi et al., 2011) as suggested by a relatively high *Artemisia* component. An early Holocene high *Artemisia* component is also visible in the Lake Ximencuo record: it is the cause of the early lower than mid-Holocene reconstructed precipitation. Whether this is a true reflection of the regional vegetation around Lake Ximencuo lake or rather reflects the vegetation changes on the upper northeastern Tibetan Plateau (and thus biases the quantitative precipitation estimates) is impossible to discern.

Non-pollen quantitative temperature records of similar length and resolution to the Lake Ximencuo record that could be used for evaluation of the obtained T_{ann} reconstructions are lacking for the Tibetan Plateau. Some pollen-based reconstructions such as those from the northeastern and central Tibetan Plateau (Herzschuh et al., 2009, Lu et al., 2011) are questionable as they are not located at a temperature sensitive position and the vegetation at these sites seems to be controlled by moisture only. However, mean annual temperature reconstructions from Lake Hidden (Tang et al., 1999) and Lake Luanhaizi (Herzschuh et al., 2006) that originate from a similar ecoclimatic position to that of Lake Ximencuo may be useful for evaluations. Both show generally similar trends and quantities of change. For example, transfer function-based results from Lake Hidden show a ~4°C difference between pre-15 cal kyr BP and the Holocene optimum and, at both sites, the strongest increase of >3°C occurred at the beginning of the Holocene at about 10.0 cal kyr BP.

The reliability of the inferred temperature trends from Lake Ximencuo pollen record is furthermore supported by its correlation to the Y/Al element ratios (Fig. 5), which probably reflect the weathering (i.e. enrichment of Y a resistant mineral relative to Al) in the catchment of Lake Ximencuo that is assumed to be high during warm phases (Zhang & Mischke, 2009).

5.3 Fluvial erosion and the tracing of heavy monsoon events

Basin morphology and the lack of ancient lake shorelines indicate that Lake Ximencuo most probably obtained a stable high lake level throughout its evolution since the LGM. Accordingly, grain-size distribution may reflect changes in the sediment input to the lake rather than distance changes between the coring position and the shoreline or river mouth to the lake. Clay-dominated EM1 most probably reflects the glacier input to the lake. EM3 shows a grain-size distribution typical for Chinese loess (An et al., 2012) and hence may reflect aerial input. This interpretation is in temporal accordance with other records from western China that find a high aolian input during the Younger Dryas (e.g. Guan et al., 2009; Liu et al., 2013). The 'residual' member might reflect a mixture of autochthonal productivity (e.g. of diatoms) and of continuous sediment supply from streams. We interpret EM2 as tracking erosion peaks related to heavy monsoon rain events that caused the transport of relatively coarse-grained sediments to the lake center, accompanied by in-washed sediments of smaller grain size even though other events such as earthquakes may have produced a similar signal (Wang et al., 2014). This record is in temporal accordance with an anoxygenic phototrophic bacteria record from Qinghai Lake (Ji et al., 2009, Fig. 5) that likewise is assumed to trace freshwater inputs in relation to heavy monsoon rain events. We therefore infer that heavy monsoon rains were lacking before 15.3 ka, were infrequent between 15.3-10 ka BP, peaked during the early and mid Holocene and decreased after 4 ka.

5.4 The moisture-advection feedback as main climate driver

The pollen-based quantitative climate reconstruction supports earlier findings that postglacial monsoonal development on the Tibetan Plateau is not a simple reflection of insolation changes. First, the postglacial temperature and precipitation optimum phase occurred during the early and early mid-Holocene, which is several thousand years after the insolation optimum as reported by several studies (Wang et al., 2011). Second, the precipitation and temperature reconstructions are not entirely in parallel at Lake Ximencuo, as would be expected for a monsoon climate directly forced by insolation. While the major increase in precipitation occurred at ~15 cal kyr BP the major temperature increase occurred at the beginning of Holocene. This supports previous qualitative climate inferences from pollen records obtained from lakes at similar bioclimatic positions on the Tibetan Plateau (e.g. Naleng Lake, Kramer et al. 2010a) and is in agreement with the finding that the major vegetation change in arid areas of the Tibetan Plateau occurred at ~15 cal kyr BP rather than at the beginning of the Holocene (Wischnewski et al., 2011). Third, vegetation change and thus inferred climate change at Lake Ximencuo is characterized by rapid transitions (as has been reported from other Tibetan records, Mischke & Zhang, 2010), which is in contrast to the smooth changes of insolation. As inferred from the Lake Ximencuo pollen record, temperature rapidly increases at the beginning of the Holocene and decreases at about 5 cal kyr BP.

In our view the observed differences between climate change on the eastern Tibetan Plateau and the insolation signal can be best explained by taking the moisture-advection feedback into account when explaining postglacial climate development. While the differential heating of land and ocean in spring is important for the initiation of the monsoon, its continuation over the entire summer until September or October is only possible with the release of latent heat associated with rainfall over the continents, which reinforces the monsoon winds (Levermann et al., 2009). According to a conceptual model of the monsoon season, this feedback leads to a non-linear response of the monsoon strength to changes in boundary conditions. In particular, a conventional large-scale monsoon circulation can only exist if atmospheric specific humidity over the ocean (which is closely related to SST) is above a specific threshold value (Schewe et al., 2012). Below the threshold, the advection and release of latent heat are insufficient to sustain monsoon rainfall over land. We hypothesize that this threshold was passed in most years between 10.4 and 5.0 cal kyr BP and the moisture-advection feedback enabled a powerful South Asian summer monsoon that extended far into the continental interior and led to marked latent heat release and heavy precipitation events throughout the entire summer in the study region. This hypothesis is consistent with the expansion of thermophile plant taxa, the frequent occurrence of fluvial erosion events, and, compared to today, an increased weathering rate in the catchment of Lake Ximencuo as inferred by this study. In contrast, we argue that the moisture-advection feedback was not or only rarely active during the Late Glacial and the second part of the Holocene, due to low sea-surface temperatures and low humidity over the ocean. A threshold behavior would also explain the observed ~1200-yr time-lag between the end of the Younger Dryas in high northern latitude records (Hoek, 2008) and the major temperature increase at Lake Ximencuo in the monsoonal realm (this study), although dating uncertainty may also have contributed to the temporal mismatch. Our inference about the importance of the moisture-advection feedback for Inner Asian climate is supported by the results obtained from driving the conceptual model with Mg/Ca-inferred SST from the Bay of Bengal (Rashid et al., 2011; Fig. 5). This experiment shows that our hypothesis is consistent with the reconstructed changes in sea-surface temperatures in the relevant ocean region, which gradually increased after the LGM and reached a maximum between approximately 10 and 5 cal kyr BP. The threshold behavior introduced by the self-amplifying moisture-advection feedback and captured in the conceptual model leads to a rapid change in monsoon strength in response to such gradual changes in boundary conditions.

At the same time, we found that total precipitation changes, as inferred from the pollen record, were much less abrupt than temperature change, and moisture was available in the eastern Tibetan Plateau both before and after this period of strong monsoon. Here it is important to note that the temperature signal recorded in the pollen abundance might directly reflect summer temperature, i.e. growing season temperature, which is particularly relevant for vegetation, whereas, the precipitation signal might integrate moisture availability over different times of the year and from other sources than monsoon precipitation (e.g. continental moisture recycling and supply from the westerlies). This difference could explain why abrupt changes in monsoon strength may be better reflected in the temperature signal.

6. Conclusion

The pollen-based reconstruction of climate changes on the eastern margin of the Tibetan Plateau since the end of the LGM reveals an abrupt and strong (~3°C) temperature increase at about 10.4 cal kyr BP and a strong decrease at 5.0 cal kyr BP. Reconstructed precipitation is highest during the first half of the Holocene, although precipitation markedly increases already by ~15 cal kyr BP and changes are generally more gradual than for temperature. The reconstruction of fluvial events from the Ximencuo record, as well as proxy-evidence from Qinghai Lake, indicate that the first half of the Holocene is not only characterized by exceptionally warm conditions but also by the frequent occurrence of strong precipitation events. The application of a simple conceptual model depicting the inland moisture transport demonstrates that a moisture-advection feedback is initiated during this time period, which may have led to the observed non-linear relationship between SST in the nearby sea areas and warmth and monsoonal precipitation in the Asian interior. Our study provides proxy evidence that the moisture-advection feedback is capable of both translating gradual insolation changes into a stepwise monsoon activity pattern and of amplifying minimal changes in tropical SST such as those originating from remote climatic events (e.g. the AMOC shut down) into a monsoon signal of large amplitude on nearby continents.

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Figures and figure captions

Fig.1 Study area of the Nianbaoyeze Mountains, showing the location of Lake Ximencuo and sites mentioned in the text. Detailed map after Lehmkuhl (1995) and Wischnewski et al. (2013).

Fig. 2 Recalculation of the age-depth model for Lake Ximencuo using the bacon procedure of Blaauw & Christen (2011) on ^{14}C dating results published in Zhang & Mischke (2009) and Mischke & Zhang (2010).

Fig. 3 Pollen diagram from Lake Ximencuo sediment core. Unshaded polygons trace the 10x magnifications.

Fig. 4 Biplot of axes 1 and 2 of a Principal Component Analyses performed on the pollen data from Lake Ximencuo.

Fig. 5 Climate change (pollen-based T_{ann} and P_{ann} reconstructions from Lake Ximencuo, this study; Y/Al element ratio from Lake Ximencuo, Zhang & Mischke, 2009) and the occurrence of heavy monsoon events on the eastern Tibetan Plateau (grain-size EM1, this study; bacteria blooms in Qinghai Lake, Ji et al., 2009) compared to the inland monsoonal precipitation estimates (arbitrary scale, this study) from driving a minimal conceptual model on the moisture-advection feedback (Levermann et al., 2009, Schewe et al., 2012) by sea-surface temperatures from the Bay of Bengal (Rashid et al. 2011). Exceptionally high temperatures at Lake Ximencuo and the indication of high-magnitude monsoon events coincide with—and are probably causally related to—the inferred initiation of the moisture-advection feedback in monsoonal Asia.

Fig. 6 Loadings of grain-size based endmember modeling of Lake Ximencuo sediment core. The extracted three endmembers are assumed to represent unmixed grain-size distributions contributed from different sources to the lake basin i.e. EM1 –

glaciofluvial input, EM2 – fluvial erosion during strong precipitation events, EM 3 – aerial input, residual member – mixed-sources.

Fig. 7 Variation in the contribution of the three endmembers and the residual member to the lake's minerogenic content throughout the sedimentation of the Lake Ximencuo record. According to our interpretation, EM1 represents the glaciofluvial input, EM2 the fluvial erosion during strong precipitation events, EM 3 the aerial input and the residual member originates from mixed-sources.