Pollen-Based Quantitative Reconstruction of Holocene Climate Changes in the Daihai Lake Area, Inner Mongolia, China

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ABSTRACT

Vegetation around the Daihai Lake, northern China, is very sensitive to climate changes. In this paper, pollen-based quantitative climate reconstructions using three methods [weighted averaging partial least squares method (WAPLS), modern analog technique (MAT), and pollen response surface method (PRS)] were conducted to obtain robust reconstructions of Holocene climate changes in the Daihai Lake area. The result obtained by the three methods all consistently show the annual precipitation to have been 50–100 mm lower in the early Holocene, 100–200 mm higher in the Mid-Holocene, and 50–100 mm lower again in the late Holocene than at present. The WAPLS and the MAT methods also show quasi-synchronous oscillations of the mean annual temperature (Ta); 1–2°C lower in the Early Holocene and 1–3°C higher in the Mid-Holocene than today. The time period from 6200 to 5100 cal yr BP was the wettest and the warmest interval, with an annual precipitation (Pa) greater than 550 mm and mean annual temperature Ta higher than 6.5°C. Several cold and dry events can be identified to occur about 8200, 6000, and 4400 cal yr BP, with an annual precipitation less than 400 mm and a mean annual temperature colder than 4.5°C, respectively. The mean temperature of the warmest month (Tw) as reconstructed using both WAPLS and MAT methods was relatively stable during the Holocene, fluctuating about ±2°C relative to the present level, but the PRS method suggests more varied Tw values in both amplitude and frequency. After 1500 cal yr BP, no consistent pattern can be observed from these three different analyses, probably because of the impact of intensified human disturbances on the natural vegetation. The fluctuations of annual precipitation (Pa) correspond to that observed in Dongge Cave in southern China. The differences might be linked to Indian monsoon and East Asia monsoon climates or caused by the different degree of dating precision, different temporal resolution, and different sensitive response of climate proxies to the climate variations.

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1. Introduction

Palynologists have been seeking robust methods to quantitatively reconstruct past climate changes using pollen data. The earliest attempts were the use of indicator taxa in pollen records (Conolly 1961; Zagwijn 1960, 1994; Faegri and Iversen 1989). Imbrie and Kipp revolutionized Quaternary paleoecology by presenting, for the first time, a numerical procedure for quantitatively reconstructing past environments from fossil pollen assemblages. Several numerical techniques have been developed in the past two or three decades, including transfer function (Imbrie and Kipp 1971; Bartlein et al. 1984), pollen response surface (PRS) (Bartlein et al. 1986; Prentice et al. 1991), modern analog technique (MAT) (Overpeck et al. 1985; Guiot 1990; Nakagawa et al. 2002), and weighted averaging partial least squares (WAPLS) (Birks et al. 1990; Birks 1995, 1998; ter Braak and Juggins 1993; Jongman et al. 1995; Li et al. 2007). These quantitative techniques have been widely employed through many regions in the world, such as Europe (Huntley and Prentice 1988; Guiot et al. 1989; Birks and Sun 1997; Liu et al. 2002; Xu et al. 2003; Li et al. 2007).

Different numerical techniques usually have certain environment ranges where they are most applicable. For example, WAPLS and PRS methods may be most suitable to reconstruct climatological proxies when the dominant pollen taxa are of narrow environmental ranges. However, at the present resolution of identification, pollen taxa can only be classified into the level of genus for arboreal pollen types or family for most herbs, and the pollen taxa in the same genus or family usually have extremely wide ranges of environmental tolerance. The optimum environment values and the most similar environment grids with modern pollen assemblage might not be ecologically meaningful, which may undermine the utility of WAPLS and PRS. MAT seems to have advantages over both the WAPLS and PRS for the reconstruction of paleoclimate using modern pollen assemblages. However, it may be very difficult or even impossible to obtain exact matches between modern and fossil pollen assemblages. Therefore, each of the numerical techniques has its applicability as well as its limitations.

A few pollen-based studies have employed quantitative methods in the reconstruction of climate change in China (Sun et al. 1996; Song and Sun 1997; Xu et al. 2003; Shen et al. 2002). However, they often rely on a simple method. Different quantitative techniques are rarely employed for the test of consistency. The difficulty of quantitative reconstructing climate changes in China may arise from the lack of natural vegetation cover largely because of a long history of human activities, and natural vegetation cover can only be found in high mountains and steppe areas.

In this paper, we present a quantitative reconstruction of Holocene climate changes in the Daihai Lake, Inner Mongolia, China, based on a high-resolution pollen record (Xiao et al. 2004). Three different quantitative techniques (WAPLS, MAT, and PRS) are used in this study to test whether similar results can be achieved from the use of different methods. In comparison with the well-accepted precipitation record (Wang et al. 2005), we obtain a robust quantitative reconstruction of Holocene climate changes in north China.

Many studies have been conducted around the Daihai Lake over the past decades. As early as in 1937, Zhang carried out a geological and geomorphological survey and identified five lacustrine strandlines at different altitudes above the present lake level (Zhang 1937). Since the early 1960s, a number of investigations have been conducted involving geology, geomorphology, hydrology, geochemistry, and sedimentology (Zhang and Lin 1992; Wang et al. 1990; Li 1979; Jin et al. 2006; Peng et al. 2005). Several pollen percentage diagrams have also been constructed (Xu et al. 2003; Xiao et al. 2004; Li et al. 2004; Sun et al. 2006). A pollen analysis of 65 samples from surface sediment of the Daihai Lake and alluvium of its inflow rivers reveals that most pollen grains in the Daihai Lake come from its inflow rivers, although rainfall and wind are also important (Xu et al. 2005). A core of 14.48 m long (99a) was raised in the center of the Daihai Lake showing the presence of sparse-wood grassland with a three-phased Younger Dryas oscillation during the time interval of 14 and 10 ka, warm and humid climate with abundant broad-leaved trees between 10 and 7 ka, more arid vegetation and less moist climate from 7 to 1.95 ka, and steppe vegetation with evidence of agricultural activities from 1.95 ka on (Li et al. 2004). However, a palynological study from the same core (99a) concluded a different result, particularly prior to 7900 cal yr BP. Xiao et al. suggested that the vegetation around the Daihai Lake was primarily arid herbs and shrubs with a mild and dry climate before 7900 cal yr BP and was mixed coniferous and broad-leaved forests with warm and humid climate between 7900 and 4450 cal yr BP. During the following period of 4450–2900 cal yr BP, woody plants declined and the climate became cooler and drier; after 2900 cal yr BP, forests disappeared as the climate became cooler and drier (Xiao et al. 2004). A study of total organic
carbon (TOC) and nitrogen (TN), carbonate content (CaCO₃), grain size, and pollen assemblages of the same core (99a) reveals a result similar to Xiao’s work (Sun et al. 2006).

2. Geographical setting

The Daihai Lake (40°29′–40°37′N, 112°33′–112°46′E; 1225 m MSL) is a closed lake in Inner Mongolia, north-central China, with a surface area of 133.46 km². The lake is located within the transition zone influenced by both warm–moist monsoon circulation and cold–dry polar air masses. The climate during summer months is dominated by a warm and moist monsoon that delivers about 80% of annual precipitation at the site, while the climate during winter months is controlled by a cold and dry monsoon that generates frequent dust storms from late autumn through the following spring. There is very little snow in winter. The mean annual temperature is 5.1°C with a July average of 20.5°C and a January average of −13.0°C. Annual precipitation measures 400 mm, but annual evaporation is 1162 mm, almost 2.8 times higher than the annual precipitation (Fig. 1) (Gao and Xu 1962; Chinese Academy of Sciences 1984; Zhang and Lin 1992).

Modern vegetation of in the Daihai Lake Basin is dominated by the temperate steppe. The hillslopes are mainly covered by a variety of grasses such as Stipa and Artemisia, Setaria, Medicago, Thymus, and others. On riversides and the lakeshore plain are mainly Carex, Achnatherum, Elymus Iris, Taraxacum, Suaeda, Potentilla, and Polygonum. Forests with Larix, Picea, Populus, Betula, Pinus, Ulmus, and Salix are sparsely distributed on the northern high mountains. Beneath trees often grow scrub such as Spiraea, Hippophaeae, Ostryopsis, Prunus, Lespedeza, Carex, Artemisia, Lilium, Anemarrhena, and Sanguisorba (Wang et al. 1990).

3. Data and methods

a. The pollen record

As mentioned above, two separate high-resolution pollen analyses for core 99a in the Daihai Lake were carried out. Li et al. used a 10-cm interval for their analysis (Li et al. 2004), while Xiao et al. analyzed pollen records at a 4-cm interval (Xiao et al. 2004). Here our pollen-based quantitative climate reconstruction will be based on the latter.

Core 99a is a 12.02-m-long sediment core recovered in the center of Daihai Lake. It was drilled in 1999 using a piston corer operated by a D1-B drilling machine (Toho Chikakoki, Japan). A total of 272 samples were collected at 4-cm intervals and subjected to pollen analysis. Eight organic-rich sediment bulk samples were ¹⁴C dated using accelerator-based mass spectrometry (AMS) at the Center for Chronological Research, Nagoya University, Japan. The calibrated ages were based on the IntCal98 program (Stuiver et al. 1998). The ages of each horizon were interpolated on the basis of radiocarbon-dated horizons. The sampling interval of 4 cm approximates an analytical resolution of ∼30 yr above 26 cm, ∼33 yr from 26 cm to 8.98 m, and 150 yr below 8.98 m (Xiao et al. 2004).

The pollen profile from the Daihai Lake can be divided into 4 pollen stages and 12 pollen substages (Xiao et al. 2004) (Fig. 2).

Nonarboreal pollen (NAP) is dominant in stage 1 (∼10 250–7900 cal yr BP), with Artemisia in particular reaching up to 61%–75.5% of the total pollen sum. Arboreal pollen (AP) makes up 12.8%–27.9% of the total pollen sum and displays a trend of gradual increase.

Stage 2 (∼7900–4450 cal yr BP) is dominated by AP. This indicates the presence of warm and humid climate, which is necessary for the growth of forest vegetation, making a clear difference from the present vegetation and climate in the Daihai area. Based on the fluctuations of arboreal pollen percentages, stage 2 can be divided into 5 substages.

AP percentages decrease sharply, compensated by significant increase of Artemisia pollen in stage 3 (∼4450–2900 cal yr BP). However, most of the samples from stage 3 still contain arboreal pollen at more than 20% of the pollen sum, indicating a forest–steppe environment.

Based on changes in pollen assemblage, stage 2 can be divided into 3 substages.

In stage 4 (∼2900 cal yr BP to present), AP percentage drops down to its minimum value, suggesting that the forests almost disappeared and were replaced by a scrub–steppe environment similar to that of the present vegetation in Daihai area (Xiao et al. 2004; Xu et al. 2003).

b. Surface pollen dataset

The surface pollen dataset was assembled using 237 surface pollen samples taken from the area 33°33′–42°32′N, 95°02′–119°35′E. This area stretches over 2000 km from east to west and ∼1000 km from south to north and contains several different environments and topographies such as mountains, valleys, and plateaus. Here the annual precipitation shows a clear gradient from east (800 mm) to west (44 mm), the annual average temperature indicates a gradient from −3.8°C to 12.6°C. July temperatures change from 8.0°C to 26°C, and January averages from −19.0°C to −1.7°C (Li et al. 2007; Wu 1980; Hou 1983; Jiao 1984). Surface samples were collected at 30–40-km intervals along 4–5 transects that are typical to this area, that is, forests, shrubs, steppes,
FIG. 1. The locations of sampling sites and weather stations in northern China.
FIG. 2. Pollen percentage diagram of Daihai (DH) 99a core sediment in the Daihai Lake.
deserts, and meadows (Fig. 1). Wherever possible, efforts were made to take samples from places with minimal human influences. Moss polsters were collected as far as available. Where moss was not present, we collected the surface layer of the soil (less than 2 cm in depth). The sampling method was taking 4–5 pieces of mosses or soils at one site and mixing them together as one sample. The sampling times were in the summer or autumn in the years of 2003–04.

The most common taxa in the surface pollen dataset are dominated by *Pinus, Quercus, Betula, Picea, Artemisia*, and *Selaginella sinensis* in the forest vegetation, where the mean annual precipitation (*P*<sub>ann</sub>) is more than 500 mm, and by *Artemisia*, Chenopodiaceae, and Poaceae in the steppe vegetation, where the *P*<sub>ann</sub> ranges from 450 to 200 mm, and by Chenopodiaceae, *Artemisia, Ephedra, Nitraria*, and Tamaricaceae in the desert areas, where the *P*<sub>ann</sub> is less than 200 mm (Li et al. 2007).

c. Meteorological data

Daily weather records from 243 meteorological observatories in northern China were taken from the China meteorological statistical annals (Provided by China National Weather Service) and averaged for the 30 years from 1961 to 1990. The annual precipitation (*P*<sub>a</sub>), Mean annual temperature (*T*<sub>a</sub>), mean temperature of the warmest month (*T*<sub>w</sub>), and mean temperature of the coldest month (*T*<sub>c</sub>) at the surface pollen sites were calculated using the parabolic interpolation algorithm with the inversed square distance as the weighting factor in the polation 1.0 program (T. Nakagawa 2005, unpublished manuscript). Typical correlation coefficients between estimated values and observed values were about 0.95 for the mean annual precipitation and 0.99–0.96 for the temperature parameters (Li et al. 2007).

4. Method

a. Selection of the climate parameters

Autocorrelation may undermine the predictive power of models (Telford and Birks 2005). To remove the effects of high autocorrelation among the environmental variables in the analyses, we examined the variance inflation factors (VIFs) for each environmental variable, and three environmental variables were selected (*P*, *T*<sub>a</sub>, *T*<sub>w</sub>) whose VIFs are less than 20 (Li et al. 2007).

b. Weighted averaging partial least squares

The theory behind the WAPLS statistical approach is summarized in Birks et al. (1990), Birks (1995, 1998), ter Braak and Juggins (1993), and Jongman et al. (1995). WAPLS is a statistical transfer function, on the other hand; it is a common method that has been used for a long time and is being continually revised. It assumes that the relationships between pollen percentage and climate are unimodal: each taxon grows best at a particular optimal value of an environmental variable and cannot survive where the value of that variable is too low or too high. If taxon ecology can be assumed to be constant, then even if the overall pollen assemblage has no modern analog a reasonable reconstruction can be given. On this aspect, this method should be more robust than the MAT if the underlying relationships between pollen and climate are actually unimodal.

In this paper, the modern climate reconstruction results given by the WAPLS transfer function model are based on Li et al. (2007), where the “estimated” and “reconstructed (inferred)” values show strong correlations in *P* (R = 0.94; standard deviation = 50 mm; reliable dynamic range of the reconstruction was 40–800 mm), *T*<sub>a</sub> (R = 0.84; standard deviation = 1°C; the reliable dynamic range of the reconstruction was −4°C–13°C), and *T*<sub>w</sub> (R = 0.79; standard deviation = 1.25°C; the safe dynamic range of the reconstruction was 8°C–26°C) (Fig. 3) (Li et al. 2007).

c. Modern analogs technology method

The modern analogs technology (Overpeck et al. 1985; Guiot 1990; Jackson and Williams 2004; Williams and Shuman 2008) uses a chord distance (Euclidian measure between two points in the n dimension space defined by the square root of the pollen percentages) to determine the similarity between each fossil pollen spectrum and each spectrum in the reference pollen dataset (8 analogs were employed; Nakagawa et al. 2002). In this paper, 121 pollen taxa appeared in the surface samples. These taxa were used to define the best modern analogs with the Daihai fossil pollen spectra and used for the reconstruction of the paleoclimate of the Daihai Basin. The accuracy of modern analogs method was checked with *R* values (the correlation of “estimated” values and the “inferred” values) and standard deviation using the Polygon program (Nakagawa et al. 2002). The results of the best modern analogs method give results similar to the WAPLS method for annual precipitation (*P*: R = 0.93, standard deviation = 94 mm) and worked moderately well for thermal parameters (*T*<sub>a</sub>: R = 0.72, standard deviation = 1.0°C; *T*<sub>w</sub>: R = 0.73, standard deviation = 0.9°C) (Fig. 3).

d. Pollen response surface method

For the pollen response surface method, the modern pollen abundances are the dependent variables and are predicted as a function of climate (Sun et al. 1996; Xu et al. 2003). Each pollen type response surface is a regressional expression of the relative position and
changes in abundance of pollen taxa in the “climate manifold.” For each taxon, the maximum and minimum pollen abundances in the response surfaces correspond to optimal and nonoptimal climate conditions, respectively. In climate reconstructions, estimates are generated by applying modern pollen response surfaces to fossil data and extracting climate values that correspond to the unique subset of climate space defined by most similar-grid modern pollen assemblage (Bartlein et al. 1986; Prentice et al. 1991; Webb et al. 1993).

In this study, modern pollen response surfaces of 6 major pollen taxa proposed by Sun et al. (1996) and Xu et al. (2003) were applied to the Daihai Lake fossil pollen data to extract climate values. The six pollen taxa are *Picea* (R = 0.63, F = 6.95), *Pinus* (R = 0.61, F = 11.10), *Betula* (R = 0.74, F = 23.40), *Quercus* (R = 0.66, F = 14.42), *Artemisia* (R = 0.42, F = 4.24), and Chenopodiaceae (R = 0.36, F = 8.78) (Sun et al. 1996; Xu et al. 2003).

5. Result

a. Paleoclimate reconstruction with WAPLS method

In Fig. 4, the curves of series A are the reconstruction results of the annual precipitation (Pa), mean annual temperature (Ta), and mean temperature of the warmest month (Tw) obtained by using the WAPLS method. The fluctuations of climate conditions for the past ~10 250 yr were basically coherent with the four stages of pollen assemblages in the Daihai Lake as described below.

1) STAGE 1 (~10 250–7900 CAL YR BP)

This time was the coolest and driest period compared with other stages during the Holocene. The Pa varied from 330 to 380 mm, Ta fluctuated from 4.5°C to 5.5°C, Tw changed from 19°C to ~20.5°C. Climate was generally stable before ~8300 cal yr BP, Pa being typically at ~350 mm, Ta at ~5°C, and Tw at ~20°C. From 8300 to 7900 cal yr BP, (Pa) gradually increased, whereas Ta and Tw showed a marked decrease.

2) STAGE 2 (~7900–4450 CAL YR BP)

Climate was warmer and wetter than all other stages in the Holocene except for a cold and dry event at about 6000 cal yr BP, where Pa was less than 400 mm, Ta was less than 4.5°C, and Tw was less than 19°C. For the rest of the period, in contrast, Pa was more than 450 mm, Ta was higher than 5.5°C, and Tw was higher than 19.7°C. At about 7400 cal yr BP and 5500 cal yr BP, climate was...
the warmest and the wettest with $P_a$ at about 630 mm, $T_a$ at about 7°C, and $T_w$ at about 20.7°C.

3) STAGE 3 (~4450–2900 CAL YR BP)

After a well-marked cold and dry event at about 4450 cal yr BP (Fig. 4), where the $P_a$ dropped down to 340 mm and $T_a$ and $T_w$ fell down to 4.5°C and 19.3°C, respectively, the climate then showed an ameliorating trend toward warm and humid conditions that lasted until ~3500 cal yr BP, when $P_a$ reached about 550 mm, $T_a$ reached about 6.5°C, and $T_w$ reached about 20.5°C. However, none of these parameters recovers to the values of stage 3. After 3500 cal yr BP, climate turned to cold and dry conditions again. The $P_a$ became lower than 450 mm, and $T_a$ and $T_w$ became lower than 5.5°C and 19.5°C, respectively.

4) STAGE 4 (~2900–0 CAL YR BP)

Precipitation continued to decrease and varied between 250 and 350 mm. Temperature fluctuated significantly, especially after ~800 cal yr BP when $T_a$ oscillated between 3.5°C and 6.7°C and $T_w$ oscillated between 18°C and 21.5°C. The driest and coldest period appeared at 500–400 cal yr BP when $P_a$ fell down to about 250 mm, $T_a$ fell to about 3.5°C, and $T_w$ fell to about 18°C. From about 1700 to 1500 cal yr BP it was the wettest period, during which $P_a$ was as high as 450 mm. There is also a remarkable cold period (though short lived) at about 1100 cal yr BP when $T_a$ was about 4°C and $T_w$ was about 18.7°C.

b. Paleoclimate reconstruction with modern analog technique

The curves of series B in Fig. 4 are the reconstruction results of climatic parameters inferred by the MAT. The inferred values varied between 250 and 650 mm for $P_a$, 4°C and 8.5°C for $T_a$, and 18°C and 22.5°C for $T_w$, which is similar to the results inferred from the WAPLS method; in particular, the values of $P_a$ showed nearly identical trends with the results of WAPLS. Some differences between the MAT and WAPLS results can be seen in the thermal parameters; for example, there were larger
amplitude and higher frequencies of fluctuations with MAT than WAPLS, especially after 4450 cal yr BP. (The minimum of thermal parameters is similar for the two methods, but the maximum of thermal parameters inferred by MAT is higher by about 2°C compared with that reconstructed by WAPLS.) Another difference was the thermal parameters inferred by MAT showing antiphase fluctuations compared with the results of WAPLS after 1000 cal yr BP.

c. Paleoclimate reconstruction with pollen response surface method

The curves of series C in Fig. 4 are the reconstruction results of the two climatic parameters inferred by the pollen response surface method, where Pa varies between 250 and 750 mm, showing similar trends to the results of WAPLS and MAT methods especially before 1500 cal yr BP, but Tw fluctuated between 14.5°C and 25°C, showing a more unstable, larger amplitude and higher-frequency oscillations compared with the results of WAPLS and MAT.

6. Discussion

a. Comparison of the different methods

Quantitative reconstruction of paleoclimate based on fossil pollen data is one of mainstream subjects of modern palynology. Though a variety of mathematical methods have been developed and tested, each method inevitably has some weak points. For example, linear regression takes the relationship between pollen and vegetation as linear and these variables were assumed to be normally distributed, but actually they are not (Prentice et al. 1986). PRS hypothesizes a continuous function in the climate space defined by selected pollen taxa as opposed to entire pollen assemblages, and these pollen types normally have a considerable degree of climatic tolerance, which reduces the accuracy of reconstructions. MAT seems to have advantages against the methods of linear regression and PRS. It takes the present climate parameters of modern surface pollen sites as the climate analog of similar fossil pollen assemblages. One of the considerable disadvantages of MAT is that it is virtually impossible to obtain exact matching between modern and fossil pollen assemblages, and the significance of the disagreement in terms of its climatic implication is ultimately unknown. WAPLS is an improved version of the transfer function method. It approximates the distribution of taxon abundances by a unimodal function of the environmental parameters. WAPLS performs surprisingly well and considerably better than direct analog matching procedures when none of the fossil assemblages are similar to the modern data (ter Braak and Juggins 1993; ter Braak 1995). The main disadvantage of WAPLS is that the implicit inverse regression in WAPLS “pulls” the predicted values toward the mean of the training set, resulting in an inevitable bias with overestimation at low values and underestimation at high values (Birks 1998).

In the contemporary circumstance, any kind of numerical approach is best suited to particular types of data and has its disadvantages. It is still risky to rely on a single reconstruction method. However, if we combine several reconstructions by different methods for the same data, and see if they are consistent, then we should be able at least partly to overcome the problems and obtain more reliable results. If the majority of the reconstruction methods give consistent results, then the inferred climatological values are likely to be real. Otherwise, if the results are inconsistent across different reconstruction methods, more work should be done.

In our work, the average Pa inferred by WAPLS, MAT, and PRS methods were very coherent before 1500 cal yr BP (Fig. 4), with 50–100 mm lower value in the early Holocene than in the present (before 7900 cal yr BP, stage 1) and 100–200 mm higher and again 50–100 mm lower values than in the present in the mid- (8000–2900 cal yr BP, stages 2 and 3; Fig. 4) and late Holocene (after 2900 cal yr BP, Fig. 2; stage 4, Fig. 4), respectively. After 1500 cal yr BP, the PRS reconstructions have a higher magnitude of fluctuations, but the WAPLS and MAT reconstructions are still very similar, indicating the WAPLS and MAT reconstructions are likely to be more reliable here.

The Tw values show great differences between the different reconstruction methods. The Tw inferred by PRS varied between 14.5°C and 25°C before 2900 cal yr BP, with Tw lower than 15°C at about 7600, 5800, 4400, and 3100 cal yr BP. After 2900 cal yr BP, Tw fluctuated at 16°C–18°C, except for at 1600 cal yr BP when Tw reached to 20°C. Though there has not been any reliable template in this region, we could probably conclude that such an amplitude of Tw changes (about 5°C–6°C higher or lower than in present) through the Holocene may not be realistic. The Tw inferred by WAPLS fluctuated at about 20°C during most periods of the Holocene, except for at the periods of 8300–7900, 6000, 4400, 2500, and 500 cal yr BP when Tw was lower than 19.5°C. However, the Tw given by MAT were lower than 19.5°C before 8000 cal yr BP and after 2500 cal yr BP and greater than 20.5°C through most periods of the mid-Holocene (7900–2500 cal yr BP) except for the periods 6000 and 4400 cal yr BP, when Tw was lower than 19.5°C. It seems that reconstructions of Tw inferred by the three methods have some coherent trends, especially for the temperature decline events at about 6000 and
4400 cal yr BP. But the reconstructed values and amplitudes of change of Tw show some differences for the three different methods.

Mean annual temperatures (Ta) were not inferred using the PRS model in the Daihai Lake Basin. Because the pollen response surface was developed as a two-dimensional graph, only two climate parameters can be adopted: precipitation and one measure of temperature. It is believed that pollen assemblages are more sensitive to Tw than Ta and Tc, thus only Tw can be constructed by PRS. In general, the WAPLS and the MAT methods showed consistent trends of Ta reconstructions before 2500 cal yr BP; that is, Ta were the highest between 5800 and 5100 cal yr BP, and were also significantly higher at about 7300 and 3600 cal yr BP, but were lower at about 4400 and 6000 cal yr BP. The Ta values in the mid-Holocene reconstructed by WAPLS and MAT were typically 1°C–2°C and 1°C–3°C higher, respectively, than those of the present. However, Ta values inferred by the MAT displayed slightly higher amplitude of fluctuations, especially after 2500 cal yr BP, showing reconstructions are less robust. Increased human influence is probably one of the main factors that bias the relationship between the vegetation and the climate in north China in the last 2500 years.

Why do the Pa reconstructions inferred by WAPLS, MAT, and PRS methods show very coherent results? The reason might be that the study area of the surface pollen dataset covers a larger gradient in precipitation from east (800 mm) to west (44 mm), but covers a small gradient in temperature (annual average temperature from −3.8°C to 12.6°C, July temperatures from 8.0°C to 26°C, and January averages from −19.0°C to −1.7°C; Li et al. 2007; Wu 1980; Hou 1983; Jiao 1984). Why do the WAPLS and the MAT methods also show quasi-synchronous oscillations of the temperatures, but the PRS method shows more varied temperature values in both amplitude and frequency? The reason might be linked to the disadvantages of the PRS method. At the present resolution of identification, pollen taxa can only be classified at the level of genus for arboreal pollen types or the level of family for most herbs, and the pollen taxa in the same genus or family usually have extremely wide ranges of environmental tolerance. So, the reconstruction temperatures inferred by the PRS method varied more roughly and sharply.

b. Comparison with results of other studies

The results of the pollen-based quantitative climate reconstruction seem to be in agreement with Xiao’s research (Xiao et al. 2004). However, there are differences in the results obtained from pollen spectra from the same sediment core, particularly prior to 7900 cal yr BP, between Li and Xiao’s studies (Xiao et al. 2004; Li et al. 2004). We believe these differences mainly arise from different interpretations of the pollen assemblages or that they may be caused by different pollen analyzers. Before 7900 cal yr BP, both pollen diagrams are dominated by herbs with a certain amount of arboreal pollen. Li et al. (2004) explained the pollen assemblages as vegetation changing from sparse-wood grassland to mixed conifer broad-leaved forest with the climate change from cool and humid to warm and humid (Li et al. 2004). Xiao et al. (2004), on the other hand, interpreted the pollen assemblages as steppes and patches of mixed pine and broad-leaved forest with a mild and dry climate (Xiao et al. 2004). The Li et al. (2004) interpretation of the vegetation as forests with warm and humid climate particularly prior to 7000 cal yr BP is mainly based on the higher pollen concentrations during this period. However, this interpretation does not seem to take into account the different deposition rates (Li et al. 2004). The sediment deposition rates were about 1.2 and 0.32 mm yr⁻¹ (inferred by interpolating between radiocarbon-dated horizons) after and before the years of 7900 cal yr BP, respectively. If the slow deposition rates were considered, they alone could explain the higher pollen concentrations before 7900 cal yr BP. Sun et al. (2006) studied the pollen influx and found lower pollen deposition rates during this period, suggesting a mild and dry climate, in accordance with Xiao’s results.

Wang et al. (2005) proposed a well-accepted and the highest resolution record of precipitation in China’s low-latitude Asian monsoon area. When compared with Wang’s result, the reconstructions (inferred by WAPLS) presented in this paper show very similar fluctuations in mean annual precipitation with Dongge’s δ18O, especially the weak Asian monsoon (AM) events centered at 500, 2700, 4300, 4900, 6300, and 7200 cal yr BP, and the departure of the Daihai Pa reconstructions from the Dongge δ18O is usually within the error in these periods. There are also some differences, for example, the fluctuations of Pa at 1600 and 5600 cal yr BP are opposite to that in the Dongge Cave, and the weak AM event at 8200 cal yr BP is not very obvious (Fig. 5). We think one of the reasons for these differences might be that the low-latitude area (the Dongge Cave) is influenced both by the Indian monsoon and the East Asian monsoon, while the Daihai Lake area was mainly influenced by the East Asian monsoon. The weak monsoon event at 1600 and 5600 cal yr BP in China’s low-latitude area became a humid event in the Daihai Lake area at that time. It might be a special feature of East Asian monsoon climate. Otherwise, the differences might be caused by the different degree of dating precision, the different
temporal resolution, or the different sensitive response of climate proxies to the climate variations.

Analysis of all Dongge Cave weak monsoon events since 9000 cal yr BP, including Bond events 0–4 and 2 North Atlantic ice-rafted debris (IRD) events (Wang et al. 2005; Bond et al. 2001), suggest that North Atlantic IRD events are linked not only to the low-latitude areas of China, but also to the midlatitude areas, such as the dry Daihai Lake area, which is close to the monsoons’ northern limit. Our reconstructions show a weak monsoon event at 4900 cal yr BP, which can also be recognized at the Dongge Cave (Wang et al. 2005), although the authors did not point it out (Fig. 4).

7. Conclusions

Weighted averaging partial least squares method (WAPLS), modern analog technique (MAT), and pollen response surface method (PRS) provided three coherent reconstructions on average annual precipitation $P_a$ with 50–100 mm lower values than present in the early Holocene (before 7900 cal yr BP; stage 4), 100–200 mm higher than present in the mid-Holocene (7900–2900 cal yr BP; stages 2 and 3), and 50–100 mm lower again than that of the present in the late Holocene (after 2900 cal yr BP; stage 1). So it seems that these reconstructions of average annual precipitations $P_a$ are reliable and thus are telling us a real story of climate changes in the Holocene. The WAPLS and the MAT methods also gave very consistent temperature reconstructions ($T_a$ and $T_w$), although the temperature reconstructions inferred by MAT fluctuated at slightly higher amplitude and frequency than those by WAPLS, perhaps because the WAPLS methods bias toward overestimating at the low end and underestimating at the high end of the reconstruction range. However, all these inferred thermal parameters show coherent fluctuations except for the out-of-phase fluctuations after 1000 cal yr BP. Mean annual temperatures $T_a$ were absent for PRS model. But the reconstruction values of $T_w$ obtained by PRS showed great differences compared with the results inferred both by the WAPLS and the MAT methods. The temperature reconstructions generally had less reliability compared with the precipitation reconstruction and need to be improved. The reconstructed fluctuations of $P_a$ in this paper are roughly coherent with those in the Dongge Cave (Wang et al. 2005). Some slightly differences might be linked to
differences in Indian monsoon and East Asia monsoon climates or caused by the different degree of dating precision, the different temporal resolution, and the different sensitive responses of climate proxies to the climate variations.

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