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An improved methodology of the modern analogues technique for palaeoclimate reconstruction in arid and semi-arid regions

WENYING JIANG, JOËL GUIOT, GUOQIANG CHU, HAIBIN WU, BAOYIN YUAN, CHRISTINE HATTÉ AND ZHENGTANG GUO

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This study presents an improved method of the plant functional type modern analogues technique (PFT-MAT) in which environmental proxies and a moisture index (α, i.e. ratio of actual evapotranspiration to potential evapotranspiration) are used to constrain the selection of modern analogues. The method is tested using high-resolution, precisely dated palaeorecords (pollen, *Pediastrum* and $\delta^{18}O$ of authigenic carbonate) from Lake Bayanchagan, northern China. The unconstrained and constrained PFT-MAT produces general agreement for Holocene climate changes, with a wet period between 11 000 and 5500 cal. yr BP and a warm interval between 11 000 and 8000 cal. yr BP. However, there are significant differences in the details of their reconstruction. The constrained PFT-MAT generally yields smaller error bars for the reconstructed climate parameters than the unconstrained PFT-MAT. In addition, three prominent climatic events are identified from the constrained reconstructions; namely, a cold event around 8400 cal. yr BP and two warm events around 6000 and 2000 cal. yr BP, which is consistent with other regional palaeoclimatic records. Our data show that changes in tree components correlate well with α variations during the entire Holocene, with the highest tree components and highest α values between 8000 and 5500 cal. yr BP, indicating the dominant role of α in the growth of trees in northern China rather than single temperature or precipitation. The improved PFT-MAT is therefore an efficient method for quantitative reconstructions of palaeoclimate in arid and semi-arid regions.

Wenying Jiang (e-mail: wjiang@mail.igcas.ac.cn), Guoqiang Chu, Haibin Wu, Baoyin Yuan and Zhengtang Guo, Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; Joël Guiot, CEREGE UMR 6635 CNRS, Univ. P. Cézanne, BP 80, 13545 Aix-en-Provence cedex 4, France; Christine Hatté, Laboratoire des Sciences du Climat et de l'Environnement, UMR 1572 CEA/CNRS, F-91198 Gif sur Yvette Cedex, France; *received 3rd April 2009, accepted 2nd July 2009.*

Quantitative reconstruction of past climate is crucial to an understanding of climate mechanisms, and provides a means of defining model boundary conditions and of evaluating palaeoclimate simulations. During recent decades, transfer functions have been used to quantitatively reconstruct past environment from biological data (e.g. pollen, diatoms, insects, molluscs, foraminifera and dinoflagelates) (cf. Birks 2003). There are two main approaches based on the principle of calculations: a regression-based technique and an analogue-based technique. The regression-based technique is also known as multivariate statistical analysis. With this method, transfer function equations are derived by modelling the responses of modern assemblages in relation to the environmental variable(s), and then by applying them to fossil samples to estimate environmental variable(s) for the geological past (e.g. Imbrie & Kipp 1971; ter Braak 1995; Birks 2003). The analogue-based technique includes the best modern analogues and response surfaces, with modern analogues being used to assign climate values to fossil assemblages (e.g. Bartlein *et al.* 1986; Guiot *et al.* 1989, 1993a, b; Bartlein & Whitlock 1993; Davis *et al.* 2003; Jiang *et al.* 2006). However, each method has its limitations. For example, the regression-based technique usually produces a systematic discrepancy, or bias, in the estimates (Robertson *et al.* 1999), while the analogue-based technique suffers from the influence of 'no analogues' or 'multiple analogues' and human activity (Guiot 1990; Guiot *et al.* 1993a; Huntley 1996).

The best modern analogues technique is one of quantitative methodologies based on pollen data, including the pollen types modern analogues technique (PT-MAT) (Guiot *et al.* 1989, 1993a, b; Cheddadi *et al.* 1997; Mangy *et al.* 2001; Jiang *et al.* 2006) and the plant functional type modern analogues technique (PFT-MAT) (Nakagawa *et al.* 2002; Davis *et al.* 2003; Jiang *et al.* 2006). The PT-MAT uses pollen type percentages to match the fossil and modern analogues. The best modern analogues selected by PT-MAT come from geographically close localities. In PFT-MAT, the PFT score assemblages substitute for the pollen types. PFTs are broad classes of plants defined by stature, leaf form, phenology and climatic thresholds (Prentice *et al.* 1992, 1996). Each pollen type is attributed to a specific PFT. Grouping pollen types into PFTs, PFT-MAT reduces the influence of 'no analogues' and anthropogenic factors (Davis *et al.* 2003), but 'multiple analogues' remains a problem. Climatic conditions between analogues may differ widely and large error bars are produced for the estimates of climate parameters (Jiang *et al.* 2006). In this context, if the selection of modern analogues could be strictly constrained, PFT-MAT would provide us with more confidence in palaeoclimate reconstruction.

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In arid and semi-arid regions, vegetation is sensitive to moisture conditions (Editorial Board for Natural Geography of China 1995; An *et al.* 2000; Zhao *et al.* 2009), i.e. the balance between precipitation and evapotranspiration. The humidity conditions have been well defined by the Priestley–Taylor parameter (α) (Priestley & Taylor 1972):

$$\alpha = E/E_p$$

where E is actual evapotranspiration and E_p is potential evapotranspiration. α is independent of temperature under a sufficient moisture supply (Hare 1980), whereas it is closely related to both temperature and precipitation in arid and semi-arid regions because of insufficient water supply. However, the effect of α on vegetation has received little attention in quantitative reconstructions of past climate.

Here, we present an improved methodology of PFT-MAT in which the relationship of α and environmental proxies is used to constrain selection of the best modern analogues. We test this model using high-resolution, precisely dated palaeorecords (pollen, *Pediastrum* and $\delta^{18}O$ of authigenic carbonate) from Lake Bayanchagan, Inner Mongolia, northern China (Jiang *et al.* 2006; Jiang & Liu 2007), and further address the Holocene climatic history.

Method

Establishment of a modern database

Climatological data from weather stations on the globe (e.g. temperature, precipitation and α) provide a basis of climate estimates for modern surface sample sites. Climate data of a specific sample site are obtained by a weighted average of observed data from its adjacent weather stations within an area of 5×5° (Guiot 1987; Guiot & Goeury 1996). Pollen spectra and climatological data of modern surface sites thus constitute a database for quantitative reconstructions of past climate (e.g. Guiot *et al.* 1993b; Tarasov *et al.* 1998; Members of China Quaternary Pollen Data Base 2001).

Estimations of climate parameters for fossil assemblages

All calculations are carried out using the 3Pbase software package (Guiot & Goeury 1996); the detailed procedure as follows (see Appendix S1 for detailed demo).

Selection of preliminary modern analogues. – For a fossil pollen assemblage, the chord distance method is used to search for analogues in modern databases (Overpeck *et al.* 1985). In this study, eight analogues with the minimum chord distance are selected and their α are averaged as a preliminary estimate of palaeo-α for this fossil assemblage (Guiot 1990; Guiot *et al.* 1993a, b; Magny *et al.* 2001). This procedure is repeated until preliminary palaeo-α for the entire sequence are obtained.

Further selection of modern analogues. – The palaeoenvironmental proxies and palaeo-α are used to further constrain the selection of modern analogues.

(1) Perform a principal component analysis on several palaeoenvironmental proxies sensitive to α changes, and then establish the first component (PC1) record for the entire sequence.
(2) Establish a preliminary palaeo-α record for the sequence.
(3) Establish a relationship of covariation between PC1 and preliminary palaeo-α, i.e. a change of

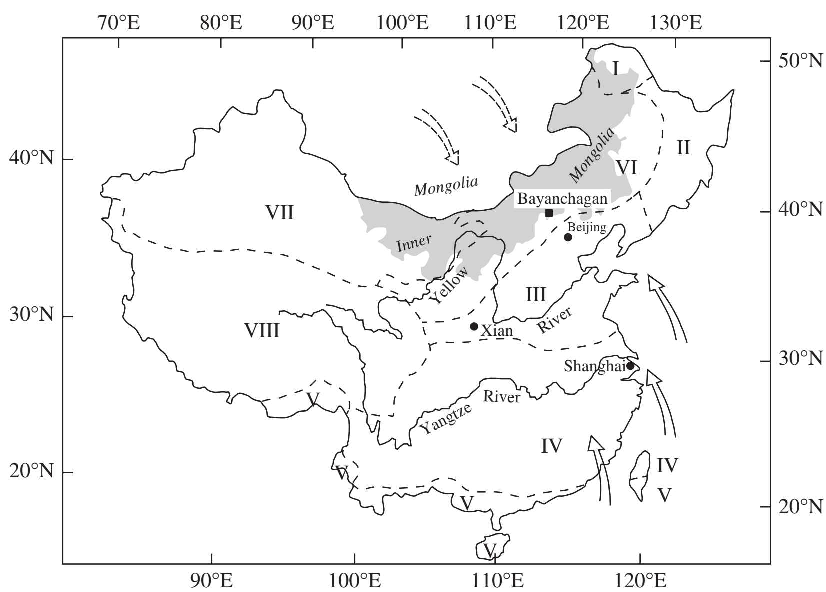

Fig. 1. Map showing the location of Lake Bayanchagan and modern vegetation zones in China (modified from Editorial Board for Flora of China 1995). I = Cold-temperate conifer forest; II = Temperate mixed conifer-broadleaved forest; III = Warm-temperate broadleaved deciduous forest; IV = Subtropical evergreen broadleaved forest; V = Tropical rainforest and seasonal rainforest; VI = Steppe; VII = Desert shrub; VIII = Tibet–Qinghai cold and highland vegetation. The dashed and solid arrows indicate the winter and summer monsoon, respectively. The shaded area indicates Inner Mongolia.

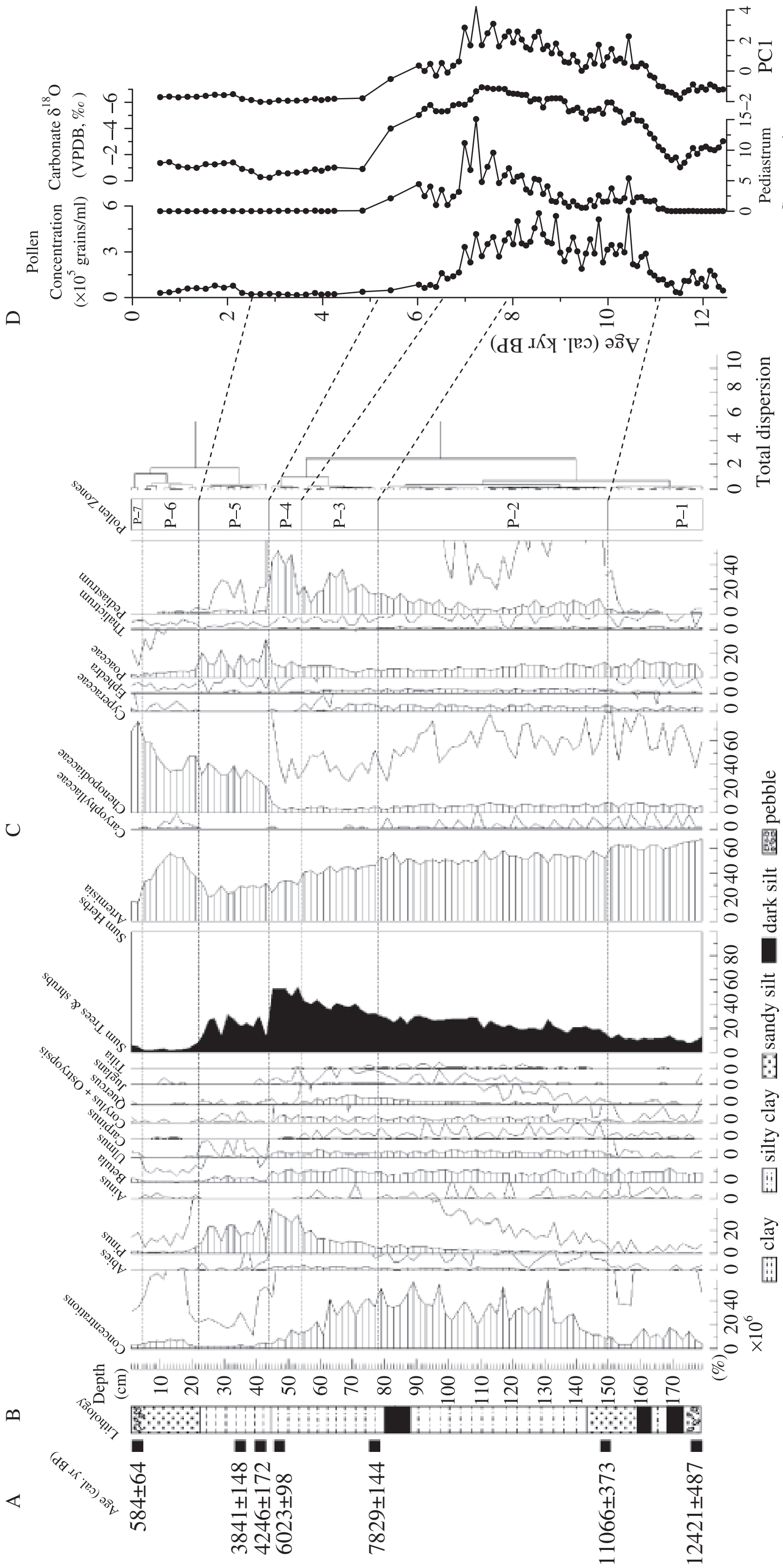

Fig. 2. Chronology (A), lithology (B), simplified pollen diagram (C) and palaeoenvironmental proxy (D) records of Lake Bayanchagan. Chronology, lithology, total land pollen concentrations and *Pediastrum* concentrations are from Jiang *et al.* (2006) and $\delta^{18}O$ values of carbonate from Jiang & Liu (2007).

Table 1. Vegetation of Lake Bayanchagan.

Pollen zone[1] Age and depth	Vegetation[1]	Palaeoenvironmental proxies[2]
Pollen zones 6 and 7 2600 cal. yr BP – present (22–0 cm)	Steppe vegetation, mainly *Artemisia* and Chenopodiaceae	Low TLPC, PC and PC1 High $\delta^{18}O$ values
Pollen zone 5 5100–2600 cal. yr BP (44–22 cm)	Steppe vegetation, mainly *Artemisia*, Chenopodiaceae and Poaceae	Low TLPC, PC and PC1 High $\delta^{18}O$ values
Pollen zone 4 6500–5100 cal. yr BP (55–44 cm)	Peak of *Pinus*	Gradual decreases in TLPC, PC and PC1 Gradual increase in $\delta^{18}O$ values
Pollen zone 3 7900–6500 cal. yr BP (79–55 cm)	Peak of deciduous trees, mainly *Betula*, *Corylus*, *Ostryopsis*, *Quercus* and *Ulmus*	High TLPC Peaks of PC and PC1 Lowest $\delta^{18}O$ values
Pollen zone 2 11 100–7900 cal. yr BP (150–79 cm)	Gradual expansion of trees and shrubs	Highest TLPC Gradual increases in PC and PC1 Gradual decrease in $\delta^{18}O$ values
Pollen zone 1 12 500–11 100 cal. yr BP (180–150 cm)	Steppe vegetation, mainly *Artemisia* and Poaceae	Low TLPC, PC and PC1 High $\delta^{18}O$ values

[1]After Jiang *et al.* (2006).

[2]Total land pollen concentrations (TLPC) and *Pediastrum* concentrations (PC) are from Jiang *et al.* (2006), and $\delta^{18}O$ values of authigenic carbonate from Jiang & Liu (2007). PC1 is the first component of the principal component analysis on TLPC, PC and $\delta^{18}O$ records.

palaeo-α (Δα) is equivalent to a change of PC1 (ΔPC1).

(4) Further select analogues using the established relationship. For the fossil assemblage *t*, the analogue *i* selected according to the principle of the minimum chord distance is kept only if the following rules are satisfied: $PC1_t - PC1_0 > \Delta PC1$ and $\alpha_i - \alpha_0 > \Delta\alpha$ or $PC1_t - PC1_0 < \Delta PC1$ and $\alpha_i - \alpha_0 < \Delta\alpha$, and: $-\Delta PC1 \leq PC1_t - PC1_0 \leq \Delta PC1$ and $-\Delta\alpha \leq \alpha_i - \alpha_0 \leq \Delta\alpha$, where $PC1_0$ and α_0 are modern values. Any of the preliminary eight analogues that do not satisfy the above rules is discarded, and the procedure is repeated until the eight ideal analogues are obtained.

(5) Calculate climatological parameters (e.g. temperature, precipitation and α) for the fossil assemblage *t* through the weighted average of the eight analogues.

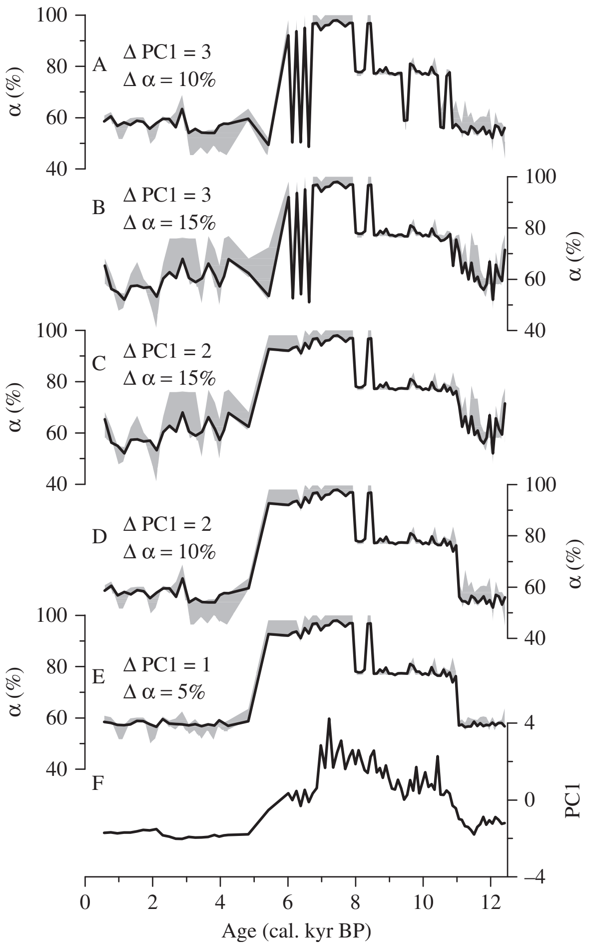

Fig. 3. Comparison of reconstructed α with uncertainty bands (shaded areas) using different values of ΔPC1 and Δα (A–D), PC1 (F).

Test of the PC1-α constrained PFT-MAT

In order to assess the efficiency of the PC1-α constrained PFT-MAT, the unconstrained and constrained PFT-MAT are used to reconstruct Holocene climate on the basis of palaeoclimate records from Lake Bayanchagan (Jiang *et al.* 2006; Jiang & Liu 2007), and their results are compared.

Environmental proxies of Lake Bayanchagan

Lake Bayanchagan (115.21°E, 41.65°N, 1355 m a.s.l.; Fig. 1), located at the northern edge of the East-Asian

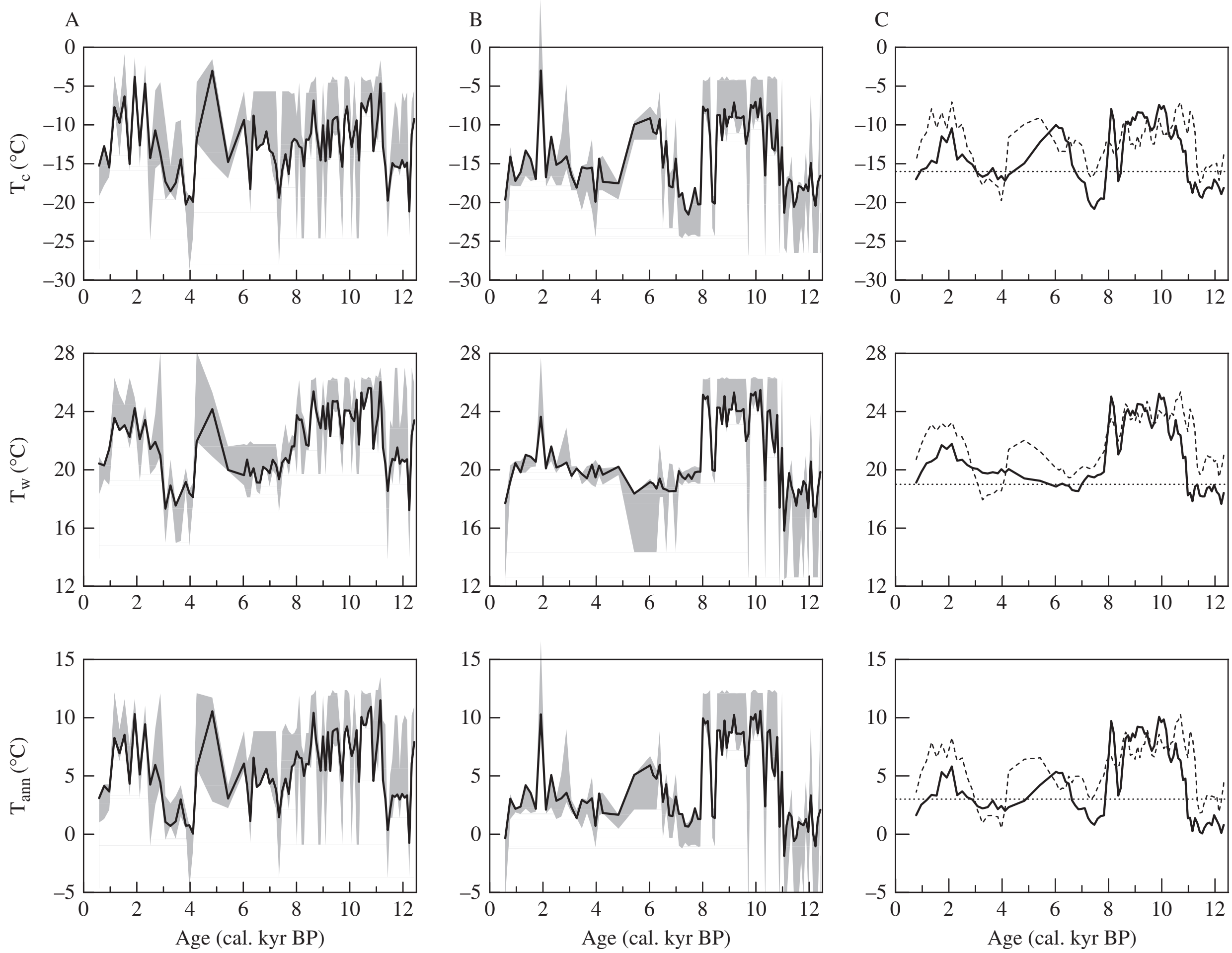

Fig. 4. Reconstructed climate parameters during the Holocene for Lake Bayanchagan. A. Mean estimates (solid lines) with uncertainty bands (shaded areas) produced by the unconstrained PFT-MAT. B. Mean estimates (solid lines) with uncertainty bands (shaded areas) produced by the PC1-α constrained PFT-MAT. C. Comparison of the mean estimates (3-point moving average) produced by the unconstrained PFT-MAT (dashed lines) and PC1-α constrained PFT-MAT (solid lines). Dotted horizontal lines indicate present-day climate (Panel C). T_c = mean temperature of the coldest month; T_w = mean temperature of the warmest month; T_{ann} = mean annual temperature.

summer monsoon, was a ~15 km^2 closed-basin lake. Lake level changes are controlled by the balance between precipitation and evaporation. The mean annual temperature in the area is about 3 °C, and total annual precipitation 300–400 mm. About 70% of the precipitation occurs in summer, a characteristic typical of the East-Asian monsoon climate.

The chronology of the lake sediment is constrained by seven radiocarbon dates of bulk organic carbon (Fig. 2A) (Jiang *et al*. 2006). Records of pollen, *Pediastrum* and $\delta^{18}O$ of authigenic carbonate have been published (Jiang *et al*. 2006; Jiang & Liu 2007) and are summarized here (Fig. 2C, D; Table 1). *Pediastrum* is a genus of green algae and favours freshwater conditions. When the East-Asian summer monsoon decreases, the salinity of lake water increases, leading to a decrease in *Pediastrum* and vice versa. $\delta^{18}O$ values of authigenic carbonate from Lake Bayanchagan are mainly controlled by the oxygen isotope value of lake water, i.e. the balance between precipitation and evaporation. Increased monsoonal precipitation produces lower water $\delta^{18}O$ values, while decreased precipitation and increased evaporation generate higher $\delta^{18}O$ values (Leng & Marshall 2004; Jiang & Liu 2007). Pollen concentrations can be affected by several factors, including regional climatic conditions, sedimentation rate and pollen preservation. Lake core from Bayanchagan consists mainly of dark to grey silt and clay (Fig. 2B) (Jiang *et al*. 2006), indicating a generally reducing environment favorable for pollen preservation. Pollen concentration shows about the same variation pattern as pollen influx (pollen concentration × sedimentation rate) (Appendix S2) and correlates well with carbonate $\delta^{18}O$ and *Pediastrum* records (Fig. 2D), suggesting the dominant effect of climate change on pollen concentration at Lake Bayanchagan. Therefore, the *Pediastrum* contents, total land pollen concentrations and $\delta^{18}O$ values of authigenic carbonate from Lake Bayanchagan are used as palaeoenvironmental proxies

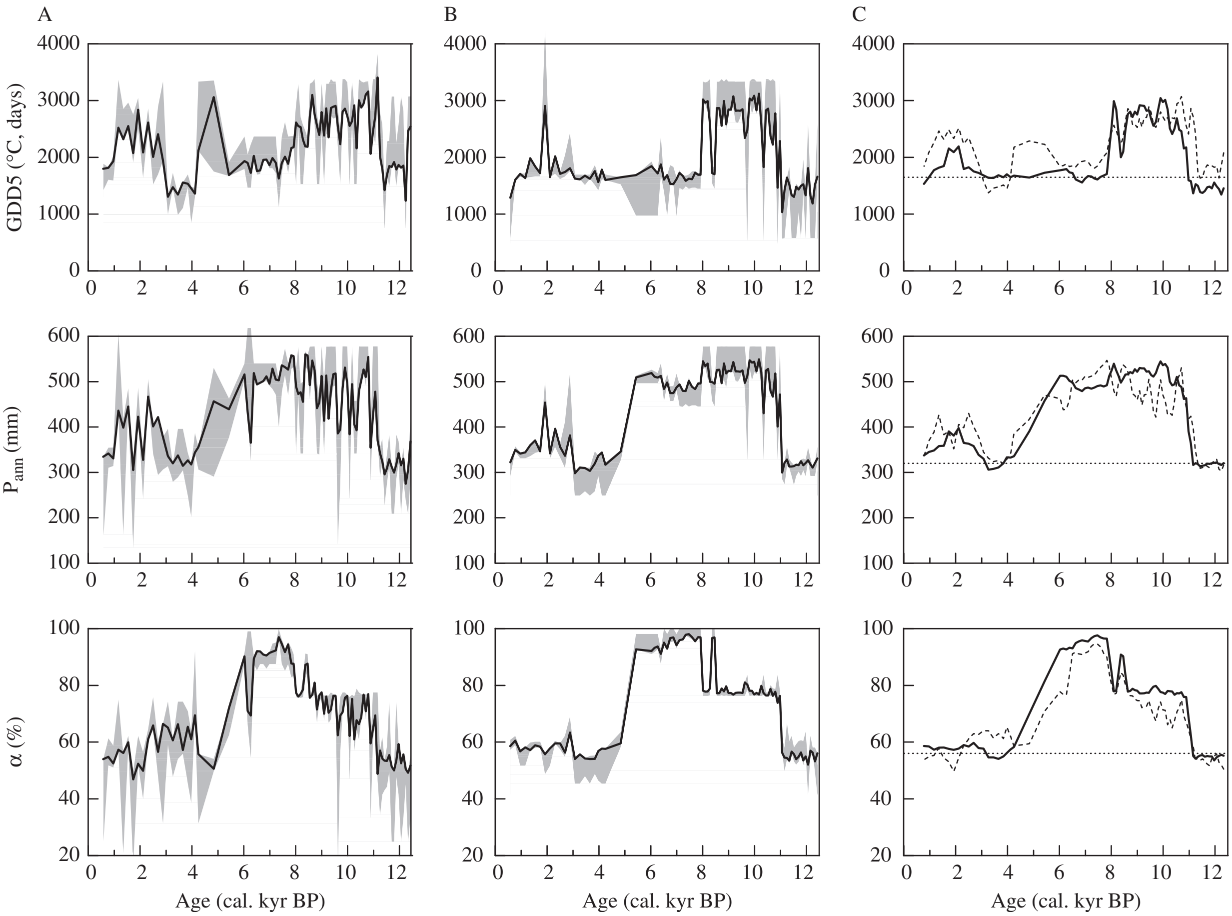

Fig. 5. Reconstructed climate parameters during the Holocene for Lake Bayanchagan. A. Mean estimates (solid lines) with uncertainty bands (shaded areas) produced by the unconstrained PFT-MAT. B. Mean estimates (solid lines) with uncertainty bands (shaded areas) produced by the PC1-α constrained PFT-MAT. C. Comparison of the mean estimates (3-point moving average) produced by the unconstrained PFT-MAT (dashed lines) and PC1-α constrained PFT-MAT (solid lines). Dotted horizontal lines indicate present-day climate (Panel C). GDD5 = growing degrees day above 5 °C; P_{ann} = annual precipitation; A = actual/potential evapotranspiration.

while the PC1-α relationship is used to further constrain the selection of modern analogues.

Comparison of quantitative results produced by the unconstrained and constrained PFT-MAT

Modern data include 211 surface pollen spectra from China (Members of China Quaternary Pollen Data Base 2001) and 1855 from Europe and Mongolia (Guiot *et al.* 1993b; Tarasov *et al.* 1998). The only difference between the two methods is that the PC1-α relationship is used to further constrain the selection of modern analogues in the new PFT-MAT. The compatibility between ΔPC1 and Δα is carefully defined after many trials. First, the ΔPC1 and Δα are defined in a range from ~20% to ~50% of the PC1 and α fluctuations, respectively, i.e. 1.0–3.0 for ΔPC1 and 10–25% for Δα. The ideal values of ΔPC1 and Δα are then confirmed when the reconstructed palaeo-α shows a variation pattern similar to PC1. As shown in Fig. 3, the palaeo-α show smaller uncertainties and exhibit a variation pattern similar to PC1 when ΔPC1 and Δα are equal to or less than 2% and 10%, respectively. Therefore, these two values (Fig. 3D) are used to reconstruct palaeoclimate for Lake Bayanchagan.

Both methods produce general agreement for Holocene climatic changes, with a period of high rainfall occurring between 11 000 and 5500 cal. yr BP and a warm interval between 11 000 and 8000 cal. yr BP (Figs 4, 5). However, there are significant differences in the details of the two reconstructions. The constrained PFT-MAT generally yields smaller error bars for the reconstructed climate parameters than the unconstrained PFT-MAT (Figs 4, 5). In addition, three prominent climatic events are identified from the constrained results, i.e. a cold event around 8400 cal. yr BP and two warm events around 6000 and 2000 cal. yr BP. The 8400 cal. yr BP cold event is not evident in the records facilitated by the unconstrained PFT-MAT (Figs 4, 5).

The cold event (~8400 cal. yr BP) is characterized by an abrupt decrease in both winter and summer temperatures, but rainfall remained unchanged (Figs 4, 5).

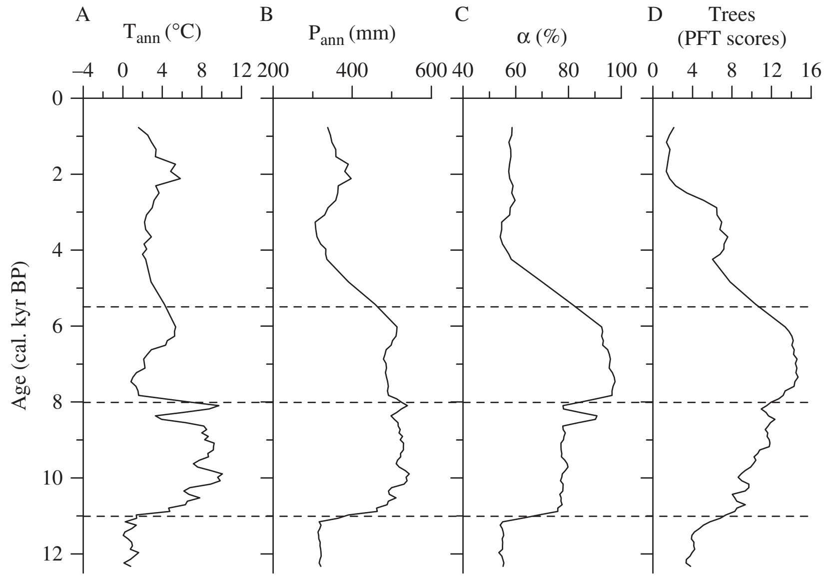

Fig. 6. A–D. Climate parameters facilitated by the constrained PFT-MAT and PFT scores of sum trees for Lake Bayanchagan. All curves represent a 3-point moving average.

Prominent climatic events between 8600 and 8080 cal. yr BP were also recorded in stalagmite in the East-Asian monsoon region (Dykoski *et al.* 2005; Shao *et al.* 2006). They appeared in broad agreement with the cooling event 8200 years ago in the Greenland ice cores (Alley *et al.* 1997; Rohling & Pälike 2005).

The warm event around 6000 cal. yr BP is accompanied by high rainfall. This temperature peak shifts to ~5000 cal. yr BP in the unconstrained curve (Figs 4, 5). To date, there is little evidence from northern China of the warm event at ~5000 cal. yr BP, but the 6000 cal. yr BP warm event is supported by other palaeoclimate records over China (Yu *et al.* 1998).

The event around 2000 cal. yr BP is characterized by a moderate increase in temperature and precipitation (Figs 4, 5). This warm and relatively wet event is also well documented in ice cores, lake sediments and stalagmite in northern China (Yang *et al.* 2002, 2004; Tan *et al.* 2003). It (~2000 cal. yr BP) coincides with the Han Dynasties (from 206 BC to AD 220), which was a time of economic prosperity in ancient China (Sun 2000; Yang *et al.* 2004; Ebrey 2008). Large-scale land reclamation activities in the Han Dynasty were performed even inside the present Mu Us desert (Sun 2000), suggesting a short interval of climatic optimum. In the unconstrained results, the temperature shows a great increase at ~2000 cal. yr BP, even as high as that during the early Holocene (11 000–8000 cal. yr BP) (Fig. 4). However, this seems unlikely. Thus, the constrained PFT-MAT produces a more reliable temperature estimate during the Holocene for Lake Bayanchagan.

The moisture index (α) exhibits a peak in the cold interval (~8400 cal. yr BP), while this remains unchanged in the warm interval (~2000 cal. yr BP) (Figs 4, 5). These may be explained by the combined effect of temperature and precipitation changes. At ~8400 cal. yr BP, temperature decreased greatly, while rainfall remained unchanged, leading to a decrease in potential evapotranspiration and hence an increased α. At ~2000 cal. yr BP, both temperature and rainfall increased substantially, leading to a synchronous increase of actual and potential evapotranspiration and hence a relatively constant α (Figs 4, 5).

In northern China, from east to west, the vegetation changes from forest to steppe and then to desert shrub (Fig. 1). Such a zonal distribution of the vegetation is consistent with the distribution pattern of rainfall and temperature (Editorial Board for Flora of China 1995; Hou 2001). Therefore, an increase in arboreal pollen in fossil pollen assemblages is traditionally explained as a result of warmer and wetter climate. However, our study indicates that the highest PFT scores of trees at Lake Bayanchagan occurs between 8000 and 5500 cal. yr BP (Fig. 6D), which is not in phase with the warmest and wettest interval between 11 000 and 8000 cal. yr BP (Fig. 6A, B). In contrast, the PFT scores of trees correlate well with α changes (Fig. 6C, D). Thus, it is inferred that the dominant factor controlling the growth of trees is α rather than single temperature or precipitation in arid and semi-arid regions.

Conclusions

Quantitative palaeoclimate reconstructions for Lake Bayanchagan, northern China, demonstrate the efficiency of the PC1-α constrained PFT-MAT, which substantially reduces the effect of 'multiple analogues'. We therefore suggest the relationship of α and environmental proxy(ies) as an effective constraint for the PFT-MAT-based quantitative palaeoclimate reconstructions in arid and semi-arid regions.

Reconstructed results show that the interval 11 000–8000 cal. yr BP is characterized by the highest temperature and rainfall during the Holocene at Lake Bayanchagan, while the interval 8000–5500 cal. yr BP is a period of highest moisture index (α). The PFT scores of trees correlate well with changes in α, with the highest tree components occurring between 8000 and 5500 cal. yr BP. This indicates the dominant effect of α on the growth of trees in arid and semi-arid regions, rather than single temperature or precipitation. In addition, a cold event around 8400 cal. yr BP and two warm events around 6000 and 2000 cal. yr BP are identified from the reconstructions facilitated by the improved PFT-MAT, which are consistent with other regional palaeoclimatic records.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1.
Appendix S2.

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