Late Quaternary hydroclimate change inferred from lake sedimentary record in arid central Asia

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Arid central Asia is a key region in the study of global climate change; however, the characteristics and mechanisms of regional hydroclimate changes during the late Quaternary remain poorly known. Here we present a new hydroclimate record from Lake Ebinur in arid northwestern China based on a comprehensive multiproxy analysis. The results show that Lake Ebinur formed at ~33.5 ka under relatively warm and humid conditions that continued to 26.7 ka. The following Last Glacial Maximum was cold and dry from 26.7 to 18.5 ka, most notably during the interval between 21.3 and 18.5 ka, suggesting a two-step hydroclimate change. The moisture conditions started to improve at 19 ka and reached their highest level during the Middle Holocene (8.7–4.4 ka). A comparison of our record with other records in the Northern Hemisphere indicated that the moisture changes in central Asia followed similar variability trends to those of the east Asia monsoon region during the last glacial period, suggesting common driving forces, such as the boreal solar insolation and its associated Northern Hemisphere ice-sheet volume. The Holocene moisture optimum in central Asia was delayed by 2000–3000 years relative to that in east Asia, which demonstrated a large influence of the remnant Northern Hemisphere ice-sheet forcings on the mid-latitude Asia atmospheric circulation (e.g. mid-latitude westerlies and Siberian High) in the Early Holocene.

The central Asia (CA) region, located in the mid-latitudes of the Asian continent, is a sensitive recorder of past climate change because of its location in the transitional region between the Asian monsoons, mid-latitude westerlies and Siberian High (SH) pressure system (Guan et al. 2019). A detailed understanding of past hydroclimate change is essential to characterize the impact of future climate changes in this arid region.

Holocene hydroclimate changes in CA have been well studied, and several Holocene moisture change patterns have been proposed (Chen et al. 2016; Cheng et al. 2016b; Xu et al. 2019), which all show an out-of-phase relationship with that of the east Asia monsoon region. Some studies have attributed this phenomenon to the influence of the meltwater from snow and glaciers (Rao et al. 2019) or different boundary conditions between glacial and interglacial (Cheng et al. 2016b). In contrast, relatively little is known about the Last Glacial hydroclimate changes in CA. Previous studies have proposed a cold-moist glacial and warm-dry interglacial pattern of the Late Pleistocene environmental changes in CA (Li 1990). This assertion was further supported by sedimentary records from Lake Karakul (Aichner et al. 2019) and from the BSK section in the western Tianshan (Li et al. 2020), which emphasized the important role of evaporation. In contrast, a large number of studies, including lake sediment records (Zhao et al. 2015; Zhou et al. 2019), loess records (Wang et al. 2018; Tian et al. 2020) and glacial activity in the Tianshan mountain (Blomdin et al. 2016), have all suggested a cold and dry climate during the Last Glacial Maximum (LGM) and have attributed the dry LGM to the positions and intensities of the mid-latitude westerlies and the SH. Therefore, the timing, patterns and driving forces of the hydroclimate fluctuations in CA during the Last Glacial remain poorly understood and additional records with high-resolution, well-dated materials are required.

Here we present a new hydroclimate change record for CA during the past 35 ka based on a multiproxy analysis of the sediment core from Lake Ebinur in northwestern China. Our aim is to elucidate the characteristics of hydroclimate variability during the past 35 ka and to compare these findings with other records to determine the possible driving forces.

Study site

Lake Ebinur (44°54′–45°08′N, 82°35′–83°10′E, 190 m a.s.l.) is a terminal lake situated in the arid region of northwestern China (Fig. 1A). The lake has a drainage area of 50 321 km², including 24 317 km² of mountainous terrain. The lake receives most of its water from the Bo and Jing rivers, which originate from precipitation in mountainous areas. Today, the lake has a surface area of
542 km², with a maximum depth of 3.5 m and a mean depth of 1.2 m. The lake has a salinity of 85–124 g L⁻¹ in total dissolved solids (Ma et al. 2011). The climate of the study region is dominated by the westerlies and is strongly continental, as indicated by high-amplitude fluctuations in annual and daily temperature records (mean annual temperature 7.8 °C). The mean annual precipitation (95 mm) is significantly less than the mean annual evaporation capacity (1315 mm), resulting in a strongly arid climate.

The modern vegetation in Lake Ebinur lowland regions is temperate desert and the vegetation in the mountainous areas of Lake Ebinur region has vertical zonation. The zones, from high to low elevations, include alpine meadows (>2700 m a.s.l.), coniferous and deciduous forests (2700–1700 m a.s.l.) and montane shrubs (1700–700 m a.s.l.), and halophytic meadow and swamp communities occupy the low reaches along the rivers and around the lake (Hou 2001) (Fig. 1B).

Material and methods

Coring and dating

A 14.8-m-long core (EB) was collected from the northwestern part of Lake Ebinur in December 2013 using an X-1 100-m power drill. The sediment core was sub-sampled at 1-cm intervals for clay layers and at 5-cm intervals for sand layers. In this study, we focused on the core segment between 0.0 and 8.8 m that was mainly composed of clay. The chronology of the EB core was established based on seven accelerator mass spectrometry (AMS) radiocarbon dates (organic sediments) measured by Beta Analytic Inc., USA and four optically stimulated luminescence (OSL) dates measured at Nanjing University. The radiocarbon ages of the seven samples were calibrated to calendar years before present using Calib 7.0 software with IntCal13 (Reimer et al. 2013).
Analytical methods

A total of 278 samples for grain size analysis were pretreated with 10% H$_2$O$_2$ to remove organic matter and 10% HCl to remove carbonates, and were dispersed with 5% (NaPO$_3$)$_6$ by ultrasonic treatment prior to measurement. The grain-size distribution was measured with a Malvern Mastersizer 2000 laser diffraction instrument with 100 bins ranging from 0.02 to 2000 μm, at the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences.

A total of 278 samples were selected for total organic carbon (TOC) analysis. The samples were treated with 5% HCl to remove carbonates and then measured using a CE440 elemental analyser. A total of 120 samples were selected for pollen analysis. An ~2 g sample was mixed with one Lycopodium spore tablet (27 637 grains) as a standard marker. Pollen grains were extracted using HCl–NaOH–HF acetylsis. The pollen was identified by comparing it with published morphological descriptions (Wang et al. 1995) and then counted under a light microscope at 400× magnification.

A total of 66 samples were processed for n-alkane analysis. Lipids were extracted from these samples with a 9:1 mixture of dichloromethane–methane for 15 min using an ultrasonic generator, then for 5 min using a centrifuge at 3000 rpm. The n-alkanes were then obtained using silica gel column chromatography and elution with 20 mL of n-hexane. The extracted n-alkanes were identified using 7900 gas chromatography (GC) with flame ionization detection. Separation of n-alkanes was carried out on a DB-5MS (30 m × 0.25 mm × 0.25 μm) with a constant nitrogen carrier gas flow of 400 mL min$^{-1}$. The GC oven programme was gradually increased from 100 to 300 °C (held for 20 min) at 10 °C min$^{-1}$. Identification of individual n-alkanes was done by comparison with mass spectra and retention times from the literature, and the area normalization method was used to quantify individual components. To evaluate the n-alkane distributions, we used the proportion of aquatic plants (Paq): Paq = (C$_{23}$+C$_{25}$)/(C$_{23}$+C$_{25}$+C$_{27}$+C$_{29}$) (Ficken et al. 2000).

 Elemental composition in the core was obtained with an Avaatech XRF core scanner at Lanzhou University. The exposed surface of the split core was carefully flattened and covered with Ultralene film (4 μm). Analysis was conducted on a 0.5-cm-wide channel with an X-ray current of 1 mA, at 15 s count time and 10 kV X-ray voltage for Ti and Cr. The XRF results are expressed in counts per second.

Principal component analysis was run on the most representative pollen, including the sum of Picea and Betula, and hygrophic herbs (including Gramineae, Typha and Cyperaceae), organic geochemistry (TOC and Paq), inorganic geochemistry (Cr/Ti) and grain size index (8–16 μm) using the SPSS 18.0 software. A previous resampling using linear interpolation was conducted to achieve equivalent resolution among different proxies. Moreover, all data were normalized by the formula $x = (x – \text{minimum})/(\text{maximum} – \text{minimum})$. Resampled and normalized data were further analysed to determine the percentage variance and scores.

Spectral analysis was performed on principal component 1 (PC1) in order to obtain cyclical periodicities using the Matlab 7.0 software. Morlet wavelet analysis was performed using Matlab 7.0 software with code available for download at http://paos.colorado.edu/research/wavelets/software.html (Torrence & Compo 1998). Before spectral analysis and wavelet analysis, the data were detrended and normalized using the formula $x = (x – \text{minimum})/(\text{maximum} – \text{minimum})$ before interpolation to a 100-year interval. This analysis focused on high frequencies above 0.0002 (5000 years) for comparison with millennial-scale oscillations. The results are shown in Fig. 6.

Results

Chronology

The results of seven AMS$^{14}$C ages and four OSL ages are shown in Fig. 2 and Table 1. To determine the continuous timescale of the EB core, we incorporated AMS$^{14}$C ages and OSL ages into the Bayesian age–depth model in Bacon software (Blaauw & Christen 2011). Results from the Markov Chain Monte Carlo iterations and the prior and posterior distributions for the accumulation rate and memory allow us to infer the reliability of the Bayesian age–depth model for the sedimentary sequence chronology construction. Two AMS$^{14}$C ages at 2.05 and 7.51 m depths appeared too young and were excluded according to the age–depth model (Fig. 2). Finally, the weighted mean age was used for each depth, and the ages for the bottom and top of the EB core were 35.2 and 4.4 ka, respectively.

Grain size analysis

A contour plot of all grain size distributions within the EB core is depicted in Fig. 3B. The EB core mainly consists of fine silt with occasional sections of coarse silt with a mean grain size of ~35 μm and of clay with a mean grain size of 3 μm. In order to assess the underlying patterns of variation within the grain-size data, principal component analysis of grain size distributions of the EB core was conducted, and the first two principal components (F1 and F2) extracted from the grain size data captured 94% of the total variation. F1 explains 84% of the total variation, and F2 explains 10% of the total variation. Therefore, the grain size variations within the EB core could be efficiently summarized by F1 and F2. F1 shows a single peak centred at 8–16 μm, which is in accordance with grain size distribution of a deposit collected from an open, deep-water environment (L1,
Fig. 3A). F1 is interpreted as an indication of lake energy. F2 has a narrow peak centred at 28–45 μm. The grain size distribution of a surface sample collected from the floodplains of Bo river also has a single peak centred at 30–60 μm (L2, Fig. 3A). Therefore, F2 is viewed as an indication of river input. In the text we use 8–16 and 28–45 μm fractions to represent F1 and F2, respectively.

**Environmental proxy variations**

Selected physical, chemical and biological proxies are shown in Fig. 4. Most of these proxies exhibited large fluctuations on the millennium scale. The Cr/Ti ratio did not display any obvious trends over the study period but had some distinct peaks (Fig. 4), suggesting that this proxy was very sensitive to abrupt environmental change events. Interestingly, most of these peaks corresponded to lower values of the Paq and higher values of the 8–16 μm fraction. The sum of *Picea* and *Betula* increased dramatically from the base of the sediment core and showed maximum values at 28–26.7 ka. It then decreased sharply, with the lowest values occurring at 21.3–17 ka. The *Picea* + *Betula* sum displayed a slowly increasing trend from 17 ka, but it increased sharply at

**Table 1.** Radiocarbon and optically stimulated luminescence (OSL) ages for the sediment core from Lake Ebinur (ages with an asterisk were abandoned).

| Method | Laboratory code | Depth (m) | Material               | Conventional age (a BP) | Calibrated age 2σ (a BP) | Median age (cal. a BP) |
|--------|----------------|----------|------------------------|------------------------|-------------------------|----------------------|
| AMS 14C | Beta470707  | 0.16     | Organic sediment       | 4190±30                | 4765–4620               | 4690                  |
| OSL    | NJU2569      | 0.25     | 4–11 μm quartz         | 7680±40                | 8550–8400               | 8480*                 |
| AMS 14C | Beta348546  | 2.05     | Organic sediment       | 16 550±70              | 20 172–19 700           | 19 960                |
| AMS 14C | Beta520367  | 2.9      | Organic sediment       | 18 330±60              | 22 429–21 994           | 22 220                |
| AMS 14C | Beta520368  | 3.6      | Organic sediment       | 19 230±60              | 23 345–22 995           | 23 170                |
| AMS 14C | Beta438619  | 4.1      | Organic sediment       | –                     | 27 000±1500             | 27 000                |
| OSL    | NJU2564      | 4.42     | 4–11 μm quartz         | 22 400±80              | 27 091–26 445           | 26 770                |
| AMS 14C | Beta520366  | 5.25     | Organic sediment       | –                     | 29 400±2600             | 29 400                |
| AMS 14C | Beta348548  | 7.51     | Organic sediment       | 23 950±130             | 29 180–28 470           | 28 820*               |
| OSL    | NJU2566      | 8.6      | 4–11 μm quartz         | –                     | 34 000±2000             | 34 000                |

AMS, Accelerator mass spectrometry.
10.9 ka and reached the highest value at 8.7 ka. Hygroptic herbs displayed an inverse trend to that of *Picea* + *Betula*. The periods 34.8–33.8 and 26.7–8.7 ka contained higher Hygroptic herb contents, while relatively low values were observed at 28–26.7 and 8.7–4.8 ka. The highest hygroptic herb value was observed at the top of the sediment core. The Paq ranged from 0.07 to 0.75 and displayed a similar trend to that of hygroptic herbs. Higher values were observed at around 33–31.5, 26.7–14.5 and 4.8–4.4 ka, and lower values appeared at around 35.2–33.8 and 14–5 ka (Fig. 4). The TOC ranged from 0.2 to 3.1, increased markedly from 35.2 ka and reached higher values at 28–26.7 ka, and then decreased upward and showed relatively low values from 26.7 to 14 ka. The TOC value increased again starting at 14 ka and reached a maximum value at 8.7 ka. The TOC was significantly correlated with the *Picea* + *Betula* sum ($R^2 = 0.548$) and was negatively correlated with the hygroptic herbs ($R^2 = -0.12$), suggesting higher terrestrial organic matter input over the sediment core. The 8–16 μm fraction ranged from 3.3 to 30.1%, increased markedly beginning at 33.9 ka and reached a maximum at 28.8 ka, and then it decreased gradually. The fraction exhibited a rapid decreasing trend starting at 23.4 ka and showed the lowest values between 21.3 and 18.5 ka, with an average of 11.1%. It then increased again and maintained relatively high values, with several exceptions of extremely low values occurring at around 16–15, 11.5 and 5.0 ka.

Cluster analysis of these various proxies revealed a significant split at 8.7 ka (Fig. 4). Based on the cluster analysis and visual inspection, the upper zone was further divided into two subzones and the lower zone was further divided into six subzones.

Fig. 3. Grain size records of the EB core. A. Comparisons between the results of principle components analysis (F1 and F2) of the grain-size data for EB core and individual grain size distributions of surface samples (L1 represents the sample collected from lake surface, L2 represents the sample collected from river flat). B. All 278 grain-size distribution curves depicted as a contour plot with overlain mean grain size (blue line). C. Variations in F1 (8–16 μm) and F2 (28–45 μm) and standard deviation along the EB core.
Discussion

Proxy interpretation

Previous studies have shown that *Picea* can tolerate cold and frosty conditions but is sensitive to water deficit (Sykes *et al.* 1996; Kousis *et al.* 2018). Investigation of the surface pollen in the Bo River catchment also showed that the content of *Picea* was positively correlated with precipitation (Li *et al.* 2014). *Betula* in the Lake Ebinur region grows in a meadow marsh soil with a low total salinity, and higher contents of *Betula* indicate improved climatic conditions (Zhang *et al.* 2013; Wang *et al.* 2021). The frequencies of *Picea* and *Betula* display a similar trend (Fig. S1; $R^2 = 0.43$); therefore, we use the sum of *Picea* and *Betula* to infer the occurrence of *Picea–Betula* mixed forest, which indicates relatively warm and wet climate conditions (Zhao *et al.* 2013). Hygrophic herbs are delimited by ecological factors (e.g. water salinity and soil moisture), and mainly grow in shallow water or dry lake beds. We therefore assume that the high frequency of hygrophic herbs is caused by frequent shifts of the lake level, which would expose a locally favourable habitat for hygrophic herb when the lake shrank. Paq represents the ratio of aquatic to terrestrial, with values <0.1 related to terrestrial plants values, values between 0.1 and 0.4 for emergent macrophytes and values >0.4 related to submerged macrophytes (Ficken *et al.* 2000). Therefore, the Paq is used as a proxy of terrestrial contribution, which is sensitive to lake level variation.

The TOC content in lake sediments represents the stability between organic matter degradation, allochthonous input and autochthonous production (Meyers 2003). Higher TOC values indicate rising productivity within the lake basin and a rising oxic–anoxic boundary, which favours the production and preservation of organic matter (Stockhecke *et al.* 2016). Chromium could be reduced through nitrate reduction, making it the most easily reduced of the traditional suite of trace metals (Gueguen *et al.* 2016). The Cr/Ti ratio has been used as a proxy for the redox conditions related to the mixing of lake water (de Mahiques *et al.* 2009; Cole *et al.* 2017). Consequently, it gives an indication of, for example, lake water depth. This was further confirmed by the consistent peaks of the Cr/Ti ratio and the 8–16 μm fraction. The Cr/Ti ratio within the sediment core is completely stable except for several peaks, indicating that this proxy is sensitive mainly to rapid changes in redox conditions that are influenced by the lake level changes.

Millennial-scale climate variability

The high-resolution and well-dated sediment core from Lake Ebinur provided valuable material to infer late
Quaternary hydroclimate changes in CA. Changes in effective moisture in arid regions typically lead to variations in both regional vegetation and lake level, which have resulted in significant changes in sources and the preservation of organic matter, grain size composition and redox conditions. Thus, complementary hydroclimate changes in the study region can be derived from the sedimentary data, including pollen (Picea, Betula, hygrophic herbs), grain size (8–16 µm fraction), n-alkanes (Paq), TOC and elements (Cr/Ti). Applying principal component analysis to these proxies enabled us to extract the common features of multiproxy/temporal hydroclimate variability.

The lowermost Ebinur sediments dated to 35.2–33.5 ka represent coarse-grained, poorly sorted, coarse silt and sand sediments as deduced from the extremely high mean grain size (M̄) and standard deviation (SD) values (Fig. 3). Combined with the lowest TOC values over the sediment core (Fig. 4), this suggests a high-energy, dynamic depositional setting that may have been largely influenced by the riverine input. The subsequent period from 33.5 to 26.7 ka witnessed the initiation of lacustrine deposition as reflected by moderately sorted, fine silt (8–16 µm) sediments (Fig. 3). Regional vegetation also flourished as reflected by the increasing abundances in Picea–Betula mixed forest. Although with some fluctuations, the climate during 33.5–26.7 ka (corresponding to the MIS 3a) was warm and wet as a whole in the Lake Ebinur region.

Evident decreases in Picea, Betula and TOC, and increases in hygrophic herbs and Paq were observed beginning at 26.7 ka, suggesting that the forest-steppe was replaced by steppe or desert landscapes, which indicated transition to a relatively cold and dry climate. The lake level inferred from the grain size record was relatively stable from 26.7 to 23.4 ka, but it fluctuated dramatically and followed a decreasing trend between 23.4 and 21 ka, which indicated an unstable sedimentary environment during lake shrinkage. The lake reached its lowest level between 21.3 and 18.5 ka. Pollen data also showed that coniferous and broad-leaved plants, such as Picea and Betula, may have disappeared in the catchment at this time, reflecting the progressive aridification in the study region. The subsequent period witnessed higher occurrences in the coniferous broad-leaved taxa, higher 8–16 µm fraction and lower Paq values, indicating increasing lake level and higher contributions from terrestrial organic matter input, suggesting improved climate conditions. Two intervals of particularly low values of Picea and Betula and the 8–16 µm fraction stand out during 16–15 and ~11.5 ka, suggesting cold and dry events, within dating errors, corresponded to H1 and Younger Dryas in the north Atlantic region (Fig. 5F; Crocker et al. 2016).

A major transition is indicated by dramatic changes in proxies beginning at 8.7 ka (Fig. 4). Increasing 8–16 µm fraction and Cr/Ti, along with TOC and Picea + Betula, suggest a transition to more favourable environmental conditions. The hydrothermal conditions might have reached the highest level over the study period during 8.7–5 ka, which was in accordance with a previous study from Lake Ebinur (Wu et al. 1995) and probably corresponded to the regional Holocene Optimum (Mischke et al. 2019). At ~6.2 and ~5 ka, sharply decreased values of Picea and Betula, along with relatively low values of Paq and TOC, suggest vegetation degradation during these two dry events. The latter event was coeval with the almost complete disappearance of the Betula pollen in the wetland on the east side of Lake Ebinur (Wang et al. 2020). Evidence from Lake Ebinur has suggested that lake levels during the Holocene initially were high but decreased progressively, especially during the interval from 5 to 4.4 ka. Although the TOC reached the highest values over the study period, the sedimentary organic matter mainly came from endogenous hygrophic herbs which grew in shallow water or dry lake beds, further supporting this period being relatively arid.

Comparisons with regional records in the Northern Hemisphere

On the basis of multiple indicators of Lake Ebinur, it is reasonable to propose that the climate in the study region was cold and dry in stadials, and warm and wet in interstadials. Here, we compare our record with other records in the Northern Hemisphere, which provides an opportunity to better understand the hydrological changes in CA.

Grain size and pollen data from EB core suggested a rapid increase in the lake level and an improvement of the regional environment from 33.5 ka that favoured the initial formation of Lake Ebinur. This transition matches well the mineral record from Lake Balikun (Gu et al. 1988). Higher lake levels during this time were also noted in the sedimentary records from Lake Manas (Rhodes et al. 1996), supporting the prior proposition of a warm and wet MIS 3a in northwestern China (Yang & Scuderi 2010). Despite chronological uncertainties associated with low temporal resolution of various sediment records, proxies here supported the presence of a lake high-stand period during MIS 3a.

Multiproxy analyses pointed to a lower lake level and lower humidity after 26.7 ka, suggesting a cold and dry LGM. This finding has been confirmed by various records in CA (Rhodes et al. 1996; Zhao et al. 2015; Tian et al. 2020). Of special note, our record suggests a two-step hydroclimate change in the LGM. The interval from 26.7 to 21.3 ka (corresponding to LGMb) was characterized by a relatively dry climate with some fluctuations, whereas the following interval from 21.3 to 18.5 ka (corresponding to LGMa) witnessed the driest episode over the study period. During this time, oxygen isotope records in Greenland ice cores and east Asia stalagmites...
do not show clear, distinct signals (Fig. 5E, H). Various marine records and climate models, however, exhibit a two-step sea-level plunge into the LGM, with a rapid build-up of global ice volume and a rapid drop of global sea level from 21 to 20 ka (Yokoyama et al. 2018). Lower 45° N insolation (Fig. 5H; Laskar et al. 2004) and somewhat reduced atmospheric carbon dioxide during 22–21 ka (Yokoyama et al. 2018) might have lessened the evaporation of water vapour in the upwind regions, resulting in an extremely dry climate in CA.

The cold and dry glacial conditions prevailed from 26.7 to 15 ka, and then the climate conditions began to improve. The onset of relatively humid conditions in the Lake Ebinur region at ~15 ka was coincident with transitions from a dry climate to wetter conditions at Lake Balikun (Zhao et al. 2015), Lake Van (Fig. 5D; Stockhecke et al. 2016) and BSK loess (Li et al. 2020). The TraCE simulation showed that the Northern Hemisphere ice-sheet volume started to drop significantly at ~15 ka (Lora et al. 2016), resulting in reduced intensity and/or a northward movement of the SH, which would have allowed for the increasing transport of moisture by the westerlies to the study region after ~15 ka.

The study region maintained a moderately humid condition in the Early Holocene until a rapid increase in effective moisture occurred at 8.7 ka, which was quite consistent with the Holocene salinity history of Lake Lop Nur (Mischke et al. 2019) and the local temperature variation recovered from Lake Balikun (Fig. 5B; Zhao et al. 2015). The results from Lake Ebinur indicated a 2000–3000 year delay relative to the solar insolation, whereas the east Asia monsoon region’s moisture generally followed the solar insolation (Xiao et al. 2008). We suggest that the delayed moisture optimum could be attributed to the influence of the remnant Northern Hemisphere ice sheet which limited the water vapour carried by the mid-latitude westerlies. Moreover, increased evaporation in the Early Holocene warm conditions also may have led to a relatively low effective

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**Fig. 5.** Comparisons of Lake Ebinur PC1 with regional and global palaeoclimatic records. A. PC1 score from Lake Ebinur (this study). B. PC1 score from Lake Balikun (Zhao et al. 2015). C. Grain size record from Yuanbao loess in the Chinese Loess Plateau (Rao et al. 2013). D. PC1 score from Lake Van in Turkey (Stockhecke et al. 2016). E. Composite east Asia monsoon δ18O record (Cheng et al. 2016a). F. Ice-rafted debris (IRD) concentration from ODP 980 core in the North Atlantic (Corcket et al. 2016). G. 45° N insolation (Laskar et al. 2004). H. North Greenland Ice Core Project (NGRIP) ice core δ18O value (NGRIP Members 2004).
moisture as the local temperature has had a strong influence on the climate in CA (Rao et al. 2019).

Possible solar forcing

The climate change pattern inferred from Lake Ebinur record has a good consistency with various records. To evaluate the potential forcing mechanisms controlling the hydrological changes during the late Quaternary in CA, we performed spectral analysis as well as wavelet analysis of the PC1 score. Analysis of the PC1 showed a significant 933-year cycle (Fig. 6B), which was most significant during 33.7–32.7, 29.7–27.6, 13.8–11.2 and 9.1–8.4 ka (Fig. 6A). The ~1000-year cycle, known as the Eddy cycle, has been reported from various sedimentary records (Debret et al. 2007; Ramos-Román et al. 2018) and is considered to be solar (Ramos-Román et al. 2018). Therefore, the results of the time series analyses of the Lake Ebinur data suggest a solar influence on the climate during the past ~35 ka in CA.

Previous studies have suggested a close link between the solar activities and the hydrological changes in CA (Wu et al. 2009). Model work with the CCSM3 proposed that hydrological conditions in CA were due to variations in temperatures and evaporation over the north Atlantic, leading to variability in water vapour advection over Eurasia (Jin et al. 2012). Moreover, the Northern Hemisphere ice sheet regulated by the solar insolation has also exerted a large influence on the atmospheric circulation (such as SH and mid-latitude westerlies), which has influenced the volume of water vapour carried to CA. Therefore, changes in Northern Hemisphere insolation perhaps exert a remarkable influence over the evolution of hydrological conditions in CA over the past ~35 ka.

Conclusions

Our multiproxies record suggests a warm and wet late MIS 3, a cold and dry LGM, moderate moisture conditions during the last deglaciation and Early Holocene and a warm and wet Middle Holocene. Our record matched well with sedimentary records from nearby regions, suggesting a two-step hydroclimate change in the LGM and a major transition at ~15 ka in CA. To a larger extent, our record also shared a similar moisture variations trend towards the east Asia in the Last Glacial period, which was followed the boreal solar insolation. The moisture changes in Lake Ebinur region, however, lag behind by 2000–3000 years during the Holocene relative to the east Asia, which suggests a large influence of the remnant Northern Hemisphere ice sheet on the mid-latitude CA climate.

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### Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

*Fig S1.* Pollen percentages diagram of EB core.