The 4.2 ka BP event: multi-proxy records from a closed lake in the northern margin of the East Asian summer monsoon

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Abstract. The 4.2 ka BP event has been widely investigated since it was suggested to be a possible cause for the collapse of ancient civilizations. With the growth of proxy records for decades, however, both its nature and its spatial pattern have become controversial. Here we examined multi-proxy data of the grain-size distribution, ostracode assemblage, pollen assemblage and the pollen-reconstructed mean annual precipitation from a sediment core at Hulun Lake in northeastern Inner Mongolia spanning the period between 5000 and 3000 cal. yr BP to identify the nature and the associated mechanism of the 4.2 ka BP event occurring in the monsoonal region of eastern Asia. Higher sand fraction contents, littoral ostracodes abundances and Chenopodiaceae pollen percentages together with lower mean annual precipitations reveal a significant dry event at the interval of 4210–3840 cal. yr BP that could be a regional manifestation of the 4.2 ka BP event in the northern margin of the East Asian summer monsoon (EASM). We suggest that the drought would be caused by a decline in the intensity of the EASM on millennial-to-centennial scales that could be physically related to persistent cooling of surface waters in the western tropical Pacific and the North Atlantic. The cooling of western tropical Pacific surface waters could reduce moisture production over the source area of the EASM, while the cooling of North Atlantic surface waters could suppress northward migrations of the EASM rainbelt, both leading to a weakened EASM and thus decreased rainfall in the northern margin of the EASM.

1 Introduction

In early 1990s, Weiss et al. (1993) identified a marked increase in aridity and wind circulation occurring in northern Mesopotamia at 2200 BC based on studies of archaeological sites on alluvial plains of the Tigris and Euphrates Rivers, suggesting that the abrupt climatic change induced a considerable degradation of land-use conditions and thus caused the collapse of the rain-fed agriculture civilization of western Asia. Years later, two articles published in the periodical Science (Weiss and Bradley, 2001; deMenocal, 2001) demonstrated that the drought that occurred 4.2 ka ago could be a possible cause for the collapse of ancient civilizations, which promoted extensive investigations into the abrupt climatic change occurring around 4.2 ka BP as well as the causal relationship between the cultural collapse and the 4.2 ka BP event.

The Holocene climatic instability has actually become a hot topic of paleoclimate researches since 1990s. Unfortunately no clear signals of the 4.2 ka BP event were identified from the proxies of Greenland ice-core records including oxygen isotope composition (Dansgaard et al., 1993), sea salt and terrestrial dust concentrations (O'Brien et al., 1995), and accumulation rate, temperature, and chloride, calcium and methane concentrations (Alley et al., 1997). Although a series of abrupt shifts were detected for the Holocene climate of the North Atlantic through an investigation of ice-rafted debris in the deep-sea sediments, the 4.2 ka BP event appears unexceptional (Bond et al., 1997). These data imply that the 4.2 ka BP event would be more complicated than previously recognized. Despite the attempts made over years, in fact, the nature of the 4.2 ka BP event itself remains controversial (Marchant and Hooghiemstra, 2004, Magny et al., 2009), let alone its impact to prehistoric cultures (Drysdale et al., 2006; Staubwasser and Weiss, 2006).

Research on the 4.2 ka BP event and its impact on cultural evolution in China have been motivated by Hsü's view that famines and mass migrations occurring in ancient China could have resulted from regional droughts related to global cooling (Hsü, 1998). Wu and Liu (2004) synthesized data from paleoclimatic records in eastern China and suggested that the climatic anomaly that occurred ~4.2 ka ago produced a drought in the north and flooding in the south, which was responsible for the collapse of neolithic cultures in the central plain of China during the late third millennium BC. Liu and Feng (2012) recently examined the newly published data of paleoclimatic and archaeological records spanning the transition from the middle to late Holocene and offered a different interpretation from that of Wu and Liu (2004). In brief, an abrupt climatic shift occurred in northern China at ~4 cal. ka BP; while in southern China the ~4 ka BP event had several effects. With the associated climatic drying at ~4 cal. ka BP, Chinese Neolithic cultures both in the north and in the south collapsed; while the Longshan Culture in the central plain thrived.

Here we examine the paleoclimatic data from a sediment core at Hulun Lake in northeastern Inner Mongolia and focus on the 4.2 ka BP event occurring in the lake region. Hulun Lake is located in the northern margin of the East Asian summer monsoon that represents a climatically sensitive zone. The multi-proxy paleoclimatic records from the lake would provide new insights into the 4.2 ka BP event. This study is aimed to identify the nature and the associated mechanism of the 4.2 ka BP event occurring in the monsoonal region of eastern Asia.

2 Study site

Hulun Lake (48°30.667' to 49°20.667'N, 117°0.167' to 117°41.667'E), the fifth largest lake in China, is situated about 30 km south of Manchuria, Inner Mongolia, China (Fig. 1). It lies in an inland graben basin that was formed in the late Pliocene (Xu et al., 1989). It has an area of 2339 km^2 and a maximum water depth of 8 m when the lake level attains highest status at an elevation of 545.3 m a.s.l. (measurements in August 1964; Xu et al., 1989). Today, the lake is closed and the maximum water depth is 5 m (Fig. 1). 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 extend from the southern and eastern shores of the lake with scattered aeolian dunes. The lake has a catchment of 37,214 km^2 within the borders of China. Two rivers, the Herlun from the southwest and the Urshen Rivers from the southeast, supply water for the lake (Fig. 1). The Dalanolom River, an intermittent river to the northeast of the lake, 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 a semi-arid area of the middle temperate zone (Fig. 1). The climate of the lake's region is influenced by the East Asian monsoon and the Westerlies (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). During summer, warm, moist southerly air-masses interact with cold air from the northwest and produce most of the annual precipitation. During winter, cold, dry northwesterly airflows prevail and generate strong winds and cold weathers. 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. Annual precipitation is 247 to 319 mm, and over 80% of the annual precipitation falls in June–September. Annual evaporation reaches 1400 to 1900 mm. The lake is covered with ~1 m of ice from November to April.

The ostracodes living in the lake today include *Limnocythere inopinata* (Baird), *Candoniella suzini* Schneider, *Pseudocandona albicans* (Brady), *Pseudocandona compressa* (Koch), *Cyclocypris serena* (Koch), *Ilyocypris gibba* (Ramdohr) and *Ilyocypris salebrosa* Stepanaiths (Xu et al., 1989; Wang and Ji, 1995). *Limnocythere inopinata* is the dominant species. Aquatic plants are scarce in the lake and confined to the areas of the river mouth and parts of the nearshore zone.

The modern natural vegetation of the lake basin belongs to the middle temperate steppe (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 distributed in the lowlands. The forests are developed on the west slopes of the Great Hinggan Range, where the Urshen and Hailar River rise, accompanied by scrubs and herbs under the trees. Larch forests cover the southern part of the Hentiy Mountains where the Herlun River rises. Patches of pine forests and birch shrubberies occur in the alpine belt.

3 Material and methods

3.1 Lithology and chronology of the HL06 core

Drilling was conducted at a water depth of 5 m in the central part of Hulun Lake in January 2006 when the lake was frozen (Fig. 1), using a TOHO drilling system. A sediment core was extracted to a depth beneath the lake floor of 1.7 m and is designated HL06 (49°07.615' N, 117°30.356' E; Fig. 1). The core section was split, photographed and described on site and then cut into 1-cm segments, resulting in 170 samples for laboratory analyses.

The sediments of the HL06 core can be divided into three parts: 1) upper blackish-grey oozy mud at depths of 0–35 cm, 2) middle dark grey to blackish-grey, massive sandy mud with scattered fragments of ostracodes and mollusk shells at depths of 35–100 cm, and 3) lower greenish-grey homogeneous mud at depths of 100–170 cm (Xiao et al., 2009).

Thirteen bulk samples were collected from organic-rich horizons of the HL06 core and dated with an Accelerator Mass Spectrometry (AMS) system (Compact-AMS, NEC Pelletron) at Paleo Labo Co., Ltd. in Japan. As shown in Xiao et al. (2009), the uppermost 0–1 cm of the core sediments yields a ^{14}C age of 685±21 yr that was considered to result from carbon reservoir effects on radiocarbon dating of the bulk organic matter of Hulun Lake sediments. To produce an age–depth model for the HL06 core, the carbon reservoir age of 685±21 yr was first subtracted from all the original ^{14}C ages, and then calibrations are performed on the carbon reservoir-free ^{14}C ages. The conventional ages were converted to calibrated ages using the OxCal3.1 radiocarbon age calibration program (Bronk Ramsey, 2001) with the IntCal04 calibration data (Reimer et al., 2004). The age–depth model indicates that the HL06 core covers the last ~11,000 yr (Xiao et al., 2009).

3.2 Proxy analyses of the HL06 core

The HL06 core has been analysed at 1-cm interval for multiple proxies including grain-size distribution (Xiao et al., 2009), ostracode assemblage (Zhai et al., 2011), and pollen assemblage (Wen et al., 2010a) in order to investigate the Holocene history of changes in the hydrology of Hulun Lake and in vegetation and climate of the lake region. Grain-size distribution was determined with a Malvern Mastersizer 2000 laser grain-size analyzer (Xiao et al., 2009). Each sample of sediment was pretreated with hydrogen peroxide to remove organic matter and then with boiled hydrochloric acid to remove carbonates. The sample residue was dispersed with sodium metaphosphate on an ultrasonic vibrator before grain-size analysis.

For the ostracode assemblage analysis, each sample of ~300 mg of air-dried sediment was pretreated with hydrogen peroxide–sodium carbonate solution (pH 9–10) to disaggregate the sediment (Zhai et al., 2011). Fossil ostracode valves were extracted by sieving in water through a 250-mesh sieve (63-μm pore size). Ostracode was identified and counted from the sieve residue spread onto a glass plate with an Olympus stereomicroscope at 40× magnifications following the taxonomy of Meisch (2000) and Hou et al. (2002). Most samples yielded 300 to 4000 ostracode valves.

For the pollen assemblage analysis, each sample of ~1 g of air-dried sediment was pretreated with hydrochloric acid to remove carbonates and with sodium hydroxide to remove organic matter; the residue was then kept in hydrofluoric acid to remove silicates (Wen et al., 2010a). Fossil pollen grains were extracted by wet sieving of the resulting residue through a sieve diameter of 10 μm with an ultrasonic cleaner. Pollen was identified and counted with an Olympus light microscope at 400× magnifications. 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.

In addition, the history of changes in precipitation in the Hulun Lake region during the Holocene was quantitatively reconstructed (Wen et al., 2010b) based on the pollen profile of the HL06 core (Wen et al., 2010a), using a pollen–climate transfer function for temperate eastern Asia (Wen et al., 2013).

3.3 Proxy data from the HL06 core used for the present study

The segment of the HL06 core spanning the period between 5000 and 3000 cal. yr BP is used for the present study to focus on the 4.2 ka BP event occurring in the Hulun Lake region. Fig. 2 shows the lithology and ages of the core segment between 105 and 55 cm at depth, which covers the segment between dated horizons of a calibrated age older than 5000 cal. yr BP and of a calibrated age younger than 3000 cal. yr BP. Ages of sampled horizons of the core segment spanning the period of 5000–3000 cal. yr BP were derived by linear interpolation between radiocarbon-dated horizons using the mean values of 2σ ranges of calibrated ages.

Data of grain-size distribution (Xiao et al., 2009), ostracode assemblage (Zhai et al., 2011), pollen assemblage (Wen et al., 2010a), and mean annual precipitation (Wen et al., 2010b) from the HL06 core for the period of 5000–3000 cal. yr BP were re-examined in the present study in order to explore the detailed process of climate changes on millennial-to-centennial scales in the Hulun Lake region around 4.2 cal. ka BP.

4 Results

The sediments of the core segment spanning the period of 5000–3000 cal. yr BP consist of dark grey to blackish-grey, massive sandy mud in which the scattered fragments of ostracode and mollusk shells can be seen (Fig. 2). Five radiocarbon dates provide age controls for the core segment spanning the period of 5000–3000 cal. yr BP (corresponding to the core depths of 97–68 cm) (Fig. 2; Table 1). Data of sand fraction content, littoral ostracodes abundance, Chenopodiaceae pollen percentage, and mean annual precipitation from the core segment spanning the period of 5000–3000 cal. yr BP were plotted against age in Fig. 3. The averages and one standard deviations (SD) of each proxy data for the period between 5000 and 3000 cal. yr BP are expressed.

As shown in Fig. 3, the content of the sand fraction in the core sediments has an average of 7.5% and a SD of 6.3% for the period of 5000–3000 cal. yr BP. At the interval of 4430–3860 cal. yr BP (core depth: 91–83 cm), the sand fraction content shows values higher than one SD with a maximum of 21.1% and an average of 15.5%. The abundance of the littoral ostracodes including *Pseudocandona albicans*, *Pseudocandona* sp., *Candoniella subellipsoida*, and *Cypridopsis* sp. from the core sediments has an average of 22 valves g^{-1} and a SD of 22 valves g^{-1} for the period of 5000–3000 cal. yr BP. At the interval of 4200–3420 cal. yr BP (core depth: 88–76 cm), the littoral ostracodes abundance shows values higher than one SD with a maximum of 70 valves g^{-1} and an average of 44 valves g^{-1}. The percentage of Chenopodiaceae pollen from the core sediments has an average of 42.9% and a SD of 10.7% for the period of 5000–3000 cal. yr BP. At the interval of 4300–3830 cal. yr BP (core depth: 89–83 cm), the Chenopodiaceae pollen percentage shows values higher than one SD with a maximum of 60.2% and an average of 56.5%. The mean annual precipitation in the lake region reconstructed on the pollen profile of the sediment core has an average of 297.3 mm and a SD of 20.3 mm for the period of 5000–3000 cal. yr BP. At the interval of 4240–3750 cal. yr BP (core depth: 88–82 cm), the mean annual precipitation shows values lower than one SD with a minimum of 264.0 mm and an average of 272.3 mm.

5 Discussion

5.1 Climatic implication of proxy data from the HL06 core

Grain-size distributions of the core sediments show that the clay, silt and sand fractions average 35.8%, 60.6% and 3.6% of the clastic materials during the Holocene, respectively (Xiao et al., 2009). Sand grains from the nearshore zone of Hulun Lake could be transported to and deposited in the central part of the lake when the lake assumed low stands. Therefore increases in the relative percentage of the sand fraction in the core sediments were interpreted to indicate drops in the water level of Hulun Lake (Xiao et al., 2009). We thus infer that higher values of the sand fraction content at the interval of 4430–3860 cal. yr BP imply lower lake levels at that time (Fig. 3).

Ostracode assemblages of the core sediments suggest that fourteen species of ostracodes belonging to nine genera occur in Hulun Lake during the Holocene and *Limnocythere inopinata* is the dominant species (Zhai et al., 2011). *Pseudocandona albicans*, *Pseudocandona* sp., *Candoniella subellipsoida*, and *Cypridopsis* sp. from the core sediments were interpreted as littoral ostracode taxa because these ostracodes usually live in small water bodies and shallow waters and have a wide tolerance to water temperature or salinity (Zhai et al., 2011). We thus infer that higher values of the littoral ostracodes abundance at the interval of 4200–3420 cal. yr BP imply lower lake levels at that time (Fig. 3).

Pollen assemblages of the core sediments suggest that dry grass steppe dominated by *Artemisia* and Chenopodiaceae plants were developed in the Hulun Lake basin during most of the Holocene (Wen et al., 2010a). In the modern steppe of northern China, Chenopodiaceae predominates over *Artemisia* in the desert steppe as compared with in the typical steppe. Therefore increases in the relative percentage of Chenopodiaceae pollen in the core sediments were interpreted to indicate decreases in the effective moisture in the lake basin (Wen et al., 2010a). We thus infer that higher values of the Chenopodiaceae pollen percentage at the interval of 4300–3830 cal. yr BP imply lower effective moisture in the lake basin at that time (Fig. 3).

The pollen-reconstructed mean annual precipitation yields a value of around 285 mm in the Hulun Lake region for the last decades (Wen et al., 2010b). This value of the mean annual precipitation falls within the range of observed data of the annual precipitation (247–319 mm), demonstrating the validity of the pollen–climate transfer function in quantitatively reconstructing the regional precipitation. Therefore lower values of the mean annual precipitation at the interval of 4240–3750 cal. yr BP denote drier conditions in the lake basin at that time (Fig. 3).

5.2 The nature and timing of the 4.2 ka BP event in the Hulun Lake region

As remarked above, the sand fraction content and the littoral ostracodes abundance of the lake sediments can be used as indicators of changes in the lake level that is closely related to changes in the water balance (precipitation plus runoff minus evaporation) of the lake; while the Chenopodiaceae pollen percentage can be used as a direct indicator of changes in the effective moisture in the lake basin. The mean annual precipitation can directly indicate changes in the amount of precipitation in the lake basin. During the period of 5000–3000 cal. yr BP, data of the sand fraction content, littoral ostracodes abundance, Chenopodiaceae pollen percentage, and the mean annual precipitation can be correlated with each other, although the intervals of a drier climate in the lake basin registered by different proxies differ in the time of start and end (Fig. 3). Discrepancies in the timing of the drier climate registered by different proxies might indicate differences in the response of different proxies to changes in the regional precipitation and the lake's hydrology.

In order to detect the pattern of temporal changes in the regional dry–wet condition during the period of 5000–3000 cal. yr BP, principle component analysis (PCA) was performed to analyze the time series of data of the sand fraction content, littoral ostracodes abundance, Chenopodiaceae pollen percentage, and the mean annual precipitation. All the raw data of the 4 proxies were standardized, and then PCA was conducted on the standardized data with the proxies as variables. F1, F2 and the first three factors of PCA capture 74.5%, 15.4% and 97.9% of the total variance within the data set, respectively. As shown in Figure 3, PCA F1 has an average of 0 and a SD of 1.02 for the period of 5000–3000 cal. yr BP. At the interval of 4210–3840 cal. yr BP (core depth: 88–83 cm), PCA F1 displays values higher than one SD with a maximum of 1.71 and an average of 1.54 (Fig. 3). PCA F1 reflects the most prominent common features of the aforementioned four proxies and defines a dry event in the Hulun Lake region that started at 4210 cal. yr BP and ended at 3840 cal. yr BP, lasting for 370 yr.

Studies on carbon concentrations of a sediment core at Dali Lake, south of Hulun Lake (cf. Fig. 1), reveal obvious decreases in total organic carbon concentration at 4450–3750 cal. yr BP, indicating a major interval of low lake stands and dry climatic conditions during the Holocene (Xiao et al., 2008). Moreover a recent synthesis of grain-size distribution, carbon concentration, pollen assemblage and pollen-reconstructed precipitation from a sediment core at Daihai Lake, southwest of Hulun Lake (cf. Fig. 1), reflects a drought at 4060–3690 cal. yr BP (Xiao et al., in press). These data lend support, within age uncertainties, to the inference of a dry event occurring in the Hulun Lake region in the present study. We thus suggest that the dry event that occurred in the Hulun Lake region at 4210–3840 cal. yr BP could be the regional manifestation of the 4.2 ka BP event in the northern margin of the East Asian summer monsoon (EASM).

5.3 Possible cause of the 4.2 ka BP event in the northern margin of the EASM

Modern observations indicate that precipitation in the Hulun Lake region reaches its peak value in July and ~70% of the annual precipitation falls in late June through early August (Xu et al., 1989). Changes in the precipitation of the lake region in the summer half-year totally follow the northward migrations of the EASM rainbelt (Fig. 4), indicating that increases in the precipitation of the northern margin of the EASM would be closely related to increases in the strength of the EASM. These data suggest that the dry event occurring in the northern margin of the EASM at 4210–3840 cal. yr BP implies a decline of the EASM at that interval.

The northward migrations of the EASM rainbelt in rainy seasons of East Asia are characterized by two discontinuous jumps (i.e., jumping first to the Yangtse River–Huaihe River basin, southwestern Japan and southern Korea in late June and then to northern China, northeastern China and northern Korea in middle July after landing in southern China in late May) (Fig. 4), which are influenced not only by the ocean–atmosphere interactions in the tropical Pacific because the moisture/rainfall brought by the EASM onto the land derives from the western tropical Pacific but also by the pattern of atmospheric circulation over Northern Hemisphere high latitudes because the EASM frontal rainfall results from the interaction between the warm-moist, southerly air-masses and the cold-dry, northwesterly airflows (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). In Fig. 5, therefore, dry–wet oscillations in the Hulun Lake region reflected by PCA F1 for the period of 5000–3000 cal. yr BP are compared with the sea-surface-temperature (SST) record from the western tropical Pacific (Stott et al., 2004) and the hematite-stained-grains (HSG) record from the North Atlantic (Bond et al., 2001).

As shown in Fig. 5, the decline of the EASM occurring at 4210–3840 cal. yr BP coincides, within age uncertainties, with decreases in the SST of the western tropical Pacific (Stott et al., 2004) and with increases in the HSG concentration in the North Atlantic sediments (Bond et al., 2001). This coincidence implies a physical link between the EASM decline on millennial-to-centennial scales and the persistent cooling of surface waters of the western tropical Pacific as well as the North Atlantic. In brief, continual decreases in sea surface temperature of the western tropical Pacific presumably caused by more intense, more frequent El Niño (Moy et al., 2002) could reduce the formation of water vapor over the source area of the EASM, thereby decreasing the moisture available for transport via the EASM circulation from the western tropical Pacific onto the Asian inland and leading to a weakened EASM. While decreases in sea surface temperature of the North Atlantic could suppress the northward migration of the EASM front, thereby hampering the northward jumps of the EASM rainbelt and resulting in weakened rainfall in the northern marginal zone of the EASM.

6. Conclusions

Multiple proxies of a sediment core at Hulun Lake in northeastern Inner Mongolia reveal a prominent dry event occurring in the lake region at the interval of 4210–3840 cal. yr BP that could be the regional manifestation of the 4.2 ka BP event in the northern margin of the EASM. The drought would have resulted from a decline of the EASM that could be physically linked with the persistent cooling of surface waters of the western tropical Pacific and the North Atlantic on millennial-to-centennial scales.

Although more and more proxy data have been obtained, an integrated view of the 4.2 ka BP event is still far beyond reach. Future studies should be focused on the investigation of high-quality, high-resolution proxy records from more, climatically sensitive and geographically representative regions in order to explore the spatiotemporal pattern of the 4.2 ka BP event and the associated dynamic mechanism.

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Figure captions

Figure 1. Map of Hulun Lake (from http://www.maps.google.com) showing the location of the HL06 core. The bathymetric survey of the lake was conducted in July 2005 with a FE-606 Furuno Echo Sounder (contours in meters). The inset gives a sketch map of China showing the current northern limit of the East Asian summer monsoon (dashed line) defined as the 400-mm isohyet of mean annual precipitation (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985) and the locations of lakes (solid circles) mentioned in the present study. 1, Hulun Lake; 2, Dali Lake; 3, Daihai Lake. EASM shown in the inset indicates the East Asian summer monsoon.

Figure 2. Lithological log and age–depth model of the segment of the HL06 core between 105 and 55 cm at core depth (covering the period between 5000 and 3000 cal. yr BP). Solid circles represent the mean values of 2σ ranges of calibrated ages of carbon reservoir-corrected radiocarbon dates. The carbon reservoir correction factor is 685±21 yr, ^{14}C age of the uppermost 1 cm of the core sediments. Modified after Xiao et al. (2009).

Figure 3. Time series of sand fraction (%) (Xiao et al., 2009), littoral ostracodes valve (valves g^{-1}) (Zhai et al., 2011), Chenopodiaceae pollen (%) (Wen et al., 2010a), and mean annual precipitation (mm) (Wen et al., 2010b) from the HL06 core spanning the period between 5000 and 3000 cal. yr BP as well as the PCA F1 obtained from the aforementioned four proxies. The chronology was derived from the carbon reservoir-corrected age–depth model; ages of

sampled horizons were determined by linear interpolation between radiocarbon-dated horizons using the mean values of 2σ ranges of calibrated ages (Xiao et al., 2009). Vertical dashed lines show the averages and one standard deviations above/below the averages of each proxy data as well as PCA F1 values during the period between 5000 and 3000 cal. yr BP. Light grey bars mark the intervals at which each proxy or PCA F1 has values higher than one standard deviation (lower than one standard deviation for mean annual precipitation).

Figure 4. A sketch map of eastern China, Korea and western Japan showing precipitation rates of the current East Asian summer monsoon. Data are averaged by observations of the years 1979–2007 and expressed in mm d^{-1} at a grid resolution of 0.25° × 0.25°. (a) On the 4th, 5th and 6th pentads of July and 1st pentad of August. (b) On the 5th and 6th pentads of June and the 1st and 2nd pentads of July. (c) On the 5th and 6th pentads of May and the 1st and 2nd pentads of June. The inset in Fig. 4a shows monthly changes of annual precipitation in the Hulun Lake region (data from observations of the years 1976–2005).

Figure 5. Correlation of dry–wet oscillation in the Hulun Lake region denoted by PCA F1 factor from the four proxies of the HL06 core with sea-surface temperature (SST, °C) reconstructed on the Mg/Ca ratio of *Globigerinoides rubber* from MD98-2176 core in the western tropical Pacific (Stott et al., 2004) and hematite-stained grain concentration (HSG, %) in VM29-191 core from the North Atlantic (Bond et al., 2001). The shaded bar marks an interval of dry event occurring in the Hulun Lake region at 4210–3840 cal. yr BP.

Table 1. AMS radiocarbon dates of samples from the segment of the HL06 core between 105 and 55 cm at core depth (covering the period between 5000 and 3000 cal. yr BP). The radiocarbon date of the uppermost 1 cm of the core sediments used for carbon reservoir correction is shown. Modified after Xiao et al. (2009).