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7 **The 4.2 ka BP event: multi-proxy records from a closed lake in the**  
8 **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 (Drysdale 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 ( $48^{\circ}30.667'$  to  $49^{\circ}20.667'$ N,  $117^{\circ}0.167'$  to  $117^{\circ}41.667'$ 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  $2339 \text{ km}^2$  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  $37,214 \text{ km}^2$  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**

147

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  $^{14}\text{C}$  age of  $685 \pm 21$  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  $685 \pm 21$  yr was first subtracted from all the original  $^{14}\text{C}$  ages, and then calibrations are  
166 performed on the carbon reservoir-free  $^{14}\text{C}$  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  $\sim 11,000$  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- $\mu$ m 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  $\mu$ m 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).

203

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  $2\sigma$  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**

221

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<sup>-1</sup>  
237 and a SD of 22 valves g<sup>-1</sup> 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<sup>-1</sup> and an average of 44 valves g<sup>-1</sup>. 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**

250

251 5.1 Climatic implication of proxy data from the HL06 core

252

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 subellipsoida*, 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

287

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).

310 PCA F1 reflects the most prominent common features of the aforementioned four  
311 proxies and defines a dry event that occurred in the lake region at the interval of 4210–3840  
312 cal. yr BP. We thus suggest that a drought occurring in the Hulun Lake basin could be the  
313 regional manifestation of the 4.2 ka BP event. This drought started at 4210 cal. yr BP and  
314 ended at 3840 cal. yr BP, lasting for 370 yr.

315

316 5.3 Possible cause of the 4.2 ka BP event in the Hulun Lake region

317

318 Hulun Lake is situated in the northern marginal zone of the East Asian summer  
319 monsoon (EASM) (Fig. 1). Modern observations indicate that precipitation in the Hulun Lake  
320 region reaches its peak value in July and ~70% of the annual precipitation falls in late June  
321 through early August (Xu et al., 1989). Changes in the precipitation of the lake region in the  
322 summer half-year totally follow the northward migrations of the EASM rainbelt (Fig. 4),  
323 indicating that increases in the precipitation of the lake region would be closely related to  
324 increases in the strength of the EASM. These data suggest that the dry event that occurred in  
325 the Hulun Lake region at 4210–3840 cal. yr BP implies a decline of the EASM.

326 The northward migrations of the EASM rainbelt in rainy seasons of East Asia are  
327 characterized by two discontinuous jumps (i.e., jumping first to the Yangtse River–Huaihe

328 River basin, southwestern Japan and southern Korea in late June and then to northern China,  
329 northeastern China and northern Korea in middle July after landing in southern China in late  
330 May) (Fig. 4), which are influenced not only by the ocean–atmosphere interactions in the  
331 tropical Pacific because the moisture/rainfall brought by the EASM onto the land derives  
332 from the western tropical Pacific but also by the pattern of atmospheric circulation over  
333 Northern Hemisphere high latitudes because the EASM frontal rainfall results from the  
334 interaction between the warm-moist, southerly air-masses and the cold-dry, northwesterly  
335 airflows (Chinese Academy of Sciences, 1984; Zhang and Lin, 1985). In Fig. 5, therefore,  
336 dry–wet oscillations in the Hulun Lake region reflected by PCA F1 for the period of 5000–  
337 3000 cal. yr BP are compared with the sea-surface-temperature (SST) record from the western  
338 tropical Pacific (Stott et al., 2004) and the hematite-stained-grains (HSG) record from the  
339 North Atlantic (Bond et al., 2001).

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

354

## 355 **6. Conclusions**

356

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

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

368

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370

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## 378        **References**

379

- 380        Alley, R. B., Mayewski, P. A., Sowers, T., Stuiver, M., Taylor, K. C., and Clark, P. U.:  
381            Holocene climatic instability: A prominent, widespread event 8200 yr ago, *Geology*, 25,  
382            483–486, 1997.
- 383        Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen,  
384            H., Hajdas, I., and Bonani, G.: A pervasive millennial-scale cycle in North Atlantic  
385            Holocene and glacial climates, *Science* 278, 1257–1266, 1997.
- 386        Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S.,

- 387 Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic  
388 climate during the Holocene, *Science*, 294, 2130–2136, 2001.
- 389 Bronk Ramsey, C.: Development of the radiocarbon calibration program, *Radiocarbon*, 43,  
390 355–63, 2001.
- 391 Chinese Academy of Sciences (Compilatory Commission of Physical Geography of China):  
392 Physical Geography of China: Climate. Science Press, Beijing, pp. 1–30, 1984 (in  
393 Chinese).
- 394 Compilatory Commission of Vegetation of China: Vegetation of China, Science Press,  
395 Beijing, pp. 932–955, 1980 (in Chinese).
- 396 Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer,  
397 C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdóttir, A. E., Jouzel, J., and Bond,  
398 G.: Evidence for general instability of past climate from a 250-kyr ice-core record,  
399 *Nature*, 364, 218–220, 1993.
- 400 deMenocal, P. B.: Cultural responses to climate change during the late Holocene, *Science*,  
401 292, 667–673, 2001.
- 402 Drysdale, R., Zanchetta, G., Hellstrom, J., Maas, R., Fallick, A., Pickett, M., Cartwright, I.,  
403 and Piccini, L.: Late Holocene drought responsible for the collapse of Old World  
404 civilizations is recorded in an Italian cave flowstone, *Geology*, 34, 101–104, 2006.
- 405 Hou, Y. T., Gou, Y. X., and Chen, D. Q.: Fossil Ostracoda of China (Vol. 1), Science Press,  
406 Beijing, 1090 pp., 2002 (in Chinese).
- 407 Hsü, K. J.: Sun, climate, hunger, and mass migration, *Science in China (Series D)*, 41, 449–  
408 472, 1998.
- 409 Liu, F. G. and Feng, Z. D.: A dramatic climatic transition at ~4000 cal. yr BP and its cultural  
410 responses in Chinese cultural domains, *Holocene*, 22, 1181–1197, 2012.
- 411 Magny, M., Vannière, B., Zanchetta, G., Fouache, E., Touchais, G., Petrika, L., Coussot, C.,  
412 Walter-Simonnet, A. V., and Arnaud, F.: Possible complexity of the climatic event  
413 around 4300–3800 cal. BP in the central and western Mediterranean, *Holocene*, 19,  
414 823–833, 2009.
- 415 Marchant, R. and Hooghiemstra, H.: Rapid environmental change in African and South  
416 American tropics around 4000 years before present: a review, *Earth-Sci. Rev.*, 66, 217–

- 417 260, 2004.
- 418 Meisch, C.: Freshwater Ostracoda of Western and Central Europe, Spektrum, Heidelberg, 522  
419 pp., 2000.
- 420 Moy, C. M., Seltzer, G. O., Rodbell, D. T., and Anderson, D. M.: Variability of El  
421 Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch,  
422 *Nature*, 420, 162–165, 2002.
- 423 O'Brien, S. R., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S., and Whitlow,  
424 S. I.: Complexity of Holocene climate as reconstructed from a Greenland ice core,  
425 *Science*, 270, 1962–1964, 1995.
- 426 Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H.,  
427 Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L.,  
428 Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer,  
429 B., McCormac, G., Manning, S., Bronk Ramsey, C., Reimer, R. W., Remmele, S.,  
430 Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and  
431 Weyhenmeyer, C. E.: Intcal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP,  
432 *Radiocarbon*, 46, 1029–58, 2004.
- 433 Staubwasser, M. and Weiss, H.: Holocene climate and cultural evolution in late prehistoric–  
434 early historic West Asia, *Quaternary Res.*, 66, 372–387, 2006.
- 435 Stott, L., Cannariato, K., Thunell, R., Haug, G. H., Koutavas, A., and Lund, S.: Decline of  
436 surface temperature and salinity in the western tropical Pacific Ocean in the Holocene  
437 epoch, *Nature*, 431, 56–59, 2004.
- 438 Wang, S. M. and Ji, L.: Paleolimnology of Hulun Lake, University of Science and  
439 Technology of China Press, Hefei, 125 pp., 1995 (in Chinese).
- 440 Weiss, H., Courty, M. A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., and  
441 Curnow, A.: The genesis and collapse of third millennium north Mesopotamian  
442 civilization, *Science*, 261, 995–1004, 1993.
- 443 Weiss, H. and Bradley, R. S.: What drives societal collapse? *Science*, 291, 609–610, 2001.
- 444 Wen, R. L., Xiao, J. L., Chang, Z. G., Zhai, D. Y., Xu, Q. H., Li, Y. C., Itoh, S., and  
445 Lomtatidze, Z.: Holocene climate changes in the mid-high latitude monsoon margin  
446 reflected by the pollen record from Hulun Lake, northeastern Inner Mongolia,

- 447 Quaternary Res., 73, 293–303, 2010a.
- 448 Wen, R. L., Xiao, J. L., Chang, Z. G., Zhai, D. Y., Xu, Q. H., Li, Y. C., and Itoh, S.: Holocene  
449 precipitation and temperature variations in the East Asian monsoonal margin from  
450 pollen data from Hulun Lake in northeastern Inner Mongolia, China, *Boreas*, 39, 262–  
451 272, 2010b.
- 452 Wen, R. L., Xiao, J. L., Ma, Y. Z., Feng, Z. D., Li, Y. C., and Xu, Q. H.: Pollen–climate  
453 transfer functions intended for temperate eastern Asia, *Quaternary Int.*, 311, 3–11, 2013.
- 454 Wu, W. X. and Liu T. S.: Possible role of the “Holocene Event 3” on the collapse of Neolithic  
455 Cultures around the Central Plain of China, *Quaternary Int.*, 117, 153–166, 2004.
- 456 Xiao, J. L., Chang, Z. G., Wen, R. L., Zhai, D. Y., Itoh, S., and Lomtadidze, Z.: Holocene  
457 weak monsoon intervals indicated by low lake levels at Hulun Lake in the monsoonal  
458 margin region of northeastern Inner Mongolia, China, *Holocene*, 19, 899–908, 2009.
- 459 Xu, Z. J., Jiang, F. Y., Zhao, H. W., Zhang, Z. B., and Sun, L.: *Annals of Hulun Lake*, Jilin  
460 Literature and History Publishing House, Changchun, 691 pp., 1989 (in Chinese).
- 461 Zhai, D. Y., Xiao, J. L., Zhou, L., Wen, R. L., Chang, Z. G., Wang, X., Jin, X. D., Pang, Q. Q.,  
462 and Itoh, S.: Holocene East Asian monsoon variation inferred from species assemblage  
463 and shell chemistry of the ostracodes from Hulun Lake, Inner Mongolia, *Quaternary  
464 Res.*, 75, 512–522, 2011.
- 465 Zhang, J. C. and Lin, Z. G.: *Climate of China*, Shanghai Scientific and Technical Publishers,  
466 Shanghai, 603 pp., 1985 (in Chinese).
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470 **Figure captions**

471

- 472 **Figure 1.** Map of Hulun Lake (from <http://www.maps.google.com>) showing the location of  
473 the HL06 core. The bathymetric survey of the lake was conducted in July 2005 with a FE-606  
474 Furuno Echo Sounder (contours in meters). The inset gives a sketch map of China showing  
475 the current northern limit of the East Asian summer monsoon (dashed line) defined as the  
476 400-mm isohyet of mean annual precipitation (Chinese Academy of Sciences, 1984; Zhang

477 and Lin, 1985) and the location of Hulun Lake (solid circle). EASM shown in the inset  
478 indicates the East Asian summer monsoon.

479

480 **Figure 2.** Lithological log and age–depth model of the segment of the HL06 core between  
481 105 and 55 cm at core depth (covering the period between 5000 and 3000 cal. yr BP). Solid  
482 circles represent the mean values of  $2\sigma$  ranges of calibrated ages of carbon reservoir-corrected  
483 radiocarbon dates. The carbon reservoir correction factor is  $685 \pm 21$  yr,  $^{14}\text{C}$  age of the  
484 uppermost 1 cm of the core sediments. Modified after Xiao et al. (2009).

485

486 **Figure 3.** Time series of sand fraction (%) (Xiao et al., 2009), littoral ostracodes valve (valves  
487  $\text{g}^{-1}$ ) (Zhai et al., 2011), Chenopodiaceae pollen (%) (Wen et al., 2010a), and mean annual  
488 precipitation (mm) (Wen et al., 2010b) from the HL06 core spanning the period between 5000  
489 and 3000 cal. yr BP as well as the PCA F1 obtained from the aforementioned four proxies.  
490 The chronology was derived from the carbon reservoir-corrected age–depth model; ages of  
491 sampled horizons were determined by linear interpolation between radiocarbon-dated  
492 horizons using the mean values of  $2\sigma$  ranges of calibrated ages (Xiao et al., 2009). Vertical  
493 dashed lines show the averages and one standard deviations above/below the averages of each  
494 proxy data as well as PCA F1 values during the period between 5000 and 3000 cal. yr BP.  
495 Light grey bars mark the intervals at which each proxy or PCA F1 has values higher than one  
496 standard deviation (lower than one standard deviation for mean annual precipitation).

497

498 **Figure 4.** A sketch map of eastern China, Korea and western Japan showing precipitation  
499 rates of the current East Asian summer monsoon. Data are averaged by observations of the  
500 years 1979–2007 and expressed in  $\text{mm d}^{-1}$  at a grid resolution of  $0.25^\circ \times 0.25^\circ$ . (a) On the 4th,  
501 5th and 6th pentads of July and 1st pentad of August. (b) On the 5th and 6th pentads of June  
502 and the 1st and 2nd pentads of July. (c) On the 5th and 6th pentads of May and the 1st and  
503 2nd pentads of June. The inset in Fig. 4a shows monthly changes of annual precipitation in  
504 the Hulun Lake region (data from observations of the years 1976–2005).

505

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

512

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

517