BOREAS An international journal of Quaternary research

Holocene precipitation and temperature variations in the East Asian monsoonal margin from pollen data from Hulun Lake in northeastern Inner Mongolia, China

RUILIN WEN, JULE XIAO, ZHIGANG CHANG, DAYOU ZHAI, QINGHAI XU, YUECONG LI AND SHIGERU ITOH

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Wen, R. L., Xiao, J. L., Chang, Z. G., Zhai, D. Y., Xu, Q. H., Li, Y. C. & Itoh, S. 2010 (April): Holocene precipitation and temperature variations in the East Asian monsoonal margin from pollen data from Hulun Lake in northeastern Inner Mongolia, China. *Boreas*, Vol. 39, pp. 262–272. 10.1111/j.1502-3885.2009.00125.x. ISSN 0300-9483.

Quantitative palaeoclimatic reconstruction with the weighted averaging partial least squares method was applied to the pollen profile from Hulun Lake in northeastern Inner Mongolia. The data provide a detailed history of variations in precipitation and temperature over the northeastern margin of the East Asian summer monsoon during the Holocene. A warm and dry climate prevailed over the lake region until *c*. 8000 cal. BP. During the period *c*. 8000–4400 cal. BP, precipitation increased markedly and temperature gradually declined. The interval between *c*. 4400 and 3350 cal. BP was marked by extremely dry and relatively cold conditions. Precipitation recovered from *c*. 3350 to 1000 cal. BP, with temperatures rising *c*. 3350–2050 cal. BP and dropping *c*. 2050–1000 cal. BP. During the last 500 years, the climate of the lake region displayed a general trend of warming and wetting. While Holocene temperature variations in the mid-high latitude monsoonal margin were controlled by changes in summer solar radiation in the Northern Hemisphere, they could also be related to the strength of the East Asian summer monsoon. The lack of precipitation during the early Holocene could be attributed to the weakened summer monsoon resulting from the existence of remnant ice sheets in the Northern Hemisphere. Changes in the monsoonal precipitation during the middle to late Holocene would have been associated with the ocean–atmosphere interacting processes occurring in the western tropical Pacific.

Ruilin Wen (e-mail: rlwen@mail.iggcas.ac.cn), Jule Xiao, Zhigang Chang and Dayou Zhai, Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, 19 Beitucheng West Road, Chaoyang District, Beijing 100029, China; Qinghai Xu and Yuecong Li, College of Resources and Environment, Hebei Normal University, Shijiazhuang 050016, China; Shigeru Itoh, Paleo Labo Co., Ltd., Saitama 335–0016, Japan; *received 14th June 2009, accepted 9th September 2009.*

The East Asian monsoon is an integral component of the earth's climate system and plays an important role in global hydrologic and energy cycles (Chinese Academy of Sciences 1984; Zhang & Lin 1985). Recently, An *et al*. (2000) suggested that the East Asian summer monsoon reached a maximum in different regions of China at different times of the Holocene, e.g. 9000 cal. BP in North China, 6000 cal. BP in the middle and lower reaches of the Yangtze River and 3000 cal. BP in South China. Inspired by this conceptual model, palaeoclimatic researchers have investigated a great number of sedimentary sequences over the past decade to come to an understanding of the process of East Asian monsoon variations during the Holocene. With the growth of proxy records, however, three conflicting views of the timing of the maximum Holocene monsoon precipitation have emerged. The monsoon precipitation was: (1) intensified during both the early and middle Holocene (Zhou *et al*. 2002; Feng *et al*. 2004); (2) strengthened during the early Holocene but weakened during the middle Holocene (Chen, C. T. A. *et al*. 2003; Chen, F. H. *et al*. 2003); and (3), weakened during the early Holocene but intensified during the middle Holocene (Xiao *et al*. 2002, 2004, 2006; An *et al*. 2003; Sun *et al*. 2006). The Holocene history of the monsoon climate is essential background for understanding the extreme climatic conditions at present and for constraining the predictions of climatic trends in the near future (An 2000). Precise reconstruction of the process of Holocene East Asian monsoon variations is becoming urgent.

Fossil pollen can provide direct information on past changes in the regional vegetation and climate. With the application of the statistical relationship between surface pollen assemblages and modern climatic conditions to fossil pollen profiles, quantitative reconstruction of palaeoclimatic parameters has proved to be a powerful tool for understanding the past history of variations in temperature and precipitation (Imbrie & Kipp 1971; Bartlein *et al*. 1984; Guiot 1987). In this study, we applied the weighted averaging partial least squares method to a Holocene pollen record of a sediment core recovered in the central part of Hulun Lake in northeastern Inner Mongolia, China. The lake is located near the northeastern margin of the current monsoon region and is an ideal target for studying the East Asian monsoon variability. Our quantitative reconstruction provides a detailed history of Holocene temperature and precipitation variations in the monsoon marginal region and contributes to a better understanding of the processes of East Asian monsoon variations during the Holocene and physical links between the East Asian monsoon regime and other subcomponents of the global climate system.

DOI 10.1111/j.1502-3885.2009.00125.x

Study area

Hulun Lake (48°30′40″–49°20′40″N, 117°00′10″–117° 41′40″E) is situated about 30 km south of Manchuria, Inner Mongolia (Fig. 1). The lake has an area of 2339 km^2 and a maximum water depth of 8 m when the elevation of the lake level is 545.3 m a.s.l. (measurements in August 1964 by Xu *et al.* 1989). Low mountains and hills border the lake on the northwest and form a fault-scarp shoreline. Broad lacustrine and alluvial plains scattered with stable and semi-stable dunes are present along the southern and eastern shores. The lake has a catchment of 37 214 km^2 within the borders of China, and two major rivers enter the lake from the southwest and southeast (Fig. 1). The Dalanolom River, an intermittent river, drains the lake when elevation of the lake level exceeds 543.4 m a.s.l. and enters the lake when the lake level is lower and the discharge of the Hailar River is larger as well (Xu *et al.* 1989) (Fig. 1).

Hulun Lake is located in the semi-arid areas of the middle temperate zone. The climate of the lake region is controlled by the Westerly winds and the East Asian monsoon (Chinese Academy of Sciences 1984; Zhang & Lin 1985). During winters, the cold, dry northwesterly airflows generated by the Mongolian High prevail and bring strong winds and cold air to the study region. During summers, the warm, moist southerly air-masses driven by the pressure gradient between the Subtropical High and the Continental Low interact with cold air from the northwest and produce most of the annual precipitation. In the study region, mean annual temperature is 0.3 °C, with a July average of 20.3 °C and a January average of −21.2 °C. Mean annual precipitation is 247–319 mm, and 80–86% of the annual precipitation falls in June–September. Mean annual evaporation reaches 1400–1900 mm, which is 5–6 times the annual precipitation. The lake is covered with ~1 m of ice from early November to late April (Xu *et al.* 1989).

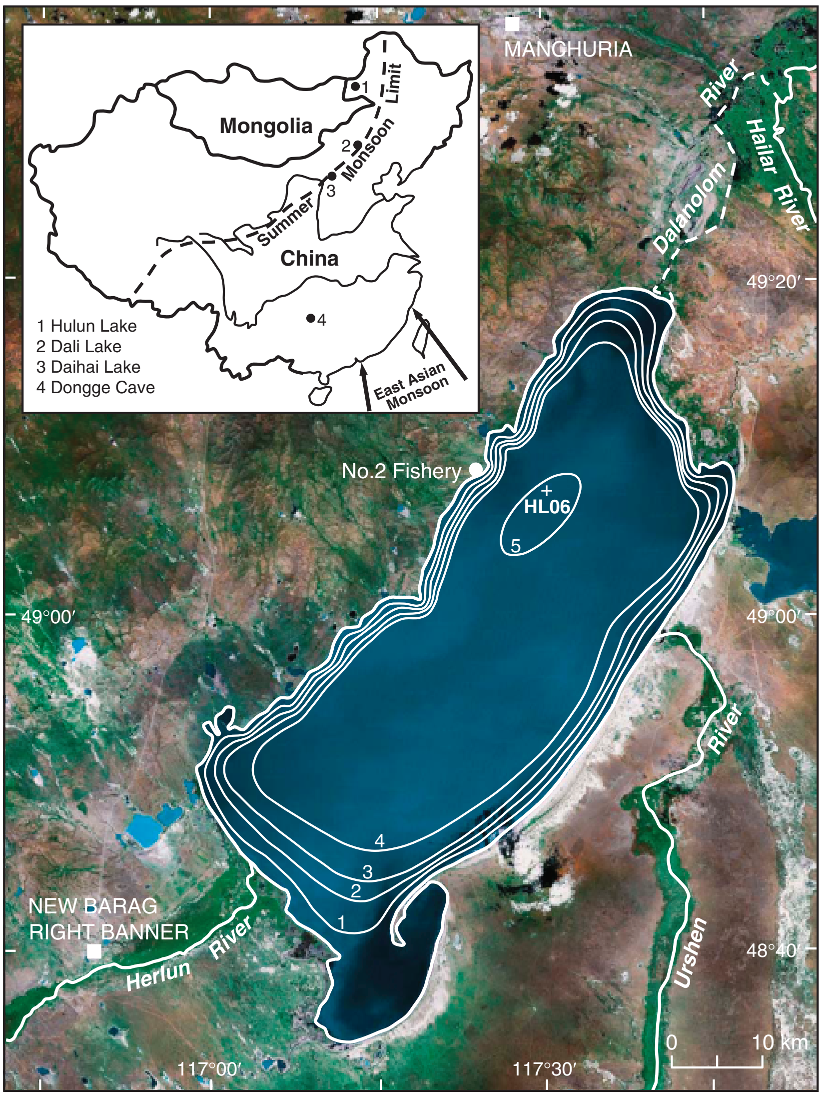

Fig. 1. Map of Hulun Lake (from http://maps.google.com) showing the location of the HL06 sediment core. The bathymetric survey of the lake was conducted in July 2005 with a FE–606 Furuno Echo Sounder (contours in metres). Inset: the current northern limit of the East Asian summer monsoon (dashed line) and the locations of lakes and Dongge Cave (solid circles) mentioned in the text. This figure is available in colour at http://www.boreas.dk.

The modern natural vegetation of the Hulun lake basin is categorized as middle temperate steppe and dominated by grasses and *Artemisia* species (Compilatory Commission of Vegetation of China 1980; Xu *et al.* 1989). The vegetation cover ranges from relatively moist forb–grass meadow–steppe in the piedmont belt to moderately dry grass steppe on the alluvial plain and dry bunchgrass–undershrub *Artemisia* steppe on the lacustrine plain. Halophilic Chenopodiaceae plants are developed in the lowlands. Small patches of open elm forests and sandy shrubs grow in the stabilized dune fields. Tall-grass meadows can be seen in the river valleys. The forests consisting of *Larix gmelini*, *Pinus sylvestris* and *Picea koraiensis* are distributed on the west slopes of the Great Hinggan Range, where the Urshen and Hailar rivers rise, accompanied by scrubs and herbs under the trees (Compilatory Commission of Vegetation of China 1980). Larch forests mixed with *Pinus sylvestris*, *Betula platyphylla* and *Populus tremula* cover the southern part of the Hentiy Mountains, where the Herlun River rises (Hilbig 1995). Patches of *Pinus sibirica* forests and *Betula rotundifolia* shrubberies exist in the alpine belt. Bogs composed of *Betula fusca*, *Carex vesicata*, *Carex canescens* and *Eriophorum* are developed in the valleys.

Material and methods

HL06 sediment core

Drilling was conducted in January 2006 on the ice in the central part of Hulun Lake (Fig. 1). The sediment core was taken in a polymethyl methacrylate tube with a piston corer, extracted to a depth beneath the lake floor of 1.7 m and designated HL06 (49°07.615′N, 117°30.356′E) (Fig. 1). The core section was cut into 1-cm segments, resulting in 170 samples for laboratory analysis.

Core sediments can be divided lithologically into three parts: upper blackish-grey oozy mud at core depths of 0–35 cm, middle dark grey to blackish-grey sandy mud at depths of 35–100 cm and lower greenish-grey homogeneous mud at depths of 100–170 cm (Fig. 2). Scattered fragments of ostracode and mollusc shells can be seen in the middle of sandy mud.

Dating method and age model

Thirteen bulk samples were collected at ~10 cm intervals from the organic-rich horizons of the HL06 sediment core (Fig. 2, Table 1) and dated with an Accelerator Mass Spectrometry (AMS) system (Compact-AMS, NEC Pelletron) at Paleo Labo Co., Ltd., Japan. Organic carbon was extracted from each sample and dated following the method described by Nakamura *et al.* (2000). The ^{14}C dates of all the samples from the HL06 core were determined with a half-life of 5568 years.

The uppermost 0–1 cm of the core sediments yields a ^{14}C age of 685 years that is closely related to the ^{14}C ages throughout the core. This age can be considered to result from 'hard-water' and other reservoir effects on radiocarbon dating of Hulun Lake sediments, although the reservoir effects probably varied with time. To produce an age–depth model for the HL06 core, we first subtracted the reservoir age of 685 years from all the original ^{14}C ages, assuming that this is constant through the core, and then performed calibrations on the reservoir-effect-free ^{14}C dates. The conventional ages were converted to calibrated ages using the OxCal v3.1 radiocarbon age calibration program (Bronk Ramsey 2001) with IntCal04 calibration data (Reimer *et al.* 2004) (Fig. 2, Table 1). Ages of sampled horizons of the sediment core were derived by linear interpolation between radiocarbon-dated horizons using the mean values of 2σ ranges of calibrated ages. The age–depth model indicates that the upper 1.7 m of the HL06 core sediments covers the last *c.* 11 000 years (Fig. 2).

Pollen analysis method

Fossil pollen was extracted following the HCl–NaOH–HF method described by Fægri *et al.* (1989). For each sample of 1 g of air-dried sediment, 10 mL of 18% hydrochloric acid (HCl) was added to remove carbonates. Then 10 mL of 10% sodium hydroxide (NaOH) was added to the residue, and the solution was heated in a water bath at 95 °C for 15 min to remove organic matter. The residue was then kept in 5 mL of 45% hydrofluoric acid (HF) for 12 h to remove silicates. After the pretreatment, pollen grains were extracted by wet-sieving of the resulting residue through a sieve diameter of 10 μm in an ultrasonic vibrator. In order to calculate pollen concentrations, 27 637 exotic spores of *Lycopodium* were added to each sample before the pretreatment with hydrochloric acid.

Fossil pollen was identified and counted under an Olympus light microscope at 400× magnification. More than 600 pollen grains were counted for each sample. The percentages of tree and herb pollen taxa are based on the sum of the total terrestrial pollen in a sample, and those of each taxon of both aquatic pollen and fern spores based on the sum of the terrestrial pollen plus the aquatic pollen or fern spores of the taxon in a sample. The percentage pollen diagram of the HL06 sediment core spanning the last *c.* 11 000 years can be divided into seven pollen assemblage zones based on stratigraphically constrained cluster analysis (CONISS, Grimm 1987) (Fig. 3).

Quantitative reconstruction method

Two-hundred-and-forty-two surface samples from northern China and Mongolia (lat. 33°57′–51°26′N,

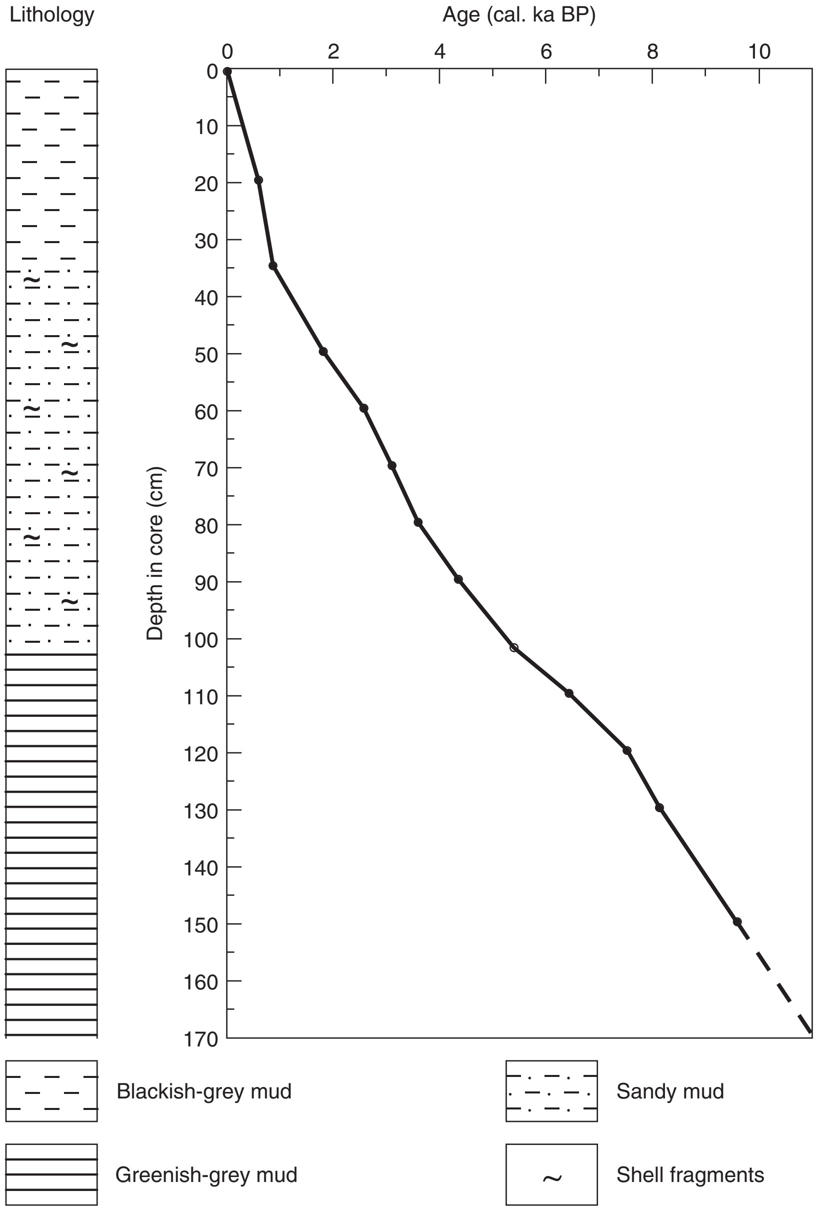

Fig. 2. Lithology and age–depth model of the HL06 sediment core recovered in the central part of Hulun Lake. Solid dots represent the mean values of ranges of calibrated radiocarbon ages with 2σ error. Dashed line was linearly extrapolated for ages of sampled horizons of the lowermost 20 cm sediment core from the calibrated ages of the two superjacent radiocarbon-dated horizons.

long. 88°18′–117°35′E, elevation 550–3600 m a.s.l.) were used to establish the data set of the relationship between surface pollen assemblages and modern climatic conditions. In the sampled region, mean annual temperature ranges from −8.9 to 3.9 °C, with a July average from 7.2 to 22.9 °C and a January average from −32.5 to −11.5 °C, and decreases with increasing latitude and altitude (Fig. 4A). Mean annual precipitation varies from 713 to 96 mm, and declines gradually northwestwards in northern China and increases northwards in Mongolia (Fig. 4B). The distribution of vegetation in the sampled region exhibits several zones, including cold-temperate conifer forests, warm-temperate deciduous broad-leaved forests, temperate steppes and deserts (Fig. 4C).

Based on the modern data set, pollen–climate transfer functions were developed using the weighted averaging partial least squares (WAPLS) method (Birks *et al.* 1990; Birks 1995, 1998; ter Braak & Juggins 1993; Jongman *et al.* 1995). The WAPLS method is based on partial least squares regression, and uses additional components that utilize the residual structure in the species data for improving the species optima and reducing the error in the final calibration function (ter Braak & Juggins 1993; Birks 1998). The WAPLS components that gave the lowest root mean square errors of prediction (RMSEP) and highest adjusted coefficients of determination (R^2) were finally selected (Table 2). This method performs well with noisy, species-rich data that cover a long ecological gradient (Hill & Gauch

Table 1. AMS radiocarbon dates of samples from the HL06 sediment core recovered in the central part of Hulun Lake.

Laboratory no.*	Depth interval (cm)	Dating material	$\delta^{13}C$ (‰)	AMS ^{14}C age (^{14}C years BP)	Corrected ^{14}C age **(^{14}C years BP)	Calibrated ^{14}C age (2σ) (cal. BP)
PLD–7489	1–0	Organic matter	−26.94	685±21	0±30	0– −10
PLD–7491	20–19	Organic matter	−25.63	1335±22	650±30	610–550
PLD–7493	35–34	Organic matter	−26.01	1611±22	926±30	930–770
PLD–7494	50–49	Organic matter	−26.40	2543±22	1858±30	1870–1710
PLD–7925	60–59	Organic matter	−26.57	3222±29	2537±36	2650–2480
PLD–7495	70–69	Organic matter	−27.73	3630±27	2945±34	3220–2970
PLD–7926	80–79	Organic matter	−26.72	4034±30	3349±37	3690–3470
PLD–7927	90–89	Organic matter	−25.40	4575±31	3890±37	4430–4230
PLD–7496	102–101	Organic matter	−28.38	5304±27	4619±34	5470–5290
PLD–7928	110–109	Organic matter	−26.34	6338±35	5653±41	6510–6310
PLD–7498	120–119	Organic matter	−30.24	7285±30	6600±37	7570–7430
PLD–7929	130–129	Organic matter	−26.53	8003±38	7318±43	8200–8010
PLD–7499	150–149	Organic matter	−30.99	9268±38	8583±43	9660–9480

*PLD: Paleo Labo Dating, laboratory code of Paleo Labo Co., Ltd., Japan.
**The reservoir correction factor is 685 years, ^{14}C age of the uppermost 1 cm of the core sediments.

1980; ter Braak & Prentice 1988), and is applicable to quantitative reconstruction in the present study.

Results

Application of the modern pollen–climate data set with the WAPLS method to pollen assemblages of the HL06 core sediments (Fig. 3) yields mean annual precipitation (P_a), mean annual temperature (T_a) and mean temperatures of the warmest month (T_w) and coldest month (T_c) in the Hulun Lake area during the Holocene (Fig. 5). The root mean square errors of prediction (RMSEP) for P_a, T_a, T_w and T_c are 81 mm, 2.1 °C, 2.4 °C and 3.7 °C, respectively; whereas the adjusted coefficients of determination (R^2) are 0.73, 0.29, 0.42 and 0.29, respectively (Table 2). The time series of the reconstructed vegetation and climate records spanning the last *c.* 11 000 years can be divided into the following seven stages corresponding to pollen assemblage zones.

Stage 7 (c. 11 000–8000 cal. BP)

The lake basin was dominated by dry steppe, as indicated by the lowest proportion of Poaceae pollen. In the surrounding mountains, almost no patches of cold-tolerant pine forests were developed, as reflected by the sparseness of *Pinus* pollen. Consistent with the inference from percentage pollen diagram, the reconstructed climate record shows that warm and relatively drier conditions prevailed during this stage. P_a was lower with an average of *c.* 300 mm, close to the present value. Temperature displayed the highest values within the entire Holocene. T_a, T_w and T_c fluctuated around 0.6 °C, 17.3 °C and −18.3 °C, respectively.

Stage 6 (c. 8000–6400 cal. BP)

The marked increase in the proportion of Poaceae pollen suggests that grasses expanded and relatively humid meadow–steppe covered the lake basin. High percentages of *Betula* and *Corylus* pollen indicate that large-scale birch forests were developed in the mountains. The frequent occurrence of *Pinus* pollen, although in low proportion, implies that the climatic condition was cooling. This stage is characterized by a significant increase in precipitation and a gradual decline in temperature. P_a reached its highest value of 340 mm, ~40 mm higher than the preceding stage 7. T_a (average of ~0.2 °C) and T_w (average of ~16.5 °C) showed a more obvious trend of decline compared with T_c (average of about −18.5 °C).

Stage 5 (c. 6400–4400 cal. BP)

Both the decreasing trend in the percentage of *Artemisia* pollen and the increasing trend in the proportion of Chenopodiaceae pollen suggest that the climate was drying during this stage. Birch forests declined and pine forests expanded in the surrounding mountains. The reconstructed climate record shows that P_a declined slightly and fluctuated around 330 mm. T_a and T_w dropped to ~0.1 and 16.2 °C. T_c displayed quite a high average value and attained up to −17.8 °C first before returning to the decreasing trend while fluctuating.

Stage 4 (c. 4400–3350 cal. BP)

Steppe desert covered the lake basin, as indicated by the lowest percentage of *Artemisia* pollen and highest proportion of Chenopodiaceae pollen. The birch forests apparently contracted in the mountains, as suggested by large decreases in the proportions of *Betula* and *Corylus* pollen. This stage is marked by the lowest P_a

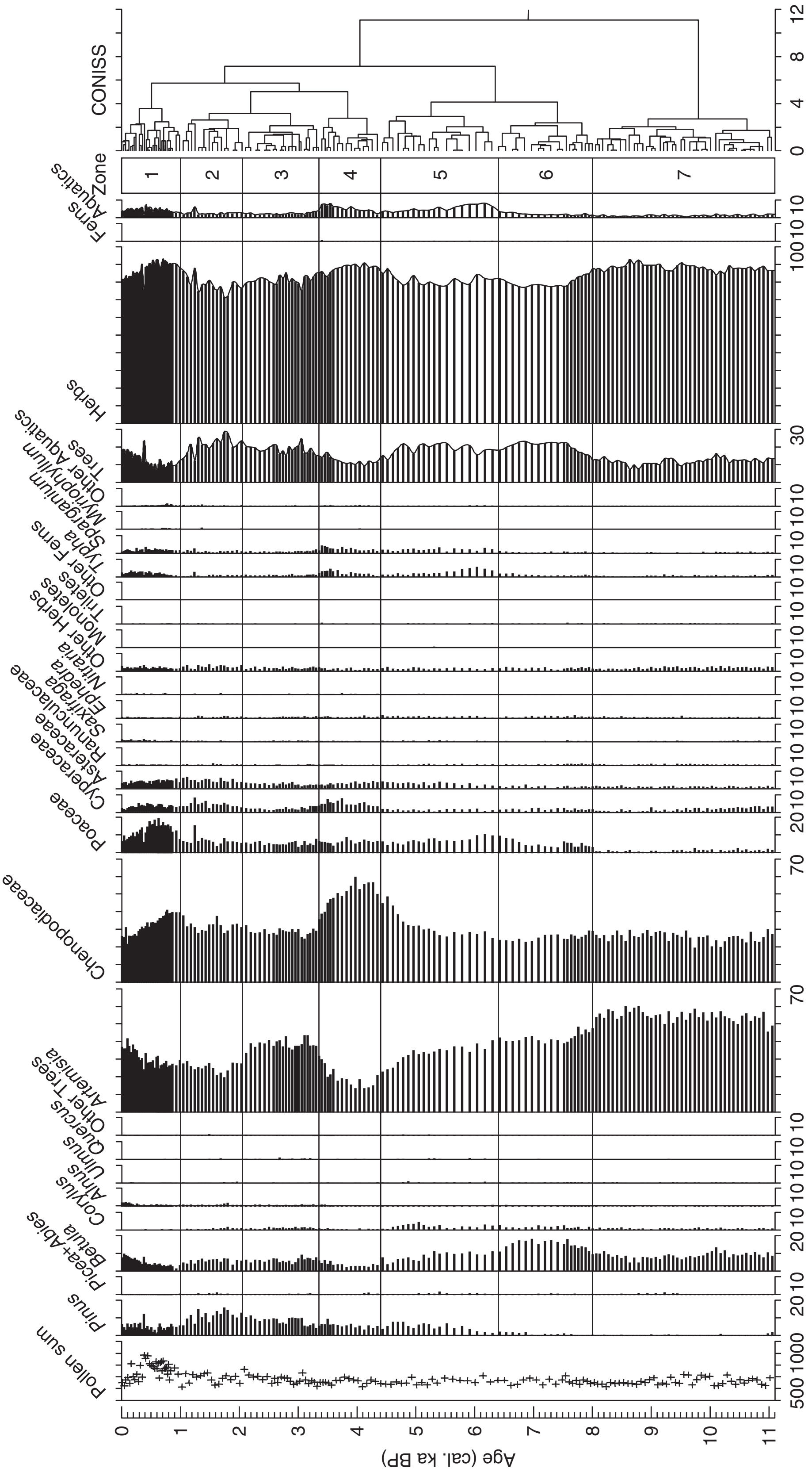

Fig. 3. Percentage pollen diagram of the HL06 sediment core spanning the last *c.* 11 000 years. Stratigraphically constrained cluster analysis (CONISS) is based on the total sum of squares. The chronology was derived from the age–depth model with the reservoir-age corrected.

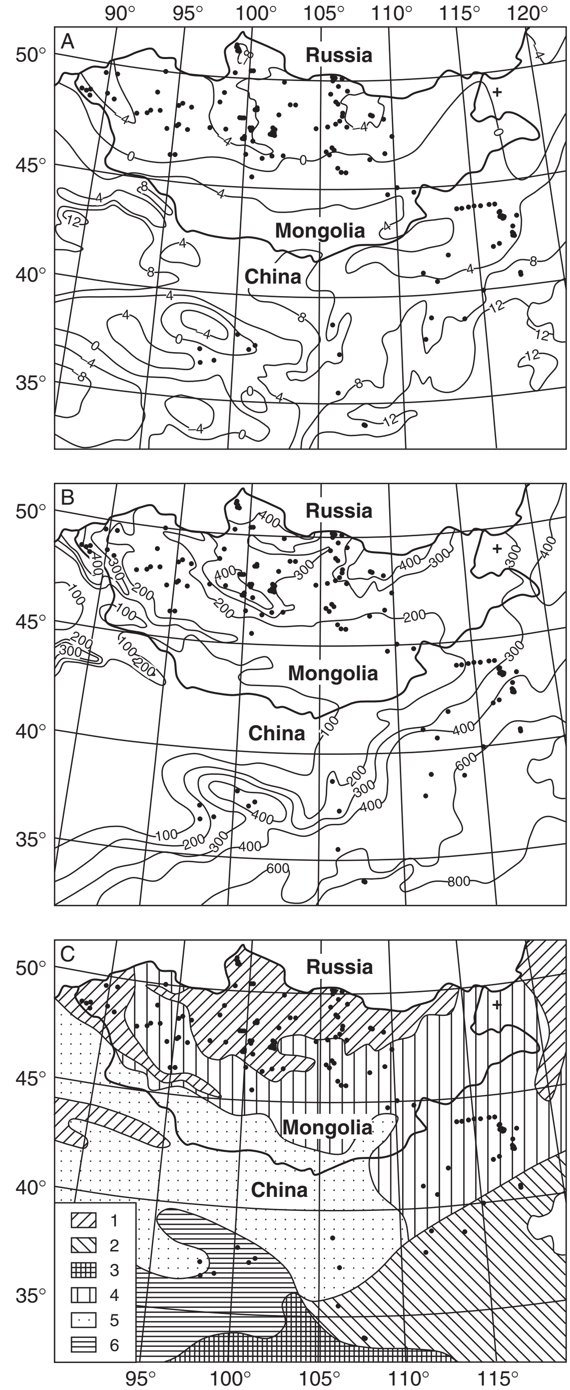

Fig. 4. Map of north China and Mongolia showing the distribution of 242 surface pollen-sampling sites (dots) and the location of Hulun Lake (cross). A. Isotherm of mean annual temperature (°C) (Chinese Academy of Sciences 1984; Orshikh *et al.* 1990). B. Isohyet of mean annual precipitation (mm) (Chinese Academy of Sciences 1984; Hilbig 1995). C. Vegetation zones (Compilatory Commission of Vegetation of China 1980; Chinese Academy of Sciences 1983; Hilbig 1995). In C, 1 = cold-temperate conifer forest; 2 = warm-temperate deciduous broad-leaved forest; 3 = subtropical mixed evergreen–deciduous forest; 4 = temperate steppe; 5 = temperate desert; 6 = steppe on the Tibetan Plateau.

values, with an average of ~260 mm within the entire Holocene. T_a decreased from ~0 to −0.5 °C. T_w varied within a range from ~16.6 to 15.8 °C. T_c was much lower than that of the preceding stage 5 and exhibited fluctuations around −18.8 °C.

Stage 3 (c. 3350–2050 cal. BP)

The grassland vegetation recovered and the climatic condition ameliorated, as suggested by a large increase in the proportion of *Artemisia* pollen. The increases in the proportion of tree pollen from *Pinus*, *Betula*, *Corylus* and *Alnus* reflect a recovery of woody plants. During this period, P_a displayed an obvious recovery and attained up to ~310 mm. T_a and T_w increased to about −0.1 and 16.5 °C, whereas T_c decreased gradually from about −18.7 to −19.2 °C.

Stage 2 (c. 2050–1000 cal. BP)

The increase in the proportion of arboreal pollen mainly derived from *Pinus* suggests the expansion of pine forests in the mountains and the cooling of climatic conditions in the lake region. During this stage, P_a (average of ~310 mm) remained largely unchanged compared with the preceding stage 3. The temperature dropped to the lowest values within the whole Holocene. T_a, T_w and T_c all showed fluctuations to a certain extent.

Stage 1 (c. 1000–0 cal. BP)

This most recent stage would be subdivided into two stages: *c.* 1000–500 and 500–0 cal. BP. Considerably lower values of all the P_a, T_a, T_w and T_c during the interval of *c.* 1000–500 cal. BP would have resulted from the expansion of Chenopodiaceae and Poaceae plants in the lake region (Figs 3, 5), which would have been associated with human activities rather than climatic changes because of almost the same *Artemisia* covers as the preceding stage 2. During the last *c.* 500 years, P_a, T_a, T_w and T_c all displayed an increasing trend, suggesting that the climate of the lake region has become warm and wet.

Discussion

The temperature record reconstructed by the pollen data from the HL06 core sediments, roughly correlated with the wax and wane of *Betula* and *Pinus* pollen proportions, shows a warm early Holocene and a gradual cooling middle and late Holocene in the Hulun Lake region (Figs 5, 6). This is in good agreement with orbitally induced variations in summer solar radiation in the Northern Hemisphere (Berger & Loutre 1991) (Fig. 6), implying that Holocene temperature changes on the

Table 2. Root mean square errors of prediction (RMSEP) and adjusted coefficients of determination (R^2) of the WAPLS components calculated by bootstrapping. The components with the lowest RMSEP and highest R^2 (asterisked) are selected for this study.

WAPLS component	P_a		T_a		T_w		T_c	
	RMSEP	R^2	RMSEP	R^2	RMSEP	R^2	RMSEP	R^2
Component 1	87	0.68	2.1	0.27	2.5	0.38	3.8	0.26
Component 2	*81	*0.73	*2.1	*0.29	*2.4	*0.42	*3.7	*0.29
Component 3	82	0.73	2.2	0.28	2.5	0.38	3.8	0.28
Component 4	86	0.71	2.3	0.23	2.8	0.33	3.9	0.26
Component 5	92	0.68	2.6	0.17	3.1	0.25	4.1	0.22
Component 6	103	0.63	3.0	0.11	3.4	0.21	4.4	0.19

orbital scale were directly controlled by changes in summer solar insolation.

Moreover, the temperature of the lake region displays obvious drops around *c.* 8500, 7500, 6500, 5700, 4400–3350, 3000, 1700 and 600 cal. BP (Figs 5, 6). These cooling events occurring on millennial to centennial scales can be correlated, within dating uncertainties, with weak East Asian monsoon events indicated by heavier shifts in $\delta^{18}O$ of the Dongge Cave stalagmite (Wang *et al.* 2005) (Figs 1, 6) and Holocene ice-rafting events in the North Atlantic (Bond *et al.* 2001). Nevertheless, more similarities between our pollen-reconstructed temperature record and the stalagmite $\delta^{18}O$ record of Dongge Cave can be seen if the frequency and relative duration and intensity of these events are taken into consideration. The close relation between cooling in the mid-high latitude monsoonal margin and weakening of the East Asian summer monsoon denotes that millennial- to centennial-scale temperature changes in the monsoon region during the Holocene might be significantly influenced by the latent heat transported by the summer monsoon circulation from the tropical Pacific onto inland China.

The percentage pollen diagram shows that relatively humid meadow–steppe replaced dry steppe in the lake basin and large-scale birch forests expanded in the mountains *c.* 8000 cal. BP (Fig. 3). Consistently, the pollen-derived reconstruction indicates that the precipitation did not begin to increase in the Hulun Lake region until *c.* 8000 cal. BP (Figs 5, 6). This pattern of changes in the precipitation is consistent with that suggested by the multiple proxy records from Daihai and Dali Lake in northern China (Xiao *et al.* 2004, 2006, 2008) (cf. Fig. 1), but distinct from that indicated by the $\delta^{18}O$ record of Dongge Cave stalagmite (Wang *et al.* 2005) (cf. Figs 1, 6). We infer that the monsoonal rainfall belt would not penetrate into its modern northern limit but would maintain in the region of the lower and middle reaches of the Yangtze River during the early Holocene. In other words, the East Asian summer monsoon did not reach its maximum intensity until *c.* 8000 cal. BP.

The East Asian monsoon is primarily controlled by the thermal contrast between the tropical Pacific Ocean and the Asian continent, and the discontinuous northward migration of the monsoon rainfall belt is largely associated with the pattern of atmospheric circulation over the middle and high latitudes of the Northern Hemisphere (Chinese Academy of Sciences 1984; Zhang & Lin 1985). Previous studies on the moraines deposited during the transition from the last glacial to the postglacial have indicated that retreat of the North American ice sheet commenced *c.* 15 000 ^{14}C years BP, reached mid-point *c.* 10 000 ^{14}C years BP and ended *c.* 6000 ^{14}C years BP, whereas the beginning and ending of the retreat of Scandinavian ice sheets were several thousand years earlier (Kutzbach & Street-Perrott 1985; Ruddiman 2001). Based on these data, we infer that the existence of remnant Northern Hemisphere ice sheets during the early Holocene would have halted the northward retreat of the Polar Front in the North Pacific Ocean and hampered the northward penetration of the summer monsoonal front, thereby suppressing monsoonal precipitation over the northern interior of China.

Moreover, the reconstructed precipitation record reveals that an extremely dry condition occurred in the Hulun Lake region from *c.* 4400 to 3350 cal. BP (Figs 5, 6), when arid-tolerant Chenopodiaceae plants prevailed and the lake basin was dominated by steppe desert. This remarkably dry event can be found from a number of proxy records from the East Asian monsoon region (Zhou *et al.* 2002; Xiao *et al.* 2004, 2008; Wang *et al.* 2005; Selvaraj *et al.* 2007), and was considered to be responsible for the collapse of Neolithic Cultures in North China (Wu & Liu 2004). Although the widespread appearance of this dry event was attributed to the cooling event, 'Holocene Event 3', occurring in the North Atlantic (Morrill *et al.* 2003; Wu & Liu 2004; Wang *et al.* 2005; Selvaraj *et al.* 2007), the question of how a moderate cooling in the North Atlantic could cause such a prominent drying in eastern Asia still remains open. It is noticeable that the sea surface temperature in the western tropical Pacific largely declined during the interval from *c.* 4400 to 3350 cal. BP (Stott *et al.* 2004) (Fig. 6) and that the Kuroshio Current, a major boundary current that transports warm and salty seawater from the western tropical Pacific to the North Pacific, weakened and shifted to the Pacific between *c.* 4600 and 2700 cal. BP (Shieh & Chen 1995; Jian *et al.* 2000). The remarkable dry event occurring *c.* 4400 to

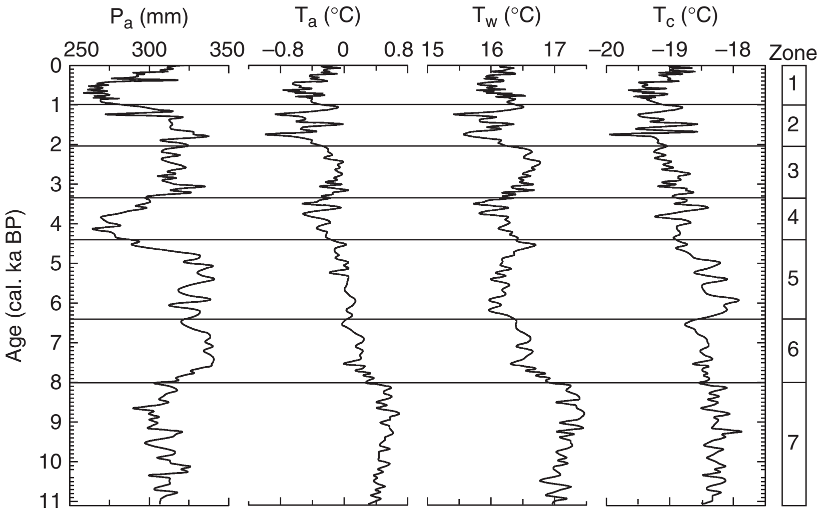

Fig. 5. Mean annual precipitation (P_a), mean annual temperature (T_a) and mean temperatures of the warmest month (T_w) and coldest month (T_c) over the Hulun Lake region during the Holocene reconstructed with the WAPLS method. The root mean square errors of prediction (RMSEP) for P_a, T_a, T_w and T_c are 81 mm, 2.1 °C, 2.4 °C and 3.7 °C, respectively; whereas the adjusted coefficients of determination (R^2) are 0.73, 0.29, 0.42 and 0.29, respectively. Horizontal lines indicate the stages characterizing the pattern of changes in the vegetation and climate over the Hulun Lake region as shown in Fig. 3.

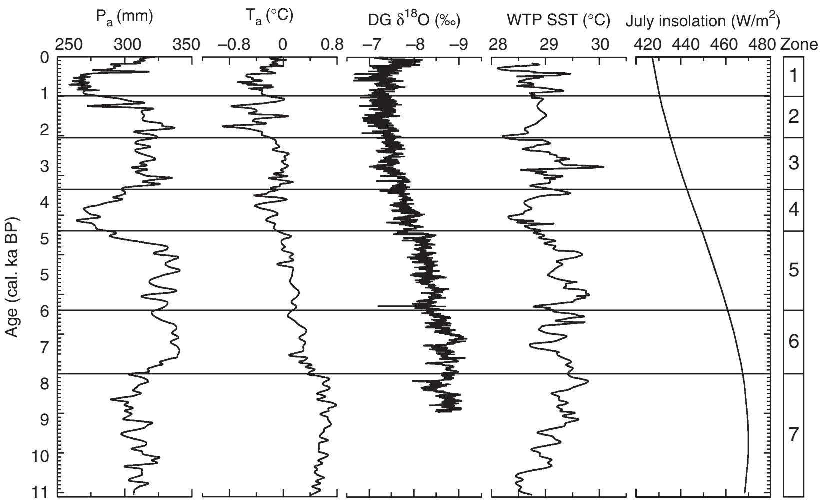

Fig. 6. Correlation of the reconstructed precipitation (P_a) and temperature (T_a) records from the HL06 sediment core at Hulun Lake with $\delta^{18}O$ of Dongge Cave stalagmite (Wang *et al.* 2005), sea surface temperature (SST) of the western tropical Pacific (Stott *et al.* 2004) and July insolation at 65°N (Berger & Loutre 1991). Horizontal lines indicate the stages characterizing the pattern of changes in the vegetation and climate over the Hulun Lake region as shown in Figs 3 and 5.

3350 cal. BP in northern China was almost coeval with the sharp decline of the water temperature in the western tropical Pacific and the eastward shift and reduction of the Kuroshio Current. We thus suggest that the ocean–atmosphere interacting processes occurring in the tropical Pacific would have played a significant role in adjusting millennial to centennial scale monsoon variability during the Holocene. Both a decreased sea surface temperature in the western tropical Pacific and a weakened, eastward shifted Kuroshio Current could reduce the formation of water vapour over the western tropical Pacific and decrease the moisture available for transport via the monsoon circulation from the low-latitude Pacific onto the Asian inland, thereby resulting in a weakened summer monsoon.

Conclusions

Quantitative palaeoclimatic reconstruction based on the pollen data from a sediment core of Hulun Lake in northeastern Inner Mongolia has provided a high-resolution record of Holocene temperature and precipitation changes in the mid-high latitude margin of the East Asian summer monsoon. The temperature was warm during the early Holocene and began to decrease gradually from *c.* 8000 cal. BP with two relatively cold intervals occurring *c.* 4400–3350 and 2050–1000 cal. BP. The precipitation was low during the early Holocene and was significantly enhanced *c.* 8000 cal. BP with an extremely low period between *c.* 4400 and 3350 cal. BP. Changes in the temperature on the orbital time scale were directly controlled by changes in the Northern Hemisphere summer insolation, whereas on millennial to centennial time scales temperature changes might be related to changes in the intensity of the East Asian summer monsoon. The monsoon precipitation did not reach its maximum until *c.* 8000 cal. BP due to the existence of remnant Northern Hemisphere ice sheets during the early Holocene, whereas during the middle to late Holocene changes in the monsoon precipitation would have been closely associated with the ocean–atmosphere interacting processes occurring in the tropical Pacific.

Acknowledgements. – We thank J. A. Piotrowski, A. E. Bjune and another anonymous reviewer for their constructive comments and suggestions. Special thanks are extended to J. A. Piotrowski for his careful revision of the manuscript. We are greatly indebted to Zhaodong Feng and Yuzhen Ma for the data of surface pollen samples from Mongolia. This study was financially supported by grants 2004CB720202, KZCX2-YW-316 and NSFC 40531001 and 40599422.

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