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

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60 **1 Introduction**

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

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

84 Research on the 4.2 ka BP event and its impact on cultural evolution in China have been
85 motivated by Hsü's view that famines and mass migrations occurring in ancient China could
86 have resulted from regional droughts related to global cooling (Hsü, 1998). Wu and Liu (2004)
87 synthesized data from paleoclimatic records in eastern China and suggested that the climatic
88 anomaly that occurred ~4.2 ka ago produced a drought in the north and flooding in the south,
89 which was responsible for the collapse of neolithic cultures in the central plain of China

90 during the late third millennium BC. Liu and Feng (2012) recently examined the newly
91 published data of paleoclimatic and archaeological records spanning the transition from the
92 middle to late Holocene and offered a different interpretation from that of Wu and Liu (2004).
93 In brief, an abrupt climatic shift occurred in northern China at ~4 cal. ka BP; while in
94 southern China the ~4 ka BP event had several effects. With the associated climatic drying at
95 ~4 cal. ka BP, Chinese Neolithic cultures both in the north and in the south collapsed; while
96 the Longshan Culture in the central plain thrived.

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

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105 **2 Study site**

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107 Hulun Lake (48°30.667' to 49°20.667'N, 117°0.167' to 117°41.667'E), the fifth largest
108 lake in China, is situated about 30 km south of Manchuria, Inner Mongolia, China (Fig. 1). It
109 lies in an inland graben basin that was formed in the late Pliocene (Xu et al., 1989). It has an
110 area of 2339 km² and a maximum water depth of 8 m when the lake level attains highest
111 status at an elevation of 545.3 m a.s.l. (measurements in August 1964; Xu et al., 1989). Today,
112 the lake is closed and the maximum water depth is 5 m (Fig. 1). Low mountains and hills of
113 Mesozoic volcanic rocks border the lake on the northwest and form a fault-scarp shoreline.
114 Broad lacustrine and alluvial plains extend from the southern and eastern shores of the lake
115 with scattered aeolian dunes. The lake has a catchment of 37,214 km² within the borders of
116 China. Two rivers, the Herlun from the southwest and the Urshen Rivers from the southeast,
117 supply water for the lake (Fig. 1). The Dalanolom River, an intermittent river to the northeast
118 of the lake, drains the lake when the elevation of the lake level exceeds 543.4 m a.s.l. and

119 enters the lake when the lake level is lower and the discharge of the Hailar River is larger as
120 well (Xu et al., 1989) (Fig. 1).

121 Hulun Lake is located in a semi-arid area of the middle temperate zone (Fig. 1). The
122 climate of the lake's region is influenced by the East Asian monsoon and the Westerlies
123 (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). During summer, warm, moist
124 southerly air-masses interact with cold air from the northwest and produce most of the annual
125 precipitation. During winter, cold, dry northwesterly airflows prevail and generate strong
126 winds and cold weathers. In the lake region, mean annual temperature is 0.3°C with a July
127 average of 20.3°C and a January average of -21.2°C. Annual precipitation is 247 to 319 mm,
128 and over 80% of the annual precipitation falls in June–September. Annual evaporation
129 reaches 1400 to 1900 mm. The lake is covered with ~1 m of ice from November to April.

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

136 The modern natural vegetation of the lake basin belongs to the middle temperate steppe
137 (Compilatory Commission of Vegetation of China, 1980; Xu et al., 1989). The vegetation
138 cover ranges from relatively moist forb-grass meadow-steppe in the piedmont belt to
139 moderately dry grass steppe on the alluvial plain and dry bunchgrass–undershrub *Artemisia*
140 steppe on the lacustrine plain. Halophilic Chenopodiaceae plants are distributed in the
141 lowlands. The forests are developed on the west slopes of the Great Hinggan Range, where
142 the Urshen and Hailar River rise, accompanied by scrubs and herbs under the trees. Larch
143 forests cover the southern part of the Hentiy Mountains where the Herlun River rises. Patches
144 of pine forests and birch shrubberies occur in the alpine belt.

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146 **3 Material and methods**

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148 **3.1 Lithology and chronology of the HL06 core**

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150 Drilling was conducted at a water depth of 5 m in the central part of Hulun Lake in
151 January 2006 when the lake was frozen (Fig. 1), using a TOHO drilling system. A sediment
152 core was extracted to a depth beneath the lake floor of 1.7 m and is designated HL06
153 (49°07.615' N, 117°30.356' E; Fig. 1). The core section was split, photographed and described
154 on site and then cut into 1-cm segments, resulting in 170 samples for laboratory analyses.

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

159 Thirteen bulk samples were collected from organic-rich horizons of the HL06 core and
160 dated with an Accelerator Mass Spectrometry (AMS) system (Compact-AMS, NEC
161 Pelletron) at Paleo Labo Co., Ltd. in Japan. As shown in Xiao et al. (2009), the uppermost 0–
162 1 cm of the core sediments yields a ^{14}C age of 685 ± 21 yr that was considered to result from
163 carbon reservoir effects on radiocarbon dating of the bulk organic matter of Hulun Lake
164 sediments. To produce an age–depth model for the HL06 core, the carbon reservoir age of
165 685 ± 21 yr was first subtracted from all the original ^{14}C ages, and then calibrations are
166 performed on the carbon reservoir-free ^{14}C ages. The conventional ages were converted to
167 calibrated ages using the OxCal3.1 radiocarbon age calibration program (Bronk Ramsey,
168 2001) with the IntCal04 calibration data (Reimer et al., 2004). The age–depth model indicates
169 that the HL06 core covers the last ~11,000 yr (Xiao et al., 2009).

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171 3.2 Proxy analyses of the HL06 core

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173 The HL06 core has been analysed at 1-cm interval for multiple proxies including
174 grain-size distribution (Xiao et al., 2009), ostracode assemblage (Zhai et al., 2011), and pollen
175 assemblage (Wen et al., 2010a) in order to investigate the Holocene history of changes in the
176 hydrology of Hulun Lake and in vegetation and climate of the lake region. Grain-size
177 distribution was determined with a Malvern Mastersizer 2000 laser grain-size analyzer (Xiao
178 et al., 2009). Each sample of sediment was pretreated with hydrogen peroxide to remove

179 organic matter and then with boiled hydrochloric acid to remove carbonates. The sample
180 residue was dispersed with sodium metaphosphate on an ultrasonic vibrator before grain-size
181 analysis.

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

189 For the pollen assemblage analysis, each sample of ~1 g of air-dried sediment was
190 pretreated with hydrochloric acid to remove carbonates and with sodium hydroxide to remove
191 organic matter; the residue was then kept in hydrofluoric acid to remove silicates (Wen et al.,
192 2010a). Fossil pollen grains were extracted by wet sieving of the resulting residue through a
193 sieve diameter of 10 μm with an ultrasonic cleaner. Pollen was identified and counted with an
194 Olympus light microscope at 400 \times magnifications. More than 600 pollen grains were counted
195 for each sample. The percentages of tree and herb pollen taxa were based on the sum of the
196 total terrestrial pollen in a sample, and those of each taxon of both aquatic pollen and fern
197 spores based on the sum of the terrestrial pollen plus the aquatic pollen or fern spores of the
198 taxon in a sample.

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

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204 3.3 Proxy data from the HL06 core used for the present study

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206 The segment of the HL06 core spanning the period between 5000 and 3000 cal. yr BP is
207 used for the present study to focus on the 4.2 ka BP event occurring in the Hulun Lake region.
208 Fig. 2 shows the lithology and ages of the core segment between 105 and 55 cm at depth,

209 which covers the segment between dated horizons of a calibrated age older than 5000 cal. yr
210 BP and of a calibrated age younger than 3000 cal. yr BP. Ages of sampled horizons of the
211 core segment spanning the period of 5000–3000 cal. yr BP were derived by linear
212 interpolation between radiocarbon-dated horizons using the mean values of 2σ ranges of
213 calibrated ages.

214 Data of grain-size distribution (Xiao et al., 2009), ostracode assemblage (Zhai et al.,
215 2011), pollen assemblage (Wen et al., 2010a), and mean annual precipitation (Wen et al.,
216 2010b) from the HL06 core for the period of 5000–3000 cal. yr BP were re-examined in the
217 present study in order to explore the detailed process of climate changes on
218 millennial-to-centennial scales in the Hulun Lake region around 4.2 cal. ka BP.

219

220 **4 Results**

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

231 As shown in Fig. 3, the content of the sand fraction in the core sediments has an average
232 of 7.5% and a SD of 6.3% for the period of 5000–3000 cal. yr BP. At the interval of 4430–
233 3860 cal. yr BP (core depth: 91–83 cm), the sand fraction content shows values higher than
234 one SD with a maximum of 21.1% and an average of 15.5%. The abundance of the littoral
235 ostracodes including *Pseudocandona albicans*, *Pseudocandona* sp., *Candoniella*
236 *subellipsoidea*, and *Cypridopsis* sp. from the core sediments has an average of 22 valves g^{-1}
237 and a SD of 22 valves g^{-1} for the period of 5000–3000 cal. yr BP. At the interval of 4200–
238 3420 cal. yr BP (core depth: 88–76 cm), the littoral ostracodes abundance shows values

239 higher than one SD with a maximum of 70 valves g^{-1} and an average of 44 valves g^{-1} . The
240 percentage of Chenopodiaceae pollen from the core sediments has an average of 42.9% and a
241 SD of 10.7% for the period of 5000–3000 cal. yr BP. At the interval of 4300–3830 cal. yr BP
242 (core depth: 89–83 cm), the Chenopodiaceae pollen percentage shows values higher than one
243 SD with a maximum of 60.2% and an average of 56.5%. The mean annual precipitation in the
244 lake region reconstructed on the pollen profile of the sediment core has an average of 297.3
245 mm and a SD of 20.3 mm for the period of 5000–3000 cal. yr BP. At the interval of 4240–
246 3750 cal. yr BP (core depth: 88–82 cm), the mean annual precipitation shows values lower
247 than one SD with a minimum of 264.0 mm and an average of 272.3 mm.

248

249 **5 Discussion**

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251 5.1 Climatic implication of proxy data from the HL06 core

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

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

269 Pollen assemblages of the core sediments suggest that dry grass steppe dominated by
270 *Artemisia* and Chenopodiaceae plants were developed in the Hulun Lake basin during most of
271 the Holocene (Wen et al., 2010a). In the modern steppe of northern China, Chenopodiaceae
272 predominates over *Artemisia* in the desert steppe as compared with in the typical steppe.
273 Therefore increases in the relative percentage of Chenopodiaceae pollen in the core sediments
274 were interpreted to indicate decreases in the effective moisture in the lake basin (Wen et al.,
275 2010a). We thus infer that higher values of the Chenopodiaceae pollen percentage at the
276 interval of 4300–3830 cal. yr BP imply lower effective moisture in the lake basin at that time
277 (Fig. 3).

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

285

286 5.2 The nature and timing of the 4.2 ka BP event in the Hulun Lake region

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

298 proxies might indicate differences in the response of different proxies to changes in the
299 regional precipitation and the lake's hydrology.

300 In order to detect the pattern of temporal changes in the regional dry–wet condition
301 during the period of 5000–3000 cal. yr BP, principle component analysis (PCA) was
302 performed to analyze the time series of data of the sand fraction content, littoral ostracodes
303 abundance, Chenopodiaceae pollen percentage, and the mean annual precipitation. All the raw
304 data of the 4 proxies were standardized, and then PCA was conducted on the standardized
305 data with the proxies as variables. F1, F2 and the first three factors of PCA capture 74.5%,
306 15.4% and 97.9% of the total variance within the data set, respectively. As shown in Figure 3,
307 PCA F1 has an average of 0 and a SD of 1.02 for the period of 5000–3000 cal. yr BP. At the
308 interval of 4210–3840 cal. yr BP (core depth: 88–83 cm), PCA F1 displays values higher than
309 one SD with a maximum of 1.71 and an average of 1.54 (Fig. 3). PCA F1 reflects the most
310 prominent common features of the aforementioned four proxies and defines a dry event in the
311 Hulun Lake region that started at 4210 cal. yr BP and ended at 3840 cal. yr BP, lasting for
312 370 yr.

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

324

325 5.3 Possible cause of the 4.2 ka BP event in the northern margin of the EASM

326

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

335 The northward migrations of the EASM rainbelt in rainy seasons of East Asia are
336 characterized by two discontinuous jumps (i.e., jumping first to the Yangtse River–Huaihe
337 River basin, southwestern Japan and southern Korea in late June and then to northern China,
338 northeastern China and northern Korea in middle July after landing in southern China in late
339 May) (Fig. 4), which are influenced not only by the ocean–atmosphere interactions in the
340 tropical Pacific because the moisture/rainfall brought by the EASM onto the land derives
341 from the western tropical Pacific but also by the pattern of atmospheric circulation over
342 Northern Hemisphere high latitudes because the EASM frontal rainfall results from the
343 interaction between the warm-moist, southerly air-masses and the cold-dry, northwesterly
344 airflows (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). In Fig. 5, therefore,
345 dry–wet oscillations in the Hulun Lake region reflected by PCA F1 for the period of 5000–
346 3000 cal. yr BP are compared with the sea-surface-temperature (SST) record from the western
347 tropical Pacific (Stott et al., 2004) and the hematite-stained-grains (HSG) record from the
348 North Atlantic (Bond et al., 2001).

349 As shown in Fig. 5, the decline of the EASM occurring at 4210–3840 cal. yr BP
350 coincides, within age uncertainties, with decreases in the SST of the western tropical Pacific
351 (Stott et al., 2004) and with increases in the HSG concentration in the North Atlantic
352 sediments (Bond et al., 2001). This coincidence implies a physical link between the EASM
353 decline on millennial-to-centennial scales and the persistent cooling of surface waters of the
354 western tropical Pacific as well as the North Atlantic. In brief, continual decreases in sea
355 surface temperature of the western tropical Pacific presumably caused by more intense, more
356 frequent El Niño (Moy et al., 2002) could reduce the formation of water vapor over the source

357 area of the EASM, thereby decreasing the moisture available for transport via the EASM
358 circulation from the western tropical Pacific onto the Asian inland and leading to a weakened
359 EASM. While decreases in sea surface temperature of the North Atlantic could suppress the
360 northward migration of the EASM front, thereby hampering the northward jumps of the
361 EASM rainbelt and resulting in weakened rainfall in the northern marginal zone of the
362 EASM.

363

364 **6. Conclusions**

365

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

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

377

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379

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485 **Figure captions**

486

487 **Figure 1.** Map of Hulun Lake (from <http://www.maps.google.com>) showing the location of
488 the HL06 core. The bathymetric survey of the lake was conducted in July 2005 with a FE-606
489 Furuno Echo Sounder (contours in meters). The inset gives a sketch map of China showing
490 the current northern limit of the East Asian summer monsoon (dashed line) defined as the
491 400-mm isohyet of mean annual precipitation (Chinese Academy of Sciences, 1984; Zhang
492 and Lin, 1985) and the locations of lakes (solid circles) mentioned in the present study. 1,
493 Hulun Lake; 2, Dali Lake; 3, Daihai Lake. EASM shown in the inset indicates the East Asian
494 summer monsoon.

495

496 **Figure 2.** Lithological log and age–depth model of the segment of the HL06 core between
497 105 and 55 cm at core depth (covering the period between 5000 and 3000 cal. yr BP). Solid
498 circles represent the mean values of 2σ ranges of calibrated ages of carbon reservoir-corrected
499 radiocarbon dates. The carbon reservoir correction factor is 685 ± 21 yr, ^{14}C age of the
500 uppermost 1 cm of the core sediments. Modified after Xiao et al. (2009).

501

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

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

513

514 **Figure 4.** A sketch map of eastern China, Korea and western Japan showing precipitation
515 rates of the current East Asian summer monsoon. Data are averaged by observations of the
516 years 1979–2007 and expressed in mm d^{-1} at a grid resolution of $0.25^\circ \times 0.25^\circ$. (a) On the 4th,
517 5th and 6th pentads of July and 1st pentad of August. (b) On the 5th and 6th pentads of June
518 and the 1st and 2nd pentads of July. (c) On the 5th and 6th pentads of May and the 1st and
519 2nd pentads of June. The inset in Fig. 4a shows monthly changes of annual precipitation in
520 the Hulun Lake region (data from observations of the years 1976–2005).

521

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

528

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

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