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Holocene climate changes in the mid-high-latitude-monsoon margin reflected by the pollen record from Hulun Lake, northeastern Inner Mongolia

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ABSTRACT

Pollen-assemblage data from a sediment core from Hulun Lake in northeastern Inner Mongolia describe the changes in the vegetation and climate of the East Asian monsoon margin during the Holocene. Dry steppe dominated the lake basin from ca. 11,000 to 8000 cal yr BP, suggesting a warm and dry climate. Grasses and birch forests expanded 8000 to 6400 cal yr BP, implying a remarkable increase in the monsoon precipitation. From 6400 to 4400 cal yr BP, the climate became cooler and drier. Chenopodiaceae dominated the interval from 4400 to 3350 cal yr BP, marking extremely dry condition. *Artemisia* recovered 3350–2050 cal yr BP, denoting an amelioration of climatic conditions. Both temperature and precipitation decreased 2050 to 1000 cal yr BP as indicated by decreased *Artemisia* and the development of pine forests. During the last 1000 yr, human activities might have had a significant influence on the environment of the lake region. We suggest that the East Asian summer monsoon did not become intensified until 8000 cal yr BP due to the existence of remnant ice sheets in the Northern Hemisphere. Changes in the monsoon precipitation on millennial to centennial scales would be related to ocean–atmosphere interactions in the tropical Pacific.

Introduction

Holocene climate is more complex both temporally and spatially than is commonly recognized because the signal of climate change is relatively muted during this epoch of postglacial warmth (Steig, 1999; Mayewski et al., 2004). Although more and more new proxy data have been obtained, an integrated view of natural climate variability during the Holocene is still far beyond reach. Solutions to this problem require high-quality, high-resolution proxy records from more, climatically sensitive and regionally representative locations.

The climate of China is dominated by the East Asian monsoon that is an important component of the global climate system and interacts with other components. During the last decades, a great number of geological records including eolian deposits, lake sediments and accretionary soils have been investigated to reconstruct a detailed history of East Asian monsoon variations during the Holocene (cf. Xiao et al., 2006). Most of these investigations have been restricted to low- and mid-latitude monsoon regions. Until recently, however, there are no substantial proxy records of Holocene climate changes from the higher-latitude monsoon margin.

In this study, we first present a pollen record of the sediment core recovered in the central part of Hulun Lake in northeastern Inner Mongolia. The lake is located at the northeastern corner of the current monsoon margin that represents a particularly sensitive region to East Asian monsoon variations on different timescales (An, 2000). Pollen in lake sediments provides direct information on past changes in the vegetation and climate over the lake region (Cohen, 2003). Therefore, the high-quality, high-resolution pollen record of Hulun Lake should reveal a detailed history of East Asian monsoon variations during the Holocene and contribute to better understanding of Holocene monsoon variability and physical links between the East Asian monsoon and other components of the global climate system.

Regional setting

Hulun Lake (48°30′40″–49°20′40″ N, 117°00′10″–117°41′40″ E) is situated in an inland graben basin that was formed in the late Pliocene (Xu et al., 1989). It lies 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 of Mesozoic volcanic rocks 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 shore of the lake. The lake has a catchment of

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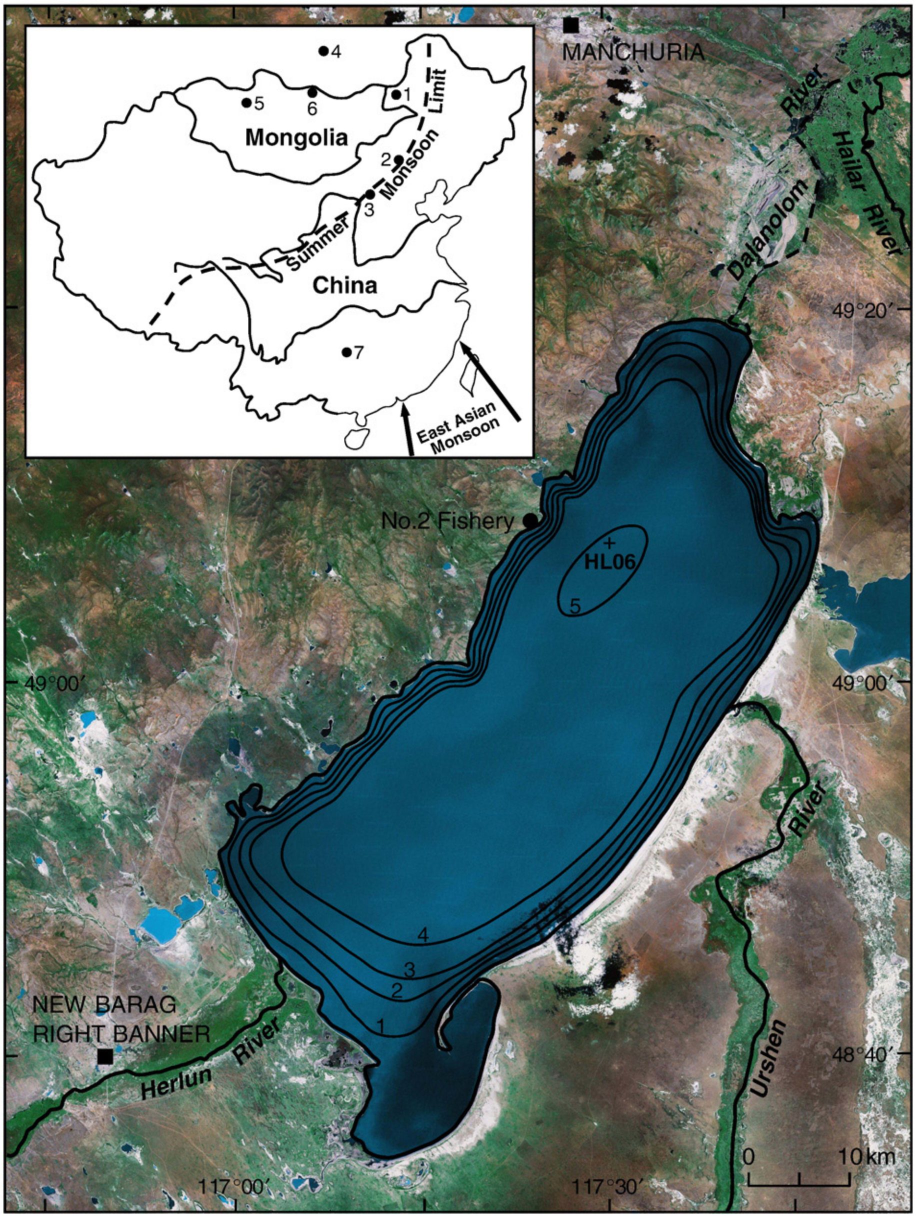

Figure 1. Map of Hulun Lake (from http://maps.google.com) showing the location of HL06 sediment core. The bathymetric survey of the lake was conducted in July 2005 with an FE-606 Furuno Echo Sounder (contours in meters). In the inset, the current northern limit of the East Asian summer monsoon (dashed line) and the locations of lakes and Dongge Cave (solid circles) mentioned in the text are shown. 1, Hulun Lake; 2, Dali Lake; 3, Daihai Lake; 4, Lake Baikal; 5, Lake Telmen; 6, Gun Lake; 7, Dongge Cave.

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 the 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 westerlies and the East Asian monsoon (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). During the summer, warm, moist air masses driven northward 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 lake region. During the winter, the cold, dry northwesterly airflows generated by the Mongolian High prevail and bring strong winds and cold airs to the lake region. In the lake 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 ca. 1 m of ice from early November to late April (Xu et al., 1989).

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 western slopes of the Great Hinggan Range, where the Urshen and Hailar River rise, accompanied by scrubs and herbs under the trees (Compilatory Commission of Vegetation of China,

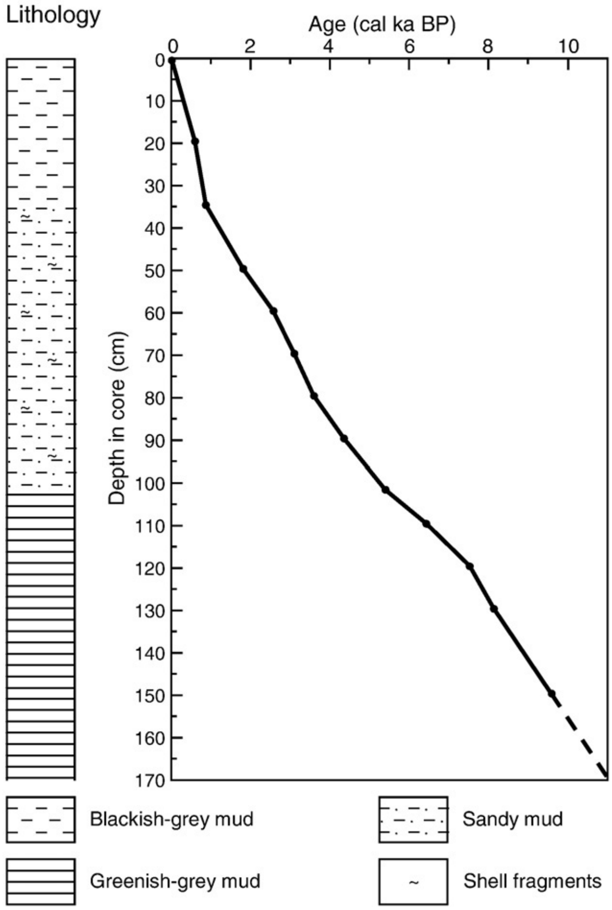

Figure 2. Lithological log and age–depth model of HL06 sediment core recovered in the central part of Hulun Lake. Solid dots represent the mean values of 2σ ranges of calibrated ages of corrected radiocarbon dates. Dashed line was derived from two superjacent calibrated ages by linear extrapolation to yield ages for sampled horizons of the lowermost 20-cm sediment core.

1980). Larch forests mixed with *P. 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

Coring and sampling

In January 2006, drilling was conducted on the ice in the central part of Hulun Lake (Fig. 1), using a Japanese-made TOHO drilling system (Model D1-B). The sediment core was 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 was collected in a polymethyl methacrylate tube using a piston corer. The core section was split, photographed and described on site and then cut into 1-cm segments, resulting in 170 samples for laboratory analyses.

Lithology

The sediments of HL06 core can be divided lithologically into three parts: upper blackish-gray oozy mud at core depths of 0–35 cm, middle dark gray to blackish-gray sandy mud at depths of 35–100 cm and lower greenish-grey homogeneous mud at depths of 100–170 cm (Fig. 2). In the middle sandy mud, the scattered fragments of ostracod and mollusk shells can be seen. The core section shows no signs of sedimentary hiatuses.

Age model

Thirteen bulk sediment samples were collected at ca. 10-cm intervals from the organic-rich horizons of 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. in 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 HL06 core were determined with a half-life of 5568 yr.

As shown in Table 1, the uppermost 0–1 cm of the core sediments yields a ^{14}C age of 685 yr. This anomalously old age can be considered to result from “hard-water” and other reservoir effects on radiocarbon dating of Hulun Lake sediments. To produce an age–depth model for HL06 core, we first subtracted the reservoir age of 685 yr from all the original ^{14}C ages, assuming that it 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 OxCal3.1 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

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

Laboratory number[a]	Depth interval (cm)	Dating material	δ^{13}C (‰)	AMS ^{14}C age (^{14}C yr BP)	Corrected ^{14}C age (^{14}C yr BP)[b]	Calibrated ^{14}C age (2σ) (cal yr 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

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

indicates that the upper 1. 7 m of HL06 core sediments covers the last ca. 11,000 yr (Fig. 2).

Pollen analysis

To extract fossil pollen grains more efficiently, we modified 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 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 with an ultrasonic cleaner (Elma Transsonic TI-H 20). To reduce the possibility of vibration-induced damage of fragile pollen grains, the cleaner was set at the lowest frequency of 25 kHz, lowest power of 40% and a cleaning time of less than 2 min. In order to calculate the pollen concentration, 27,637 exotic spores of *Lycopodium* were added to each sample before the pretreatment with hydrochloric acid.

Fossil pollen was identified and counted with an Olympus light microscope at 400× magnification. Microscopic observations indicate that pollen grains of *Larix* and Cyperaceae and air sacs of *Pinus* might be occasionally damaged due to ultrasonic cleaning but the identification and counting of fossil pollen would not be significantly affected by the selective damages. More than 600 pollen grains were counted for each sample. The percentages of tree and herb pollen taxa were 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 total pollen concentration was deduced from the counts of fossil pollen and *Lycopodium* spores in a sample and expressed in pollen grains per gram of air-dried samples.

Principal component analysis

To ordinate the pollen data from HL06 sediment core and detect patterns of the local terrestrial vegetation development, ordination techniques were performed using CANOCO version 4.5 (ter Braak, 1988; ter Braak and Smilauer, 2002). In CANOCO, a square-root transformation was applied to the data in addition to the default settings. Detrended correspondence analysis showed that the gradient length of the first axis is 0.670, indicating a likely linear response of the pollen assemblages to environmental variables (ter Braak, 1988; ter Braak and Prentice, 1988). Principal component analysis (PCA) was therefore chosen for ordination of the pollen data from HL06 sediment core. Eight pollen taxa with percentages >3% in any sample were used for PCA in the present study. The PCA centers both by the samples and by the pollen species to better represent the real "ecological distance" between the samples and compare differences in the species composition among the samples.

Results

Seventy-two taxa of pollen and spores were identified from the samples of HL06 sediment core. These include major trees of *Pinus*, *Picea*, *Abies*, *Betula*, *Corylus*, *Alnus*, *Ulmus* and *Quercus*, major herbs and shrubs of *Artemisia*, Chenopodiaceae, Poaceae, Cyperaceae, Asteraceae, Ranunculaceae, *Saxifraga*, *Ephedra* and *Nitraria*, major aquatic taxa of *Typha*, *Sparganium* and *Myriophyllum* and few fern taxa. The percentage pollen diagram of HL06 sediment core spanning the last ca. 11,000 yr can be divided into seven pollen assemblage zones based on stratigraphically constrained cluster analysis (CONISS, Grimm, 1987) (Fig. 3).

Zone 7 (ca. 11,000–8000 cal yr BP, 170–128 cm): Arboreal pollen mainly derived from *Betula* (5.2–13.6%) accounts for 7.2–16.3% of the pollen sum, and the proportion of herb pollen reaches 83.7–92.8%. *Artemisia* pollen occupying 45.8–60.2% of the total pollen sum displays the highest average percentage within the whole Holocene, accompanied by 20.0–30.5% of Chenopodiaceae pollen. Total pollen concentrations fluctuate between 137,300 and 602,400 grains g^{-1} with a higher average than the subsequent zones.

Zone 6 (ca. 8000–6400 cal yr BP, 128–109 m): The proportion of tree pollen increases up to 12.7–23.1% of the total pollen sum. *Betula* is the predominant contributor, reaching its highest percentage of 18.5%, accompanied by *Corylus*. *Artemisia* pollen decreases to 39.1–48.8% of the pollen sum, whereas Poaceae pollen shows an obvious increase in the proportion ranging from 3.4% to 10.0%. Total pollen concentrations decrease remarkably to 82,600–232,400 grains g^{-1}.

Zone 5 (ca. 6400–4400 cal yr BP, 109–90 cm): The proportions of both tree and herb pollen remain largely unchanged as compared with the preceding zone 6. However *Pinus* pollen displays an obvious trend of increase in the proportion, whereas *Betula* pollen was much lower than the preceding zone 6. *Artemisia* continues to decrease, whereas Chenopodiaceae shows a trend of gradual increase in the percentage. This zone is characterized by a significant increase in the proportions of both Asteraceae and aquatic pollen. The latter attains up to 2.7–7.9% of the total pollen sum. Total pollen concentrations maintain 78,100–159,400 grains g^{-1}.

Zone 4 (ca. 4400–3350 cal yr BP, 90–75 cm): The most striking feature of this zone is a considerably high proportion of Chenopodiaceae pollen reaching its maximum of 60.2% of the pollen sum. *Artemisia* pollen (13.7–30.1%) decreases to its lowest average percentage. Both *Betula* and *Corylus* decline markedly, leading to an evident decrease in the proportion of tree pollen. Aquatic pollen remains largely unchanged as compared with the preceding zone 5. Total pollen concentrations vary within a range from 89,300 to 180,300 grains g^{-1}.

Zone 3 (ca. 3350–2050 cal yr BP, 75–53 cm): This zone is marked by a prominent recovery of *Artemisia* pollen to 32.2–43.8% of the pollen sum. Chenopodiaceae pollen decrease abruptly down to proportions at the previous zones 5, 6 and 7. Tree pollen derived from *Pinus*, *Betula*, *Corylus* and *Alnus* increase to 14.9–24.6% of the total pollen sum. Aquatic pollen is much lower than the preceding zone 4. Total pollen concentrations maintain 85,100–195,900 grains g^{-1}.

Zone 2 (ca. 2050–1000 cal yr BP, 53–37 cm): Arboreal pollen continues to increase. *Pinus* pollen accounts for 6.1–16.3% of the total pollen sum and attains its highest average percentage within the whole Holocene. Herb pollen decreases slightly with a remarkable decline in the proportion of *Artemisia* pollen (19.9–29.1%) as compared with the preceding zone 3. Asteraceae pollen increases gradually to 3.6–6.9% of the pollen sum. Total pollen concentrations show a gradual increase from 102,900 to 203,600 grains g^{-1}.

Zone 1 (ca. 1000–0 cal yr BP, 37–0 cm): Tree pollen declines to 7.0–23.5% of the pollen sum as a result of obviously decreased *Pinus* and *Betula* pollen. The proportions of both Chenopodiaceae and Poaceae pollen display a remarkable increase as compared with the preceding zone 2, whereas *Artemisia* pollen occupying 24.4–42.2% of the total pollen sum remains largely unchanged. Total pollen concentrations continue to increase to a peak value of 398,900 grains g^{-1} and then decrease gradually.

PCA ordination of main terrestrial pollen taxa and samples from HL06 sediment core reflects the features of the percentage pollen diagram and the pattern of the local terrestrial vegetation development (Fig. 4). The first and second axes capture 66.23% and 11.55% of the total variance within the pollen data set. Seven clusters of points corresponding to pollen assemblage zones are clearly separated from each other on the biplot of PCA scores along the first two axes. As shown in Figure 4, eight pollen taxa were classified into four ecological groups: (1) *Artemisia*; (2) Poaceae, Cyperaceae, Chenopodiaceae and Asteraceae; (3) *Pinus*; and (4) *Betula* and *Corylus*. Zone 7 is characterized by *Artemisia* and *Betula*, zone 6 characterized by

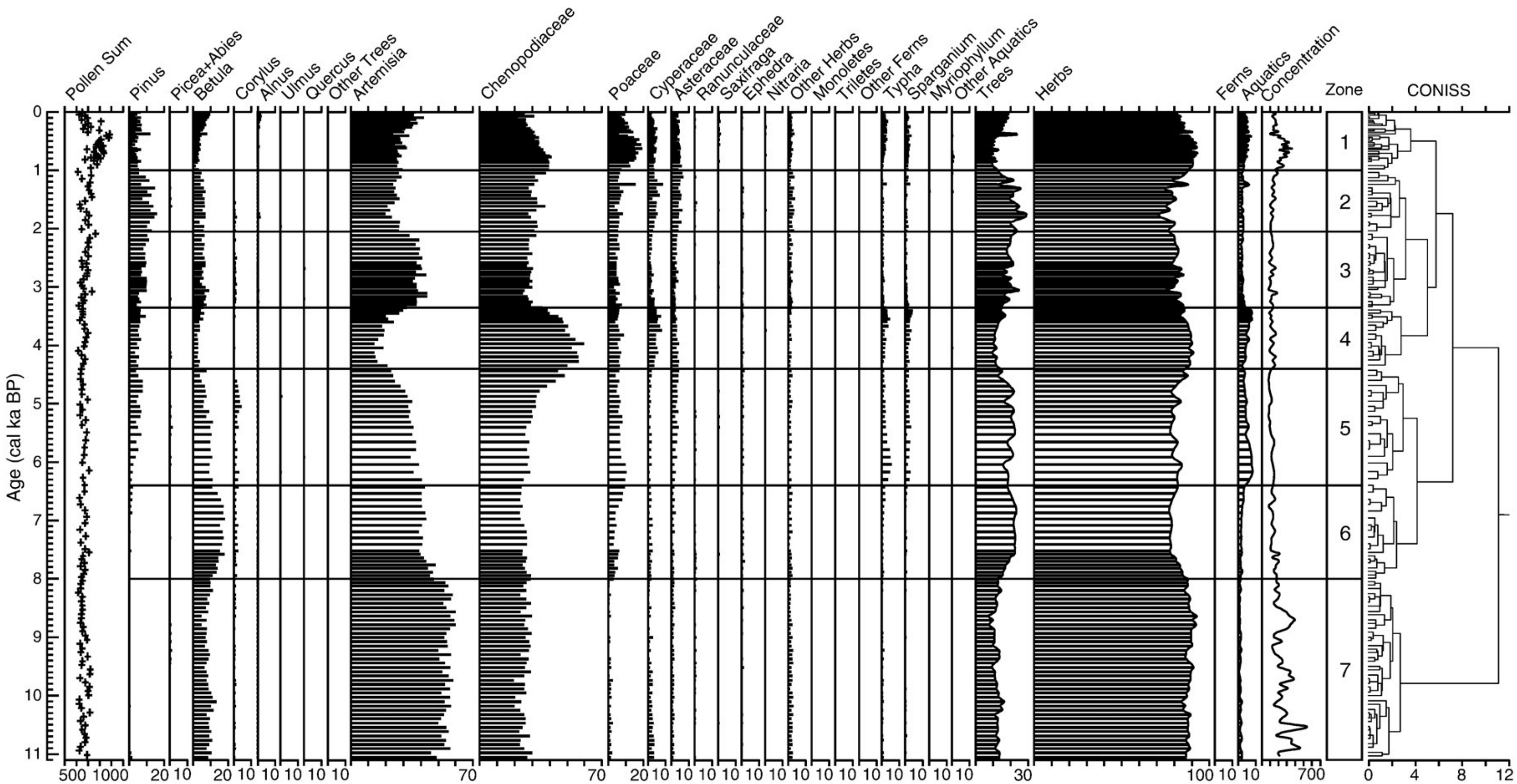

Figure 3. Percentage pollen diagram of HL06 sediment core spanning the last ca. 11,000 yr. Pollen concentrations are expressed in $\times 10^3$ grains g^{-1}. Cluster analysis (CONISS) is based on the total sum of squares. The chronology was derived from the age–depth model with the reservoir-age corrected.

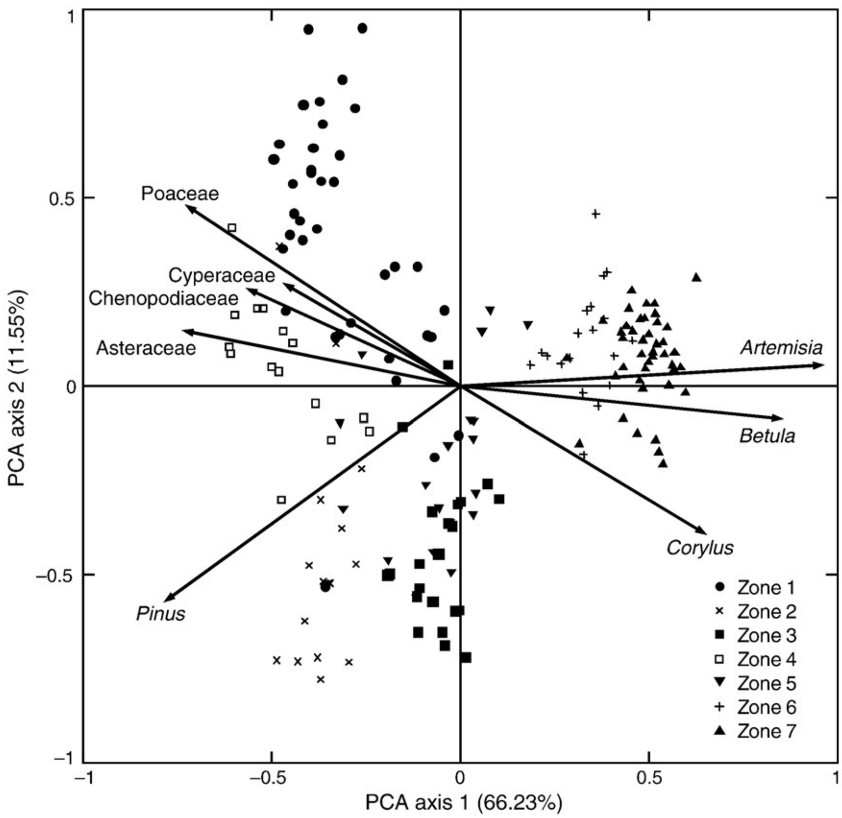

Figure 4. PCA ordination of eight pollen taxa with percentages >3% in any sample and the total pollen data of HL06 sediment core recovered in the central part of Hulun Lake. Eigenvalues of the first four axes are 0.6623, 0.1155, 0.0970 and 0.0575, respectively. The first and second axes capture 77.78% of the total variance within the data set.

Betula, *Artemisia* and *Corylus*, zone 5 characterized by *Pinus* and *Corylus*, zone 4 characterized by Chenopodiaceae and Cyperaceae, zone 3 characterized by *Pinus* and *Corylus*, zone 2 characterized by *Pinus* and zone 1 characterized by Poaceae and Chenopodiaceae.

Discussion

Vegetational and climatic implications of major pollen taxa

The modern natural vegetation of the Hulun Lake basin is characterized by dry grass steppe and forb-grass meadow-steppe. Forests are distributed on the western slopes of the Great Hinggan Range ca. 300 km east of the lake and on the southern part of the Hentiy Mountains ca. 600 km west of the lake. Forest-steppe communities prevail in the piedmont belt. Based on the pattern of modern vegetation distribution in the lake region, we infer that changes in the herb pollen mainly indicate the development of the herb plants in the lake basin, whereas changes in the tree pollen mainly represent the development of the forests in the surrounding mountains. In general, the evolution of vegetation communities in the lake region should be closely related to variations in the regional climate.

In the modern steppe and desert of northern China, *Artemisia* predominates over Chenopodiaceae plants in the desert steppe as compared with in the steppe desert (Compilatory Commission of Vegetation of China, 1980). *Artemisia* and Chenopodiaceae have, in common, the need for open environments, the preference for continental conditions and the ability to tolerate intense summer droughts but differ in the moisture requirements (El-Moslimany, 1990; Van Campo and Gasse, 1993; Van Campo et al., 1996). The ratio of pollen Artemisia to Chenopodiaceae (A/C) can thus be used as an indicator of changes in the effective moisture in the steppe of the lake region, and higher A/C ratios indicate increases in the moisture over the lake region.

In the meadow-steppe and forest-steppe communities, Poaceae prevails over both Chenopodiaceae and *Artemisia* (Compilatory Commission of Vegetation of China, 1980). Poaceae is categorized as mesoxerophytes and considered to demand more moisture for growth than does *Artemisia*. Therefore the ratio of pollen Poaceae to Chenopodiaceae (P/C) should be closely associated with changes in the regional humidity. In the present study, the P/C ratio was used, when necessary, to provide further evidence for the climatic inference from the A/C ratio.

In the lake region, Cyperaceae is developed in the lowlands, lakesides and river valleys and under the trees of the forest-steppe. Consequently the occurrence of Cyperaceae pollen might be related to the development of both regional and local vegetation.

Pinus and *Betula* dominate the arboreal pollen identified from HL06 sediment core. In the mountains surrounding the lake basin, patches of pines and birches are distributed in the gaps or margin of the larch forests (Compilatory Commission of Vegetation of China, 1980; Hilbig, 1995). Coniferous pine trees are endurable under colder and drier conditions as compared with broadleaved birch trees, and birth forests expand when the climate becomes warmer and wetter (Compilatory Commission of Vegetation of China, 1980; Hilbig, 1995). Consequently changes in the relative proportion of pollen *Pinus* and *Betula* would be indicative of variations in the regional vegetation and climate. It is worth mentioning that birches include trees and shrubs. *Betula* pollen from birch shrubs would affect the climatic interpretation, because the shrubs can exist under cool and drier conditions. In the present study, *Betula* pollen was considered to mainly derive from tree birches because arboreal birches have an absolute advantage over birch shrubs both in the Great Hinggan Range and in the Hentiy Mountains (Compilatory Commission of Vegetation of China, 1980; Hilbig, 1995).

Typha and *Sparganium* generally grow along the lakeshore, and *Myriophyllum* plants grow in the shallow-water zone of the lake. An increase in the proportion of these aquatic pollen grains could have resulted from a decline in the lake level that positions the lake edge closer to the core site.

As shown in Figure 4, PCA axis 1 distinguishes steppe *Artemisia* and broadleaved arboreal *Betula* from desert Chenopodiaceae and coniferous arboreal *Pinus*, whereas PCA axis 2 separates herb taxa in the lake basin from tree taxa in the surrounding mountains. This implies that the first principle component mainly represent humidity with the sample scores on the axis 1 positively related to wet conditions, and that the second principle component mainly represent temperature with the sample scores on the axis 2 positively related to warm conditions. It is noticeable that hygrophilous Poaceae and Cyperaceae were gathered together with xeric Chenopodiaceae (Fig. 4). This might be caused by local factors functioning during zones 4 and 1 rather than the close "ecological distance" (see below for further details).

Pollen assemblages of the surface sediments of Hulun Lake generally reflect the characteristics of the modern natural vegetation developed in the lake basin and the surrounding mountains, providing a basis for reconstructing the history of past vegetation and climate changes according to the pollen data.

Holocene vegetation and climate changes

The pollen assemblage of the HL06 sediment core reveals a detailed history of changes in the vegetation and climate over the Hulun Lake region during the Holocene (Figs. 3 and 5). During the early Holocene between ca. 11,000 and 8000 cal yr BP, the lake basin was dominated by steppe, and humidity was high as indicated by the highest values of both A/C ratios and PCA-1 scores. Contrary to both indices, however, P/C ratios display the lowest values, implying relatively dry conditions in the lake basin during this stage. In the surrounding mountains, lower proportion of arboreal pollen suggest that trees were not better developed during this stage as compared with the subsequent stages. Moreover almost no patches of cold-tolerant pine forests were distributed in the mountains during this stage. Taking these data together, we infer that the climate was warm and relatively dry during the early Holocene. We speculate that the summer monsoon was not strong enough to bring rainfall to such an interior inland region, and the humidity of the lake basin might result from the input of the snow/ice melt from the surrounding mountains.

During the period between ca. 8000 and 6400 cal yr BP, increases in P/C ratios resulting from obvious increases in the proportion of Poaceae pollen suggest 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. Changes in the vegetation pattern denote that the climate became wetter owing to increased rainfall brought by the intensified East Asian summer monsoon. This stage can be viewed as the Holocene climatic optimum (a relatively warm and humid period) in the Hulun Lake region.

Between ca. 6400 and 4400 cal yr BP, arid-tolerant plants of Chenopodiaceae and Asteraceae gradually predominated the steppe of the lake basin. A/C and P/C ratios and PCA-1 scores all exhibit a gradually decreasing trend. These data imply that the climate became drier during this stage. Birch forests declined and pine forests expanded, suggesting that temperature started to fall ca. 6400 cal yr ago. On the other hand, an obvious increase in the proportion of aquatic pollen indicates the onset of shrinkage of Hulun Lake.

The interval from ca. 4400 to 3350 cal yr BP was marked by much drier condition. Both A/C ratios and PCA-1 scores assumed the lowest

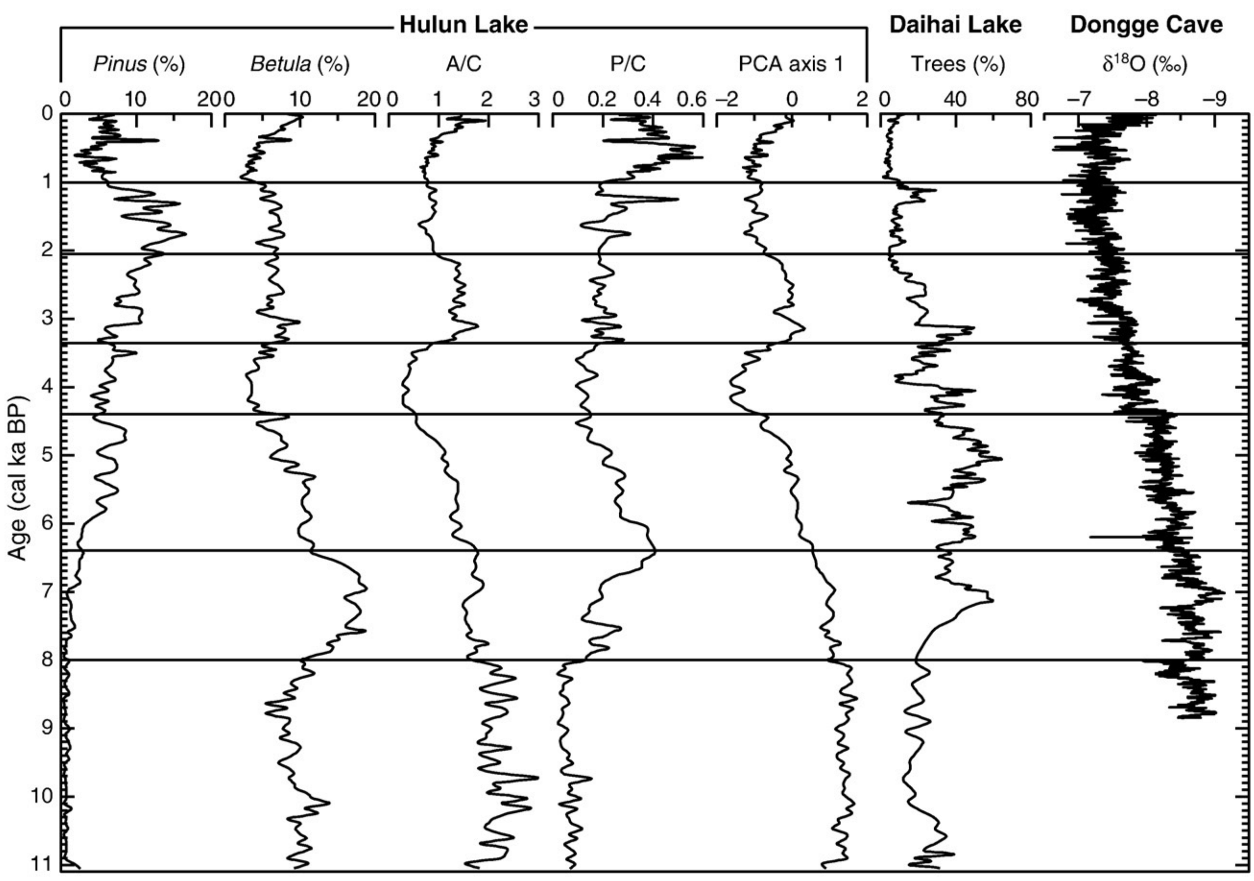

Figure 5. Percentages of *Pinus* and *Betula*, ratios of *Artemisia* to Chenopodiaceae (A/C) and Poaceae to Chenopodiaceae (P/C) and pollen PCA axis 1 of HL06 sediment core spanning the last ca. 11,000 yr, compared with tree pollen percentage of Daihai Lake sediments (Xiao et al., 2004) and $\delta^{18}O$ of Dongge Cave stalagmite (Wang et al., 2005). Horizontal lines bracket the stages characterizing the pattern of changes in the vegetation and climate over the Hulun Lake region during the Holocene.

values within the Holocene, and P/C ratios were also considerably lower, indicating that steppe desert was developed in the lake basin. The birch forests apparently contracted as suggested by large decreases in the proportions of *Betula* and *Corylus* pollen, denoting an evident decline both in precipitation and in temperature. High percentages of aquatic pollen reflect low stands of the lake level during this interval. An obvious increase in the percentage of Cyperaceae pollen during this stage would have resulted from flourishing sedges in the wetlands around the lake, which accounts for the identification of hygrophilous Cyperaceae with xeric Chenopodiaceae by the PCA ordination (Fig. 4). This stage would be an episode of extremely dry conditions in the lake region during the Holocene.

Following the extremely dry period, the grassland vegetation recovered and conditions became moister ca. 3350–2050 cal yr BP as suggested by large increases in A/C and P/C ratios and PCA-1 scores. The increases in the proportion of tree pollen from *Pinus*, *Betula*, *Corylus* and *Alnus* reflect a recovery of woody plants and a rise in temperature and precipitation during this stage.

During the period from ca. 2050 to 1000 cal yr BP, decreases in A/C ratios and PCA-1 scores and an increase in arid-tolerant Asteraceae pollen percentage indicate a decline in the humidity over the lake basin. 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.

Since ca. 1000 cal yr BP, changes in the vegetation of the lake region might have been more affected by human activities rather than by climate changes. Chenopodiaceae increased remarkably, but *Artemisia* remained largely unchanged in the first 300 yr of this stage as compared with the preceding stage (Fig. 3). This fact contradicts climatic forcing on the relative changes in the abundance of *Artemisia* and Chenopodiaceae plants. Moreover the expansion of arid Chenopodiaceae was accompanied by the increase of hygrophilous Poaceae during the interval from ca. 900 to 400 cal yr BP, which, on one hand, further excludes the possibility of the climatic forcing on the evolution of both plants, and on the other hand, accounts for the identification of Poaceae with Chenopodiaceae by the PCA ordination (Fig. 4). We infer that the successive rises of the Liao (A.D. 907–1125), Jin (A.D. 1115–1234) and Yuan (A.D. 1206–1368) Dynasties of nomadic people in northeastern China would be responsible for expansions of both Chenopodiaceae and Poaceae plants. During the last 400 yr, however, the gradual development of birch forests and the general trend of increases in A/C ratios and PCA-1 scores might imply that the climate of the lake region became warmer and wetter.

Regional comparison of paleoclimatic proxy records

Studies on grain-size distributions of the HL06 sediment core indicate that low levels occurred at Hulun Lake ca. 8000–7850, 6400–6050, 5150–4900, 4500–3800, 3050–2800, 1650–1400, 1150–900, 700–600 and 400–350 cal yr BP, as reflected by high percentages of the nearshore components, high proportions of the sand fractions and coarse median grain sizes (Xiao et al., 2009). The low lake stands during these intervals were interpreted to represent the brief weakening of the East Asian summer monsoon (Xiao et al., 2009). The pollen data show that grasses and birch forests started to expand in the Hulun Lake basin ca. 8000 cal yr ago, implying that the East Asian summer monsoon did not become intensified until that time. Considering the great variability of the summer monsoon precipitation on millennial scale (An, 2000), the initiation of the intensified East Asian summer monsoon ca. 8000 cal yr ago inferred from the pollen data would be in agreement with the grain-size-based inference of frequent occurrences of the weakened summer monsoon after ca. 8000 cal yr BP. Although the type and coverage of the vegetation in the lake basin would respond to the monsoonal precipitation in a different way in which the grain-size distribution of clastic materials in the lake would do, the expansion of Chenopodiaceae during the interval from ca. 4400 to 3350 cal yr BP occurred almost coeval with the drop in the lake level between ca. 4500 and 3800 cal yr BP, indicating an episode of extremely reduced monsoonal precipitation during the Holocene.

Sedimentological and palynological studies on an outcrop exposure of interbedded lacustrine and eolian deposits, about 10 km northeast of Hulun Lake, suggested that eolian sands were accumulated and arid plants of *Ephedra* and Chenopodiaceae prevailed in the lake region during the period between ca. 5000 and 3000 ^{14}C yr BP (Wang and Ji, 1995; Yang and Wang, 1996). Our pollen record of the core sediments reveals an extremely dry interval between ca. 4400 and 3350 cal yr BP that is in good agreement with the period of accumulation of eolian sands and expansion of arid plants in the lake basin. The optical dating of sand dunes in the lake area indicated that dune stabilization and soil formation occurred during the early Holocene and dune mobilization commenced ca. 4400 yr ago (Li and Sun, 2006). Our pollen record showed that Chenopodiaceae started to dominate the lake basin ca. 4400 cal yr ago, suggesting a coincidence of the expansion of arid-tolerant plants with the mobilization of sand dunes in the lake region.

Changes in the climatic condition over the Hulun Lake region can be correlated with the proxy data from two lakes (Daihai and Dali) in the middle latitude monsoonal margin (cf. Fig. 1). Pollen assemblage of the core sediments of Daihai Lake (Xiao et al., 2004) (Fig. 5) and total organic and inorganic carbon concentrations of Dali Lake core sediments (Xiao et al., 2008) reveal a prominent increase in the monsoon precipitation ca. 8000 cal yr ago, coincident with the onset of increased humidity over the Hulun Lake region. Decreased woody and increased herb plants in the Daihai Lake region ca. 4450–3950 cal yr BP (Xiao et al., 2004) (Fig. 5) and low organic carbon and high inorganic carbon concentrations in Dali Lake sediments ca. 4450–3750 cal yr BP (Xiao et al., 2008) indicated a major interval of decreased monsoonal precipitation during the Holocene. These data lend support to an extremely dry event occurring ca. 4400–3350 cal yr ago over the Hulun Lake region. Moreover this interval of weakened East Asian summer monsoon can be seen in the stalagmite δ^{18}O record of Dongge Cave (Wang et al., 2005) (cf. Fig. 1), as indicated by shifts towards heavier δ^{18}O values (Fig. 5).

Correlation between the pollen record from Hulun Lake and proxy data from the lakes in the mid-high latitude inland regions reveals an inconsistency in the climatic conditions of the two regions. The highest abundance of diatom frustules and chrysophyte cysts in Lake Baikal (cf. Fig. 1) suggests that the Holocene climatic optimum occurred in this interior part of Asia during the early-middle Subboreal period, 4500–2500 ^{14}C yr BP (Karabanov et al., 2000). Sedimentological and palynological data from Lake Telmen, north-central Mongolia (cf. Fig. 1) suggest a sequence of arid conditions from ca. 7000 to 4500 cal yr BP and humid conditions since ca. 4500 cal yr BP (Peck et al., 2002; Fowell et al., 2003). In Gun Lake (cf. Fig. 1), the highest contents of organic matter in the core sediments at depths of 450 to 130 cm were interpreted to represent the most humid conditions during the period of approximately 5600 to 2500 ^{14}C yr BP (Feng et al., 2005). The discrepancy between the paleoclimatic records from Hulun Lake and the lakes in the mid-high latitude continental interior implies that Holocene climatic changes might have occurred asynchronously in the monsoon and non-monsoon regions.

Possible mechanism for Holocene East Asian monsoon variability

Summer solar radiation in the Northern Hemisphere reached a maximum (7% more than the present value) 11,000–10,000 cal yr BP and largely decreased after 6000 cal yr BP (Kutzbach and Street-Perrott, 1985; COHMAP Members, 1988). Temperature started to decrease in the Hulun Lake region ca. 6400 cal yr ago, as indicated by the expansion of pine forests (Figs. 5 and 6), displaying a close link with orbitally induced variations in insolation. This implies that changes in the temperature in the mid-high latitude region during the Holocene were controlled by changes in summer solar radiation in the Northern Hemisphere. The increase in the concentrations of both the sea-salt sodium in Greenland ice core (Mayewski et al., 1997) and the hematite-stained grains in North Atlantic sediments (Bond et al., 2001) about 6400 cal yr ago (Fig. 6) provides support for our pollen-based inference of the temperature drop in the mid-high latitude region during the Holocene. It has been suggested that a unique cold event occurred 8200 yr ago around the North Atlantic (Alley et al., 1997; Barber et al., 1999; Alley and Ágústsdóttir, 2005; Beget and Addison, 2007). As shown in Figure 5, the pollen records from both Hulun and Daihai Lake did not yield a counterpart of the event. In fact, there are few reports about the existence of the 8.2-ka event in the paleoclimatic records from northern China. We therefore speculate that this cold event might not be registered by the geological sequences in the monsoon marginal region due to its abruptness. Alternatively there may remain uncertainties about how widespread the anomalies of the event were.

The East Asian monsoon is primarily controlled by the thermal contrast between the tropical Pacific Ocean and the Asian continent (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). On glacial–interglacial timescales, the monsoon variations are closely related to changes in the Northern Hemisphere summer solar radiation resulting from progressive changes in the Earth's orbital parameters (An, 2000). During the Holocene, however, the summer monsoon did not reach its maximum intensity and the monsoonal rainfall belt did not penetrate into its modern northern limit until ca. 8000 cal yr ago as suggested by proxy records from Daihai and Dali Lake (Xiao et al., 2004, 2006, 2008). The pollen data from Hulun Lake are in good agreement with this inference about the timing of the maximum summer monsoon intensity during the Holocene (Figs. 5 and 6). The time lag of about 3000 yr between the maximum summer monsoon intensity and the maximum summer solar radiation in the Northern Hemisphere might be attributed to the stagnant northward retreat of the polar front in the North Pacific Ocean due to the existence of remnant Northern Hemisphere ice sheets, which would hamper the northward penetration of the summer monsoonal front, thereby suppressing monsoonal precipitation over the northern interior of China. This inference is supported by the rapid decline in the sodium deposition at GISP2 8200–7800 cal yr ago (Fig. 6) that may reflect diminution of polar atmospheric circulation resulting from a poleward shift of circumpolar air masses (Stager and Mayewski, 1997; Mayewski et al., 2004).

The moisture/rainfall brought by the East Asian summer monsoon onto the land derives from low latitudes of the western Pacific (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). Therefore ocean–atmosphere interactions in the tropical Pacific may play a substantial role in driving the monsoon circulation. In this regard, the Kuroshio Current and the Western Pacific Warm Pool (WPWP) can be considered as significant driving forces.

Studies of the abundance of warm-water planktonic foraminifera *Pulleniatina obliquiloculata*, an indicator species of the path and intensity of the Kuroshio Current, in a sediment core from the northern Okinawa Trough (Fig. 6) suggested that the Kuroshio Current, a major boundary current that transports warm and salty seawater from the western tropical Pacific to the North Pacific, shifted eastward and weakened ca. 4600 cal yr ago, leading to a decrease in the moisture transport from the western tropical Pacific to the North Pacific (Jian et al., 2000). The extremely dry condition occurring in the Hulun Lake region during the period from ca. 4400 to 3350 cal yr BP (Figs. 5 and 6) coincides with the eastward shift and reduction of the Kuroshio Current within age uncertainties. Moreover, this dry event registered by the pollen record from Hulun Lake occurred in close association with the decline of surface water temperatures in the western tropical Pacific (Stott et al., 2004) (Fig. 6). These data suggest that changes in the monsoon precipitation on millennial to centennial

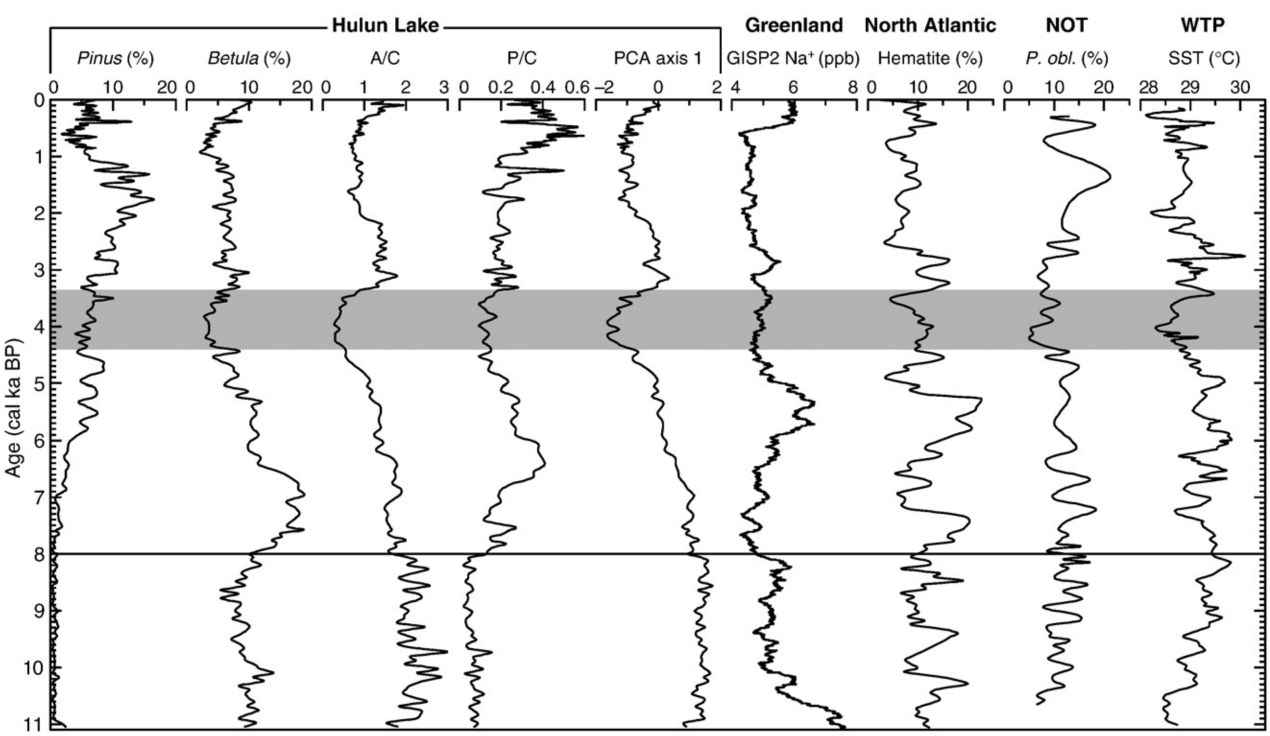

Figure 6. Correlation of *Pinus* and *Betula* percentages, *Artemisia*/Chenopodiaceae (A/C) and Poaceae/Chenopodiaceae (P/C) ratios and pollen PCA axis 1 from Hulun Lake with sea-salt sodium flux (Na^+, ppb) from Greenland GISP2 (Mayewski et al., 1997), hematite-stained grain concentration (hematite, %) from the North Atlantic (Bond et al., 2001), *Pulleniatina obliquiloculata* abundance (*P. obl.*, %) from the northern Okinawa Trough (NOT) (Jian et al., 2000) and sea surface temperature (SST, °C) from the western tropical Pacific (WTP) (Stott et al., 2004). Horizontal line indicates the onset of East Asian summer monsoon intensification during the Holocene. Shaded bar marks the interval of a drastic decline in the summer monsoon precipitation during the middle Holocene.

scales might be related to ocean–atmosphere interactions in the tropical Pacific. A weakened, eastward shifted Kuroshio Current and decreased WPWP surface temperatures could remove warm tropical waters eastward, cause the convection in the Pacific Ocean to occur further east and reduce the formation of water vapor over the western tropical Pacific, thereby decreasing the moisture available for transport via the monsoon circulation from the low-latitude Pacific onto the Asian inland and leading to a weakened summer monsoon.

Conclusions

Palynological analyses of a sediment core recovered in the central part of Hulun Lake in northeastern Inner Mongolia revealed a detailed history of vegetation and climate changes in the East Asian monsoon margin during the Holocene. During the early Holocene at ca. 11,000–8000 cal yr BP, dry steppe dominated the lake basin and woody plants were less developed in the surrounding mountains, suggesting a warm and drier climate in the lake region. Grasslands expanded and large-scale birch forests developed between 8000 and 6400 cal yr BP, implying a remarkable increase in the monsoon precipitation. From 6400 to 4600 cal yr BP, *Artemisia*/Chenopodiaceae ratios decreased and broadleaved forests declined and coniferous forests expanded, suggesting that the climate became cooler and drier. The interval between 4400 and 3350 cal yr BP was marked by an extremely dry condition when arid Chenopodiaceae prevailed in the lake basin at that time. A recovery of *Artemisia* occurred 3350–2050 cal yr BP, denoting an amelioration of climatic conditions. During the episode of 2050–1000 cal yr BP, *Artemisia* plants declined and pine forests were developed, indicating decreases both in temperature and in precipitation. During the last 1000 yr, human activities might have a significant influence on the environment of the lake region. Comparisons of the pollen data from Hulun Lake with other paleoclimatic records suggest that the East Asian summer monsoon was not intensified until 8000 cal yr BP and the monsoon variations on millennial to centennial scales would be related to ocean–atmosphere interactions occurring in the tropical Pacific.

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References

An, Z.S., 2000. The history and variability of the East Asian paleomonsoon climate. Quaternary Science Reviews 19, 171–187.

Alley, R.B., Ágústsdóttir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149.

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: a prominent widespread event 8200 yr ago. Geology 25, 483–486.

Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., Gagnon, J.M., 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide Lakes. Nature 400, 344–348.

Beget, J.E., Addison, J.A., 2007. Methane gas release from the Storegga submarine landslide linked to early-Holocene climate change: a speculative hypothesis. The Holocene 17, 291–295.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–2136.

Bronk Ramsey, C., 2001. Development of the radiocarbon calibration program. Radiocarbon 43, 355–363.

Chinese Academy of Sciences (Compilatory Commission of Physical Geography of China), 1984. Physical Geography of China: Climate. Science Press, Beijing, pp. 1–30 (in Chinese).

COHMAP Members, 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science 241, 1043–1052.

Cohen, A.S., 2003. Paleolimnology: the History and Evolution of Lake Systems. Oxford University Press, New York. 500 pp.

Compilatory Commission of Vegetation of China, 1980. Vegetation of China. Science Press, Beijing, pp. 932–955 (in Chinese).

El-Moslimany, A.P., 1990. Ecological significance of common nonarboreal pollen: examples from drylands of the Middle East. Review of Palaeobotany and Palynology 64, 343–350.

Fægri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis 4th Edition. John Wiley & Sons, New York, pp. 69–89.

Feng, Z.D., Wang, W.G., Guo, L.L., Khosbayar, P., Narantsetseg, T., Jull, A.J.T., An, C.B., Li, X.Q, Zhang, H.C., Ma, Y.Z., 2005. Lacustrine and eolian records of Holocene climate changes in the Mongolian Plateau: preliminary results. Quaternary International 136, 25–32.

Fowell, S.J., Hansen, B.C.S., Peck, J.A., Khosbayar, P., Ganbold, E., 2003. Mid to late Holocene climate evolution of the Lake Telmen Basin, north central Mongolia, based on palynological data. Quaternary Research 59, 353–363.

Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers and Geosciences 13, 13–35.

Hilbig, W., 1995. The Vegetation of Mongolia. SPB Academic Publishing, Amsterdam, pp. 236–238.

Jian, Z.M., Wang, P.X., Saito, Y., Wang, J.L., Pflaumann, U., Oba, T., Cheng, X.R., 2000. Holocene variability of the Kuroshio Current in the Okinawa Trough, northwestern Pacific Ocean. Earth and Planetary Science Letters 184, 305–319.

Karabanov, E.B., Prokopenko, A.A., Williams, D.F., Khursevich, G.K., 2000. A new record of Holocene climate change from the bottom sediments of Lake Baikal. Palaeogeography, Palaeoclimatology, Palaeoecology 156, 211–224.

Kutzbach, J.E., Street-Perrott, F.A., 1985. Milankovitch forcing of fluctuations in the level of tropical lakes from 18 to 0 kyr BP. Nature 317, 130–134.

Li, S.H., Sun, J.M., 2006. Optical dating of Holocene dune sands from the Hulun Buir Desert, northeastern China. The Holocene 16, 457–462.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S.I., Yang, Q.Z., Lyons, W.B., Prentice, M., 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. Journal of Geophysical Research 102, 26345–26366.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. Quaternary Research 62, 243–255.

Nakamura, T., Niu, E., Oda, H., Ikeda, A., Minami, M., Takahashi, H., Adachi, M., Pals, L., Gottdang, A., Suya, N., 2000. The HVEE Tandetron AMS system at Nagoya University. Nuclear Instruments and Methods in Physics Research B172, 52–57.

Peck, J.A., Khosbayar, P., Fowell, S.J., Pearce, R.B., Ariunbileg, S., Hansen, B.C.S., Soninkhishig, N., 2002. Mid to Late Holocene climate change in north central Mongolia as recorded in the sediments of Lake Telmen. Palaeogeography, Palaeoclimatology, Palaeoecology 183, 135–153.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Bronk Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Intcal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1029–1058.

Stager, J.C., Mayewski, P.A., 1997. Abrupt early to mid-Holocene climatic transition registered at the equator and the poles. Science 276, 1834–1836.

Steig, E.J., 1999. Mid-Hoocene climate change. Science 286, 1485–1487.

Stott, L., Cannariato, K., Thunell, R., Haug, G.H., Koutavas, A., Lund, S., 2004. Decline of surface temperature and salinity in the western tropical Pacific Ocean in the Holocene epoch. Nature 431, 56–59.

ter Braak, C.J.F., 1988. CANOCO—a FORTRAN Program for Canonical Community Ordination by (Partial) (Detrended) (Canonical) Correspondence Analysis, Principal Components Analysis and Redundancy Analysis (Version 2.1). Technical Rep. LWA-88-02, GLW, Wageningen, 95 pp.

ter Braak, C.J.F., Prentice, I.C., 1988. A theory of gradient analysis. Advances in Ecological Research 18, 271–317.

ter Braak, C.J.F., Smilauer, P., 2002. CANOCO 4.5. Biometrics. Wageningen University and Research Center, Wageningen. 500 pp.

Van Campo, E., Gasse, F., 1993. Pollen- and diatom-inferred climatic and hydrological changes in Sumxi Co basin (Western Tibet) since 13,000 yr B.P. Quaternary Research 39, 300–313.

Van Campo, E., Cour, P., Hang, S.X., 1996. Holocene environmental changes in Bangong Co basin (Western Tibet). Part 2: The pollen record. Palaeogeography, Palaeoclimatology, Palaeoecology 120, 49–63.

Wang, S.M., Ji, L., 1995. Paleolimnology of Hulun Lake. University of Science and Technology of China Press, Hefei. 125 pp (in Chinese).

Wang, Y.J., Cheng, H., Edwards, R.L., He, Y.Q., Kong, X.G., An, Z.S., Wu, J.Y., Kelly, M.J., Dykoski, A.D., Li, X.D., 2005. The Holocene Asian monsoon: link to solar changes and North Atlantic climate. Science 308, 854–857.

Xiao, J.L., Xu, Q.H., Nakamura, T., Yang, X.L., Liang, W.D., Inouchi, Y., 2004. Holocene vegetation variation in the Daihai Lake region of north-central China: a direct indication of the Asian monsoon climatic history. Quaternary Science Reviews 23, 1669–1679.

Xiao, J.L., Wu, J.T., Si, B., Liang, W.D., Nakamura, T., Liu, B.L., Inouchi, Y., 2006. Holocene climate changes in the monsoon/arid transition reflected by carbon concentration in Daihai Lake of Inner Mongolia. The Holocene 16, 551–560.

Xiao, J.L., Si, B., Zhai, D.Y., Itoh, S., Lomtatidze, Z., 2008. Hydrology of Dali Lake in central-eastern Inner Mongolia and Holocene East Asian monsoon variability. Journal of Paleolimnology 40, 519–528.
Xiao, J.L., Chang, Z.G., Wen, R.L., Zhai, D.Y., Itoh, S., Lomtatidze, Z., 2009. Holocene weak monsoon intervals indicated by low lake levels at Hulun Lake in the monsoonal margin region of northeastern Inner Mongolia. China. The Holocene 19, 899–908.
Yang, X.D., Wang, S.M., 1996. The vegetational and climatic-environmental changes in Hulun Lake and Wulungu Lake during Holocene. Oceanologia et Limnologia Sinica 27, 67–72.
Xu, Z.J., Jiang, F.Y., Zhao, H.W., Zhang, Z.B., Sun, L., 1989. Annals of Hulun Lake. Jilin Literature and History Publishing House, Changchun. 691 pp (in Chinese).
Zhang, J.C., Lin, Z.G., 1985. Climate of China. Shanghai Scientific and Technical Publishers, Shanghai. 603 pp (in Chinese).