Lateglacial and Holocene climate change in the NE Tibetan Plateau : Reconciling divergent proxies of Asian summer monsoon variability

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Lateglacial and Holocene climate change in the NE Tibetan Plateau: Reconciling divergent proxies of Asian summer monsoon variability

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Abstract:	The nature of Holocene Asian summer monsoon (ASM) evolution documented by diverse natural archives remains controversial, with a contentious issue being whether or not a strong Asian summer monsoon prevailed during the early Holocene. Here we present sequences of multiple proxies measured in sediment cores from Genggahai Lake in the NE Tibetan Plateau (NETP). The results suggest that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. This finding clearly reflects the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms. The early Holocene high stand of the lake, as demonstrated by the stratigraphic variability of the remains of aquatic biota, may have responded to the strengthened ASM and increased monsoonal precipitation; the relatively low vegetation cover in the marginal region of the Asian monsoon during the early Holocene, and the coeval widespread active sand dune mobility in both the NE Tibetan Plateau and NE China, most likely resulted from a low level of effective moisture due to high evaporation, and hence they cannot be interpreted as evidence of a weak ASM. Our results potentially reconcile the current divergent interpretations of various proxy climate records from the region. Our findings suggest that the ASM evolution was characterized by a consistent pattern across the monsoonal regions, as indicated by the oxygen isotope record of Chinese speleothems.

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Editor

November 26, 2020

Dear Editor,

We are resubmitting a manuscript, entitled 'Lateglacial and Holocene climate change in the NE Tibetan Plateau: Reconciling divergent proxies of Asian summer monsoon variability' with a reference code of CATENA12849. We thank you for your efforts to evaluate this work.

In light of the comments and suggestions raised by the reviewers, we have carefully revised the manuscript. The major revisions are outlined as follows:

We made small adjustments to the zonation of biota stratigraphy according to reviewer #1's comments, highlighting that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP.

We hope that the revisions are satisfactory to you. Please let us know if you have any questions regarding the revisions. Thank you!

Yours sincerely,

Yuan Li and other co-authors

Highlights (for review)

- Early Holocene high lake level and low vegetation cover occurred synchronously.
- Early Holocene high lake level suggests stronger monsoonal circulation.
- Early Holocene low vegetation cover did not reflect a weakened monsoon.

Lateglacial and Holocene climate change in the NE Tibetan Plateau: Reconciling divergent proxies of Asian summer monsoon variability

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Abstract

The nature of Holocene Asian summer monsoon (ASM) evolution documented by diverse natural archives remains controversial, with a contentious issue being whether or not a strong Asian summer monsoon prevailed during the early Holocene. Here we present sequences of multiple proxies measured in sediment cores from Genggahai Lake in the NE Tibetan Plateau (NETP). The results suggest that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. This finding clearly reflects the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms. The early Holocene high stand of the lake, as demonstrated by the stratigraphic variability of the remains of aquatic biota, may have responded to the strengthened ASM and increased monsoonal precipitation; the relatively low vegetation cover in the marginal region of the Asian monsoon during the early Holocene, and the coeval widespread active sand dune mobility in both the NE Tibetan Plateau and NE China, most likely resulted from a low level of effective moisture due to high evaporation, and hence they cannot be interpreted as evidence of a weak ASM. Our results potentially reconcile the current divergent interpretations of various proxy climate records from the region. Our findings suggest that the ASM evolution was characterized by a consistent pattern across the monsoonal regions, as indicated by the oxygen isotope record of Chinese speleothems.

Key words: Holocene; monsoon; China; Micropaleontology; lake level; vegetation.

1 Introduction

The Asian monsoon system affects more than half of the world's population and the associated ecosystems (Webster et al., 1998). Understanding the variability of the Asian monsoon has significant implications for the social and ecological systems in the region (Hansen and Lebedeff, 1987; Mishra et al., 2019). Precipitation in the marginal regions dominated by the Asian summer monsoon (ASM) is highly dependent on the strength of the ASM: a stronger ASM circulation can transport more water vapor, leading to higher precipitation, and vice versa (Zhou et al., 2009). Therefore, precipitation in these marginal regions can directly reflect the strength of the ASM (Chen et al., 2015). Over the past two decades, numerous studies of the Holocene evolution of the ASM have been conducted based on diverse natural archives from the region (e.g., Chen et al., 2015; Dykoski et al., 2005; Goldsmith et al., 2017; Hu et al., 2008; Li et al., 2014; Wang et al., 2005; Wei et al., 2020). However, the nature of ASM evolution during the Holocene still remains controversial, with a contentious issue being whether or not a strong Asian summer monsoon prevailed during the early Holocene. For example, the early Holocene high-stand of lakes in the marginal regions dominated by the ASM (Fig. 1A), including lakes Dali (Goldsmith et al., 2017), Dabusu (Li and Lv, 2001) and Kuhai (Mischke et al., 2010), reflects an intensified ASM which is consistent with monsoonal records from Chinese speleothems (Dykoski et al., 2005; Hu et al., 2008; Wang et al., 2005). However, records of pollen assemblages and/or pollen-based precipitation from the lakes in the region (Fig. 1A), including lakes Gonghai (Chen et al., 2015), Dalianhai (Cheng et al., 2013), Daihai (Xiao et al., 2004), Dali (Wen et al., 2017) and Hulun (Wen et al., 2010), together with evidence for widespread sand dune mobility in NE China (Li et al., 2014), indicate the occurrence of dry terrestrial conditions at this time, possibly related to a weak ASM. Furthermore, even diverse proxies generated from the same study site may exhibit divergent patterns of Holocene climate change and ASM evolution. For example, at Qinghai Lake, the geochemical proxies (An et al., 2012; Jin et al., 2015; Lister et al., 1991) generally suggest a high lake level and a strong ASM during the early Holocene. In contrast, the shoreline deposits (Liu et al., 2015) and the pollen assemblages (Shen et al., 2005) suggest that the lake level probably was low at this time, induced by high evaporation or a weak ASM. These seemingly contradictory interpretations, especially those from the same site (e.g., Qinghai Lake), cannot be explained by the spatial and temporal differentiation of ASM evolution, or by chronological uncertainties. Therefore, a comprehensive analysis of the driving mechanisms of these proxies and their linkage to the ASM are essential for reconciling the controversy.

Genggahai Lake is a small, shallow lake in the NE Tibetan Plateau (NETP) (Fig. 1A), located in the marginal region dominated by the ASM. The sediments are rich in the remains of aquatic biota and terrestrial pollen, which provide the opportunity to conduct multi-proxy investigations of ASM evolution. Qiang et al. (2013b) have discussed the lake-level fluctuations over the past 16 kyr based mainly on plant macrofossil assemblages in the sediments from a single core (GGH-A) recovered from the lake. However, the early Holocene high-stand of the lake was indirectly inferred by geochemical variables (total organic carbon, total nitrogen and carbon isotopic composition of bulk sediment organic matter), due to the absence of plant macrofossils (Qiang et al., 2013b). In addition, the evolution of lake bathymetry may also lead to lake-level fluctuations on a long timescale (Hilton, 1985; Lehman, 1975), which was not differentiated from the influence of climatic factors in the previous study (Qiang et al., 2013b). Therefore, comprehensive analyses of diverse bioindicators (e.g., plant macrofossils, Cladocera, diatoms) from multiple cores are essential not only for the reliable reconstruction of lake-level fluctuations, but also for assessing the influence of the evolution of lake bathymetry on the lake-level fluctuations, and for understanding regional hydroclimatic changes (Dearing, 1997). Moreover, the evolution of the regional terrestrial vegetation and its potential linkages to the ASM remain unclear.

Here we present sequences of aquatic (plant macrofossils, Cladocera, diatoms) and terrestrial (terrestrial pollen) proxies derived from multiple sediment cores from Genggahai Lake. Combined with hydrological and ecological investigations of the modern lake, and with reference to independent climatic records from the marginal regions dominated by the ASM, our aims were to reconstruct the regional ASM variability during the Lateglacial and the Holocene, and to reconcile the current divergent results of proxy indicators of ASM evolution.

2 Materials and Methods

Genggahai Lake (36°11′N, 100°06′E) is located in the central Gonghe Basin (Fig. 1B) at an altitude of 2,860 m a.s.l. The lake is small (surface area, ~2 km^2) and shallow (maximum water depth, ~1.8 m) and has an elevated salinity (~1.2 $g\ L^{-1}$) and pH (~9.1). *Potamogeton pectinatus*, *Myriophyllum spicatum*, and *Chara* spp. dominate the submerged macrophyte communities in the current lake. The lake is mainly fed by groundwater. Sever small spring-water streams flow into the lake. Three sediment cores were recovered from Genggahai Lake in January 2008 and January 2013 using a modified Livingstone piston corer. Cores GGH-A (length 782 cm) and GGH-C (length 774 cm) were recovered from the center of the lake in a water depth of 170 cm (Fig. 1C), and core GGH-E (length 765 cm) was recovered from the northwest littoral area in a water depth of 110 cm (Fig. 1C). Due to the lack of terrestrial plant remains, samples of

the leaves of aquatic macrophytes were picked from the sediments for accelerator mass spectrometry (AMS) ^{14}C dating, conducted by Beta Analytic Inc. (Miami, USA) (Table S1). The reservoir age of the lake was estimated at 1,010 ^{14}C years on average, based on the AMS ^{14}C dating results of the dissolved inorganic carbon of the lake water, macrophyte remains in the lake's surface sediments and living *P. pectinatus* (Li et al., 2017b). A total of 26 ^{14}C ages from cores GGH-A (cited from Qiang et al. 2013b), GGH-C, and GGH-E (Table S1), which are in stratigraphic order, were calibrated to calendar years (Calib 6.0.1, Reimer et al., 2009) after subtracting an average reservoir age (1,010 yr). The age-depth models of the three cores were generated by the Bacon Bayesian age-modeling software (Blaauw and Christen, 2011), using the calibrated radiocarbon ages. The age versus depth profiles of the three cores agree well with each other, which supports their reliability (Fig. S1).

Plant macrofossils, including *Chara* gyrogonites (Fig. 2B, 2D, 2F) and encrustations of *Chara* spp. and *P. pectinatus* (or *M. spicatum*) (Fig. 2A, 2C, 2E), were picked from cores GGH-A (cited from Qiang et al. 2013b), GGH-C, and GGH-E. Cladocera (Fig. 2G) and diatom (Fig. 2I, 2G) analyses were conducted on core GGH-C using standard methods (Korhola and Rautio, 2001; Weckström et al., 1997). In addition, fossil pollen (Fig. 3A, 3C) was extracted from core GGH-A following the methods of Fægri and Iversen (1989). In order to comprehensively depict the terrestrial vegetation conditions in the marginal regions dominated by the ASM, we compiled six lacustrine tree pollen records from the region, including from lakes Qinghai (Shen et al., 2005), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010). Since the changes in the tree pollen content of these records show a similar trend, a synthesized tree pollen index covering the past 12 kyr (obtained by taking the average of the normalized tree pollen contents from the six lakes) was used to portray changes in tree cover in the marginal regions dominated by the ASM (Fig. 3). Further details about the method are given in the supplements.

3 Results and discussion

3.1. Patterns of hydroclimatic evolution indicated by lake level and pollen sequences

In general, submerged macrophytes, Cladocera, and diatoms in freshwater lakes are sensitive to changes in water level, and thus their fossil remains in lake sediments can be used to reconstruct past water-level fluctuations (Birks, 1993; Heggen et al., 2012). The aquatic plant macrofossils in the sediments of Genggahai Lake mainly originate from *Chara* spp., *P. pectinatus* and *M. spicatum*. These species also dominate the lake today and they are common in shallow lakes worldwide (Wilson et al., 1941). The spatial distribution of submerged macrophytes in the modern lake is mainly modulated by the water depth, and the shallow water

zone of the lake is occupied by *Chara* spp. (Fig. S2) (Qiang et al., 2013b). Therefore, the occurrence of the fossil remains of *Chara* spp. and *P. pectinatus* (or *M. spicatum*) in the lake sediments, especially the occurrence of abundant *Chara* gyrogonites, most likely reflects a shallow water environment. As for fossil Cladocera, only two littoral species (*Chydorus sphaericus* and *Coronatella rectangula*) which prefer macrophyte habitats were identified in the sediments of Lake Genggahai (Walseng, B., 2016a, 2016b). Diatoms in the sediments are relatively diverse, consisting of both planktonic (e.g., *Lindavia comta* and *Cyclotella distinguenda*) and non-planktonic species (e.g., *Gomphonema angustum* and *Achnanthes minutissima*). Based on changes in submerged macrophytes, Cladocera and diatoms in the lake sediments (Fig. 2), the history of lake-level fluctuations was divided into the following four stages:

15.4–11.3 cal kyr BP The lake sediments contain abundant submerged-macrophyte encrustations, *Chara* gyrogonites and littoral cladoceran fossils, reflecting a shallow lake. In addition, the diatom assemblages are dominated by both planktonic (e.g., *L. comta* and *C. distinguenda*) and non-planktonic species (e.g., *G. angustum*). Notably, *C. distinguenda* is a *tychoplanktonic species* which can adapt to shallow water conditions. Therefore, the lake level most likely was low during this period.

11.3–8.6 cal kyr BP Submerged macrophytes and Cladocera largely disappear from the sediments. In addition, the diatom assemblages are dominated by an euplanktonic species (i.e., *L. comta*). Thus we conclude that the lake level was high during this period, and it may have exceeded the depth limit for submerged macrophytes, resulting in the absence of Cladocera macrophyte habitats and increasing the abundance of planktonic diatoms.

8.6–5.5 cal kyr BP Submerged macrophyte encrustations occur episodically and *Chara* gyrogonites are relatively scarce. Cladocera fossils largely disappear from the sediments, probably in response to the scarcity of macrophyte habitats. The diatom assemblages are dominated by both planktonic (e.g., *L. comta* and *C. distinguenda*) and non-planktonic species. Thus we conclude that the lake level during this period was probably high overall, but lower than during the previous stage.

5.5 kyr cal BP to the present The lake sediments contain abundant submerged-macrophyte encrustations, *Chara* gyrogonites, littoral Cladocera fossils, and non-planktonic diatoms, reflecting a shallow lake.

The terrestrial pollen in lake sediments is mainly derived from the catchment and hence it reflects the local and regional terrestrial vegetation conditions (Pennington, 1979). Changes in total terrestrial pollen concentrations (Fig. 3A) and tree pollen contents (Fig. 3C) in the

sediments of Genggahai Lake are largely in agreement with those at nearby Qinghai Lake (Fig. 3B, 3D) and the synthesized tree pollen index (Fig. 3J), showing that optimal vegetation conditions occurred during 8.6–6.9 cal kyr BP. Overall, the aquatic and animal fossils (macrophytes, Cladocera, diatoms) and terrestrial pollen in the sediments of Genggahai Lake indicate that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. This implies the occurrence of different hydroclimatic conditions between the lake and its catchment (Fig. 4A, 4I). This apparent contradiction is also reflected in proxy sequences from other lakes in the marginal regions dominated by the ASM: e.g., at Lakes Qinghai (An et al., 2012; Shen et al., 2005), Dali (Goldsmith et al., 2017; Wen et al., 2017) and Chagan Nur (Li et al., 2020a).

3.2. Implications for the evolution of the Asian summer monsoon

The early Holocene high lake levels and low total pollen concentrations (or tree percentages) recorded by lake sediments from the margins of the regions dominated by the ASM are mutually contradictory in terms of their interpretation as evidence for ASM strength (e.g., An et al., 2012; Chen et al., 2015), or as evidence for the spatial differentiation of ASM evolution (Zhang et al., 2019). However, these seemingly contradictory patterns most likely reflect the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms (cf., Wilson et al., 2015), and they cannot simultaneously be interpreted as proxies of ASM strength.

In general, lake-level fluctuations are controlled by the water balance of the lake. However, previous studies have demonstrated that the evolution of lake bathymetry on a long timescale may also result in lake-level fluctuations (Hilton, 1985; Lehman, 1975). Increased allochthonous input of detrital materials will enhance the sedimentation rate in the deepest parts of the lake due to gravity (i.e., the “sediment-focusing effect”) which will lead to decreases in water depth (Hilton, 1985). However, at Genggahai Lake, the AMS ^{14}C dating results show that the sedimentation rate of the central cores (GGH-A and GGH-C) was largely consistent with that of the littoral core (GGH-E) during the Lateglacial and Holocene (Fig. S1), indicating that changes in lake bathymetry since the Lateglacial were probably minor, exerting little effect on the lake level. This could be ascribed to the flat lake basin morphometry and the dense growth of submerged macrophytes, which largely restricted re-suspension and transport of sediments to the depocenter (cf. Dearing, 1997). Therefore, lake-level fluctuations mainly represent the balance between water inflows and losses. Currently, there are no large glaciers on the summits of the mountains surrounding Genggahai Lake. In addition, the Lateglacial glaciers on these mountains

were mainly distributed in areas above 4,500 m a.s.l. (Fig. 1B) (Li et al., 1991) and therefore their total extent was relatively small. Thus they are unlikely to have continuously contributed meltwater which could sustain the high lake level during the early Holocene (11.3–8.6 cal kyr BP), given the temperature increase of ~3 °C at the onset of the Holocene (Herzschuh et al., 2014; Li et. al., 2017a). Genggahai Lake is fed mainly by groundwater. Loose, porous fluvio-lacustrine sediments of the Gonghe Formation (Perrineau et al., 2011) and surficial fluvial-fan sediments largely constitute the catchment substrate of groundwater. In addition, the deep incision of the Yellow River in the eastern Gonghe Basin led to a steep hydraulic gradient of the basin (Craddock et al., 2010). Therefore, the catchment of groundwater was highly permeable, and hence precipitation can infiltrate rapidly into the ground and feed the lake. The evaporation losses during the infiltration process were most likely low. In addition, the catchment area of the groundwater feeding the lake is far larger than the lake's surface area (Fig. 1B). Therefore, evaporation may play a minor role in the water balance of the lake, and hence the lake-level fluctuations can be interpreted as indicating changes in regional precipitation, reflecting the strength of the ASM in the study area. The pattern of water-level fluctuations at Genggahai Lake largely coincides with that of other lakes in the marginal regions dominated by the ASM (e.g., Qinghai, Kuhai, Dali, Dabusu and Chagan Nur) (Fig. 4B–F). This consistent pattern suggests a weak ASM during 15.4–11.3 cal kyr BP, a significantly intensified ASM during 11.3–8.6 cal kyr BP, and a gradually weakening ASM thereafter. In addition, the results of a modeling study of water level changes at Qinghai Lake also reveal an early Holocene high-stand (Fig. 4C) (Li et al., 2020b).

The evolution of terrestrial vegetation is generally the integrated reactions to multiple environmental factors, including temperature, precipitation and the available water capacity of the soil (Prentice et al., 1992). The sparse terrestrial vegetation in the marginal regions dominated by the ASM during 15.4–11.3 cal kyr BP and 5.5–0 cal kyr BP mainly resulted from low monsoonal precipitation and low temperatures (Lu et al., 2011). In addition, the relatively low total terrestrial pollen concentration (Fig. 4I) during the early Holocene (11.3–8.6 kyr cal BP) suggests that the terrestrial vegetation did not respond to the significantly ameliorated environmental conditions, although the monsoonal precipitation increased sharply. Significantly, changes in terrestrial vegetation are modulated mainly by effective moisture rather than by precipitation (Prentice et al., 1992). Furthermore, changes in effective moisture do not always respond linearly to variations in precipitation, but rather they depend on the balance between precipitation and evaporation. Therefore, the relatively low terrestrial vegetation cover in the study area during the early Holocene mostly likely reflects a low level of effective moisture. Notably, the low effective moisture during this interval is also documented by the widespread

sand dune mobility in both the NETP and NE China (Fig. 4K, 4L) (Li et al., 2014; Qiang et al., 2013a). Given that the enhanced monsoonal precipitation during the early Holocene may have infiltrated rapidly into the ground due to the porous nature of the soils and the steep hydraulic gradient of the catchment, the water retained in the soils probably could not compensate for the intense evaporation loss as a consequence of the high temperatures (Li et. al., 2017a) and high summer insolation. This may have led to a low level of effective moisture and further restricted the development of both the terrestrial vegetation and paleosols (Mason et al., 2009; Qiang et al., 2013a, 2016). In addition, the strong ASM during this period would have resulted in the strong release of latent heat by water (Herzschuh et al., 2014), which may have further increased temperatures and evaporation. By contrast, decreased temperatures (Li et. al., 2017a), due to the reduction in both summer insolation and release of latent heat by water vapor during the period from 8.6 to 6.9 cal kyr BP, likely resulted in the weakened evaporation of soil water and hence led to the widespread development of vegetation (Fig. 3) and palaeosols (Li et al., 2014; Qiang et al., 2013a) in the marginal regions dominated by the ASM. In addition, given that the terrestrial vegetation has a lagged response to precipitation changes, the different response rates of the lake water and terrestrial vegetation to climate change may also have contributed to the occurrence of different hydroclimatic conditions between Genggahai Lake and its catchment (Zhao et al., 2017).

The diverse proxies derived from sediments of Genggahai Lake clearly reveal the synchronous occurrence of high lake levels and relatively low terrestrial vegetation cover, which are correlative with evidence for widespread sand dune mobility in the marginal regions dominated by the ASM during the early Holocene. These features do not reflect different climatic patterns, but rather they reflect different aspects of monsoonal climate change. The consistent high-stand of the lakes from these monsoon margin areas suggests increased monsoonal precipitation during the early Holocene, providing compelling evidences for the spatial consistency of ASM evolution documented by oxygen isotopic records from Chinese cave deposits (Cheng et al., 2019; Dykoski et al., 2005; Hu et al., 2008; Wang et al., 2005). The strong ASM and the increased monsoonal precipitation in the marginal regions dominated by the ASM during the early Holocene are ascribed to the enhanced thermal contrast between land and sea in spring and summer due to the increased orbitally-induced summer insolation (Fig. 4G, 4H). The relatively low terrestrial vegetation cover during the early Holocene, as well as the widespread dune sands in eolian sections in both the NETP and NE China, most likely reflect low effective moisture conditions due to high evaporation, and hence they cannot be interpreted as evidence of a weak monsoon.

4 Conclusions

The water-level fluctuations of Genggahai Lake and the vegetation conditions in its catchment were reconstructed from the aquatic biota and pollen preserved in the lake sediments. The results suggest a higher lake level and a stronger ASM during 11.3–5.5 cal kyr BP, compared to the intervals of 15.4–11.3 cal kyr BP and 5.5–0 cal kyr BP. However, the total terrestrial pollen concentration indicates relatively lower terrestrial vegetation cover during the early Holocene (11.3–8.6 cal kyr BP), compared with the period from 8.6 to 6.9 kyr cal BP. In contrast to the lake-level fluctuations, the vegetation cover in the catchment cannot be used as a proxy for variations in monsoonal precipitation and thus ASM strength. Rather, the relatively low vegetation cover mainly reflects a low level of effective moisture conditions, as a result of intense evaporation due to high temperatures during the early Holocene.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure and table captions

Fig. 1. Location and modern environmental context of Genggahai Lake. (A) Overview map showing locations of the paleoclimatic sites referenced in the text, and the dominant circulation systems of the westerlies and the Asian monsoon. Genggahai Lake is indicated by a star. Lakes Qinghai (Shen et al., 2005), Kuhai (Mischke et al., 2010), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Chagan Nur (Li et al., 2020a), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010), Dabusu Lake (Li and Lv, 2001) and Dongge Cave (Dykoski et al., 2005) are indicated by circles. The modern Asian summer monsoon limit is shown by a green dashed line (after Gao et al., 1962). (B) Physical environment of the Gonghe Basin. Mountain areas above 4,500 m a.s.l. and the potential catchment area of groundwater-fed Genggahai Lake are delineated by the white dashed line and the blue dashed line (after Qiang et al., 2017), respectively. (C) Vegetation (after Qiang et al., 2013b.) and coring sites.

Fig. 2. Records of plant macrofossils (A–F), Cladocera (G, H), and diatoms (I, J, K) from the sediments of Genggahai Lake and the reconstructed lake level (L). (G, I, J) Relative abundance of Cladocera, planktonic diatoms and non-planktonic diatoms, respectively. (H, K) Total counted individuals of Cladocera and diatoms, respectively. In (A, C, E) green and red bars denote *Potamogeton pectinatus* (or *Myriophyllum spicatum*) and *Chara* encrustations, respectively. Macrofossil stem encrustations are identified in the stratigraphy. *Chara* gyrogonites are presented as individuals/dm^2 per year.

Fig. 3. Comparison of the synthesized tree pollen index (J, this study) and pollen records from the marginal regions dominated by the ASM. (A, B) Total terrestrial pollen concentration from lakes Genggahai (this study) and Qinghai (Shen et al., 2005), respectively. (C−I) Tree pollen percentages from lakes Genggahai (this study), Qinghai (Shen et al., 2005), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010), respectively. The gray bar indicates the optimal vegetation conditions during 8.6–6.9 cal kyr BP.

Fig. 4. Comparison of the lake-level record (A) and total terrestrial pollen concentration (I) from Genggahai Lake and other paleoclimatic records. (B) Asian summer monsoon (ASM) index based on the sedimentary carbonate and TOC content of the sediments of Qinghai Lake (An et al., 2012). (C) Simulated water level of Qinghai Lake (Li et al., 2020b). (d) Mz (φ) grain-size record from Dabusu Lake (Li and Lv, 2001). (E, F) Water level of Chagan Nur (Li et al., 2020a) and Dali Lake (Goldsmith et al., 2017), respectively. (G) Summer insolation at 35°N (Berger and Loutre, 1991). (H) $\delta^{18}O_c$ record from Dongge Cave (Dykoski et al., 2005). (J) Synthesized tree pollen index (this study). (K) Probability density plot of the OSL ages of eolian sand samples from the NETP (Qiang et al., 2013a). (L) Synthesized sand percentages in eolian deposits in northeast China (Li et al., 2014).

Title: Lateglacial and Holocene climate change in the NE Tibetan Plateau: Reconciling divergent proxies of Asian summer monsoon variability

DETAILED RESPONSES TO THE COMMENTS FROM REVIEWERS

Response to Reviewer #1:

The authors try to reconstruct the ASM since 15.4 ka based on some proxies. The attempt is encouraging. However, this version has some fundamental problems. Terrestrial proxy, pollen, is important in this manuscript. The authors indicate that sparse vegetation cover occurred during the early Holocene (11.3-8.4 cal kyr BP). Obviously, it is not correct. Fig. 3 shows that total terrestrial pollen concentrations and tree pollen percentages are highest on average in the whole sequence during 11-5.5 cal kyr BP. Thus, this period should occur relatively dense vegetation. The authors should reconsider how to reorganize the manuscript.

Thank you for your comments. We agree that the total terrestrial pollen concentrations and the tree pollen percentages are overall higher during 11.3-5.5 cal kyr BP, compared with the periods from 15.4 to 11.3 and from 5.5 to 0 cal kyr BP. However, the records further suggest that optimal vegetation conditions occurred during 8.6–6.9 cal kyr BP and that the terrestrial vegetation cover was relatively lower during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP (see the figure below). This is clearly inconsistent with the aquatic biota inferred lake level record which shows the highest lake level during the early Holocene. This finding clearly reflects the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms. We changed 'sparse terrestrial vegetation during the early Holocene' to 'relatively lower vegetation cover during the early Holocene, compared with the period from 8.6 to 6.9 kyr cal BP' . In addition, we made small adjustments to the zonation of biota stratigraphy. See Fig. 2, 3 and 4, Lines 19-21, 25, 152, 157, 170-175, 220-221, 228-229, 235, 248-249, 256, 267, 275-280 (Line and figure number refers to the revised version in the responses).

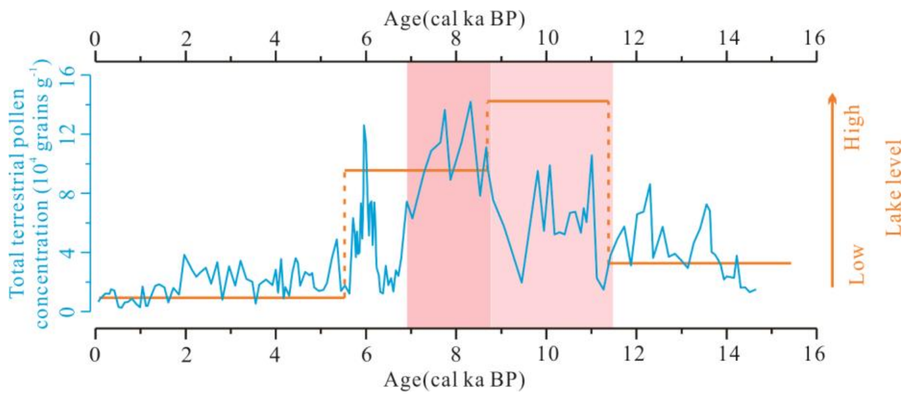

Fig. comparison of the lake level record and the total terrestrial pollen concentrations of Genggahai Lake

Response to Reviewer #2:

Li et al., presented a lake sediment record from the Asian monsoon-dominated area covering the late glacial and Holocene period focusing on the lake level fluctuations and terrestrial vegetation evolution to deeply understand the influences of the Asian summer monsoon to the lake and its catchment, especially during the early Holocene because they found distinct inconsistence derived from different proxies. I must declare that this is a manuscript which I have reviewed twice. In its first version, I found several major problems and the authors has revised a lot based on the comments from the reviewers and gave quite detailed responses and interpretations point by point which greatly improved the manuscript. I actually was satisfied with its revision and recommended publication.

I compared in details the current version to the previous one, there is only very minor changes therefore I have no any other major comments for this paper.

I think the interpretation of effective moisture which eventually influenced the vegetation development in the catchment were more convincing, it is a good idea to distinguish the different response to the precipitation/evaporation between lake and the catchment taking the infiltration process into account. Moreover, the discussion about the relationship between lake level changes and effective moisture within the catchment is much more detailed and this can give a more convincing mechanism behind the results included in the paper. In general, I believe the findings will be helpful to deeply understand the evolution of ASM during the early Holocene and its impact to the environment.

Thank you for your efforts to review this work. Your comments have greatly improved the manuscript. In the new version, We made small adjustments to the zonation of biota stratigraphy according to reviewer #1's comments, highlighting that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. See Fig. 2, 3 and 4.

Lateglacial and Holocene climate change in the NE Tibetan Plateau: Reconciling divergent proxies of Asian summer monsoon variability

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Abstract

The nature of Holocene Asian summer monsoon (ASM) evolution documented by diverse natural archives remains controversial, with a contentious issue being whether or not a strong Asian summer monsoon prevailed during the early Holocene. Here we present sequences of multiple proxies measured in sediment cores from Genggahai Lake in the NE Tibetan Plateau (NETP). The results suggest that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. This finding clearly reflects the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms. The early Holocene high stand of the lake, as demonstrated by the stratigraphic variability of the remains of aquatic biota, may have responded to the strengthened ASM and increased monsoonal precipitation; the relatively low vegetation cover in the marginal region of the Asian monsoon during the early Holocene, and the coeval widespread active sand dune mobility in both the NE Tibetan Plateau and NE China, most likely resulted from a low level of effective moisture due to high evaporation, and hence they cannot be interpreted as evidence of a weak ASM. Our results potentially reconcile the current divergent interpretations of various proxy climate records from the region. Our findings suggest that the ASM evolution was characterized by a consistent pattern across the monsoonal regions, as indicated by the oxygen isotope record of Chinese speleothems.

Key words: Holocene; monsoon; China; Micropaleontology; lake level; vegetation.

1 Introduction

The Asian monsoon system affects more than half of the world's population and the associated ecosystems (Webster et al., 1998). Understanding the variability of the Asian monsoon has significant implications for the social and ecological systems in the region (Hansen and Lebedeff, 1987; Mishra et al., 2019). Precipitation in the marginal regions dominated by the Asian summer monsoon (ASM) is highly dependent on the strength of the ASM: a stronger ASM circulation can transport more water vapor, leading to higher precipitation, and vice versa (Zhou et al., 2009). Therefore, precipitation in these marginal regions can directly reflect the strength of the ASM (Chen et al., 2015). Over the past two decades, numerous studies of the Holocene evolution of the ASM have been conducted based on diverse natural archives from the region (e.g., Chen et al., 2015; Dykoski et al., 2005; Goldsmith et al., 2017; Hu et al., 2008; Li et al., 2014; Wang et al., 2005; Wei et al., 2020). However, the nature of ASM evolution during the Holocene still remains controversial, with a contentious issue being whether or not a strong Asian summer monsoon prevailed during the early Holocene. For example, the early Holocene high-stand of lakes in the marginal regions dominated by the ASM (Fig. 1A), including lakes Dali (Goldsmith et al., 2017), Dabusu (Li and Lv, 2001) and Kuhai (Mischke et al., 2010), reflects an intensified ASM which is consistent with monsoonal records from Chinese speleothems (Dykoski et al., 2005; Hu et al., 2008; Wang et al., 2005). However, records of pollen assemblages and/or pollen-based precipitation from the lakes in the region (Fig. 1A), including lakes Gonghai (Chen et al., 2015), Dalianhai (Cheng et al., 2013), Daihai (Xiao et al., 2004), Dali (Wen et al., 2017) and Hulun (Wen et al., 2010), together with evidence for widespread sand dune mobility in NE China (Li et al., 2014), indicate the occurrence of dry terrestrial conditions at this time, possibly related to a weak ASM. Furthermore, even diverse proxies generated from the same study site may exhibit divergent patterns of Holocene climate change and ASM evolution. For example, at Qinghai Lake, the geochemical proxies (An et al., 2012; Jin et al., 2015; Lister et al., 1991) generally suggest a high lake level and a strong ASM during the early Holocene. In contrast, the shoreline deposits (Liu et al., 2015) and the pollen assemblages (Shen et al., 2005) suggest that the lake level probably was low at this time, induced by high evaporation or a weak ASM. These seemingly contradictory interpretations, especially those from the same site (e.g., Qinghai Lake), cannot be explained by the spatial and temporal differentiation of ASM evolution, or by chronological uncertainties. Therefore, a comprehensive analysis of the driving mechanisms of these proxies and their linkage to the ASM are essential for reconciling the controversy.

Genggahai Lake is a small, shallow lake in the NE Tibetan Plateau (NETP) (Fig. 1A), located in the marginal region dominated by the ASM. The sediments are rich in the remains of aquatic biota and terrestrial pollen, which provide the opportunity to conduct multi-proxy investigations of ASM evolution. Qiang et al. (2013b) have discussed the lake-level fluctuations over the past 16 kyr based mainly on plant macrofossil assemblages in the sediments from a single core (GGH-A) recovered from the lake. However, the early Holocene high-stand of the lake was indirectly inferred by geochemical variables (total organic carbon, total nitrogen and carbon isotopic composition of bulk sediment organic matter), due to the absence of plant macrofossils (Qiang et al., 2013b). In addition, the evolution of lake bathymetry may also lead to lake-level fluctuations on a long timescale (Hilton, 1985; Lehman, 1975), which was not differentiated from the influence of climatic factors in the previous study (Qiang et al., 2013b). Therefore, comprehensive analyses of diverse bioindicators (e.g., plant macrofossils, Cladocera, diatoms) from multiple cores are essential not only for the reliable reconstruction of lake-level fluctuations, but also for assessing the influence of the evolution of lake bathymetry on the lake-level fluctuations, and for understanding regional hydroclimatic changes (Dearing, 1997). Moreover, the evolution of the regional terrestrial vegetation and its potential linkages to the ASM remain unclear.

Here we present sequences of aquatic (plant macrofossils, Cladocera, diatoms) and terrestrial (terrestrial pollen) proxies derived from multiple sediment cores from Genggahai Lake. Combined with hydrological and ecological investigations of the modern lake, and with reference to independent climatic records from the marginal regions dominated by the ASM, our aims were to reconstruct the regional ASM variability during the Lateglacial and the Holocene, and to reconcile the current divergent results of proxy indicators of ASM evolution.

2 Materials and Methods

Genggahai Lake (36°11′N, 100°06′E) is located in the central Gonghe Basin (Fig. 1B) at an altitude of 2,860 m a.s.l. The lake is small (surface area, ~2 km^2) and shallow (maximum water depth, ~1.8 m) and has an elevated salinity (~1.2 g L^{-1}) and pH (~9.1). *Potamogeton pectinatus*, *Myriophyllum spicatum*, and *Chara* spp. dominate the submerged macrophyte communities in the current lake. The lake is mainly fed by groundwater. Sever small spring-water streams flow into the lake. Three sediment cores were recovered from Genggahai Lake in January 2008 and January 2013 using a modified Livingstone piston corer. Cores GGH-A (length 782 cm) and GGH-C (length 774 cm) were recovered from the center of the lake in a water depth of 170 cm (Fig. 1C), and core GGH-E (length 765 cm) was recovered from the northwest littoral area in a water depth of 110 cm (Fig. 1C). Due to the lack of terrestrial plant remains, samples of

the leaves of aquatic macrophytes were picked from the sediments for accelerator mass spectrometry (AMS) ^{14}C dating, conducted by Beta Analytic Inc. (Miami, USA) (Table S1). The reservoir age of the lake was estimated at 1,010 ^{14}C years on average, based on the AMS ^{14}C dating results of the dissolved inorganic carbon of the lake water, macrophyte remains in the lake's surface sediments and living *P. pectinatus* (Li et al., 2017b). A total of 26 ^{14}C ages from cores GGH-A (cited from Qiang et al. 2013b), GGH-C, and GGH-E (Table S1), which are in stratigraphic order, were calibrated to calendar years (Calib 6.0.1, Reimer et al., 2009) after subtracting an average reservoir age (1,010 yr). The age-depth models of the three cores were generated by the Bacon Bayesian age-modeling software (Blaauw and Christen, 2011), using the calibrated radiocarbon ages. The age versus depth profiles of the three cores agree well with each other, which supports their reliability (Fig. S1).

Plant macrofossils, including *Chara* gyrogonites (Fig. 2B, 2D, 2F) and encrustations of *Chara* spp. and *P. pectinatus* (or *M. spicatum*) (Fig. 2A, 2C, 2E), were picked from cores GGH-A (cited from Qiang et al. 2013b), GGH-C, and GGH-E. Cladocera (Fig. 2G) and diatom (Fig. 2I, 2G) analyses were conducted on core GGH-C using standard methods (Korhola and Rautio, 2001; Weckström et al., 1997). In addition, fossil pollen (Fig. 3A, 3C) was extracted from core GGH-A following the methods of Fægri and Iversen (1989). In order to comprehensively depict the terrestrial vegetation conditions in the marginal regions dominated by the ASM, we compiled six lacustrine tree pollen records from the region, including from lakes Qinghai (Shen et al., 2005), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010). Since the changes in the tree pollen content of these records show a similar trend, a synthesized tree pollen index covering the past 12 kyr (obtained by taking the average of the normalized tree pollen contents from the six lakes) was used to portray changes in tree cover in the marginal regions dominated by the ASM (Fig. 3). Further details about the method are given in the supplements.

3 Results and discussion

3.1. Patterns of hydroclimatic evolution indicated by lake level and pollen sequences

In general, submerged macrophytes, Cladocera, and diatoms in freshwater lakes are sensitive to changes in water level, and thus their fossil remains in lake sediments can be used to reconstruct past water-level fluctuations (Birks, 1993; Heggen et al., 2012). The aquatic plant macrofossils in the sediments of Genggahai Lake mainly originate from *Chara* spp., *P. pectinatus* and *M. spicatum*. These species also dominate the lake today and they are common in shallow lakes worldwide (Wilson et al., 1941). The spatial distribution of submerged macrophytes in the modern lake is mainly modulated by the water depth, and the shallow water

zone of the lake is occupied by *Chara* spp. (Fig. S2) (Qiang et al., 2013b). Therefore, the occurrence of the fossil remains of *Chara* spp. and *P. pectinatus* (or *M. spicatum*) in the lake sediments, especially the occurrence of abundant *Chara* gyrogonites, most likely reflects a shallow water environment. As for fossil Cladocera, only two littoral species (*Chydorus sphaericus* and *Coronatella rectangula*) which prefer macrophyte habitats were identified in the sediments of Lake Genggahai (Walseng, B., 2016a, 2016b). Diatoms in the sediments are relatively diverse, consisting of both planktonic (e.g., *Lindavia comta* and *Cyclotella distinguenda*) and non-planktonic species (e.g., *Gomphonema angustum* and *Achnanthes minutissima*). Based on changes in submerged macrophytes, Cladocera and diatoms in the lake sediments (Fig. 2), the history of lake-level fluctuations was divided into the following four stages:

15.4–11.3 cal kyr BP The lake sediments contain abundant submerged-macrophyte encrustations, *Chara* gyrogonites and littoral cladoceran fossils, reflecting a shallow lake. In addition, the diatom assemblages are dominated by both planktonic (e.g., *L. comta* and *C. distinguenda*) and non-planktonic species (e.g., *G. angustum*). Notably, *C. distinguenda* is a *tychoplanktonic species* which can adapt to shallow water conditions. Therefore, the lake level most likely was low during this period.

11.3–8.6 cal kyr BP Submerged macrophytes and Cladocera largely disappear from the sediments. In addition, the diatom assemblages are dominated by an euplanktonic species (i.e., *L. comta*). Thus we conclude that the lake level was high during this period, and it may have exceeded the depth limit for submerged macrophytes, resulting in the absence of Cladocera macrophyte habitats and increasing the abundance of planktonic diatoms.

8.6–5.5 cal kyr BP Submerged macrophyte encrustations occur episodically and *Chara* gyrogonites are relatively scarce. Cladocera fossils largely disappear from the sediments, probably in response to the scarcity of macrophyte habitats. The diatom assemblages are dominated by both planktonic (e.g., *L. comta* and *C. distinguenda*) and non-planktonic species. Thus we conclude that the lake level during this period was probably high overall, but lower than during the previous stage.

5.5 kyr cal BP to the present The lake sediments contain abundant submerged-macrophyte encrustations, *Chara* gyrogonites, littoral Cladocera fossils, and non-planktonic diatoms, reflecting a shallow lake.

The terrestrial pollen in lake sediments is mainly derived from the catchment and hence it reflects the local and regional terrestrial vegetation conditions (Pennington, 1979). Changes in total terrestrial pollen concentrations (Fig. 3A) and tree pollen contents (Fig. 3C) in the

sediments of Genggahai Lake are largely in agreement with those at nearby Qinghai Lake (Fig. 3B, 3D) and the synthesized tree pollen index (Fig. 3J), showing that optimal vegetation conditions occurred during 8.6–6.9 cal kyr BP. Overall, the aquatic and animal fossils (macrophytes, Cladocera, diatoms) and terrestrial pollen in the sediments of Genggahai Lake indicate that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. This implies the occurrence of different hydroclimatic conditions between the lake and its catchment (Fig. 4A, 4I). This apparent contradiction is also reflected in proxy sequences from other lakes in the marginal regions dominated by the ASM: e.g., at Lakes Qinghai (An et al., 2012; Shen et al., 2005), Dali (Goldsmith et al., 2017; Wen et al., 2017) and Chagan Nur (Li et al., 2020a).

3.2. Implications for the evolution of the Asian summer monsoon

The early Holocene high lake levels and low total pollen concentrations (or tree percentages) recorded by lake sediments from the margins of the regions dominated by the ASM are mutually contradictory in terms of their interpretation as evidence for ASM strength (e.g., An et al., 2012; Chen et al., 2015), or as evidence for the spatial differentiation of ASM evolution (Zhang et al., 2019). However, these seemingly contradictory patterns most likely reflect the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms (cf., Wilson et al., 2015), and they cannot simultaneously be interpreted as proxies of ASM strength.

In general, lake-level fluctuations are controlled by the water balance of the lake. However, previous studies have demonstrated that the evolution of lake bathymetry on a long timescale may also result in lake-level fluctuations (Hilton, 1985; Lehman, 1975). Increased allochthonous input of detrital materials will enhance the sedimentation rate in the deepest parts of the lake due to gravity (i.e., the “sediment-focusing effect”) which will lead to decreases in water depth (Hilton, 1985). However, at Genggahai Lake, the AMS ^{14}C dating results show that the sedimentation rate of the central cores (GGH-A and GGH-C) was largely consistent with that of the littoral core (GGH-E) during the Lateglacial and Holocene (Fig. S1), indicating that changes in lake bathymetry since the Lateglacial were probably minor, exerting little effect on the lake level. This could be ascribed to the flat lake basin morphometry and the dense growth of submerged macrophytes, which largely restricted re-suspension and transport of sediments to the depocenter (cf. Dearing, 1997). Therefore, lake-level fluctuations mainly represent the balance between water inflows and losses. Currently, there are no large glaciers on the summits of the mountains surrounding Genggahai Lake. In addition, the Lateglacial glaciers on these mountains

were mainly distributed in areas above 4,500 m a.s.l. (Fig. 1B) (Li et al., 1991) and therefore their total extent was relatively small. Thus they are unlikely to have continuously contributed meltwater which could sustain the high lake level during the early Holocene (11.3–8.6 cal kyr BP), given the temperature increase of ~3 °C at the onset of the Holocene (Herzschuh et al., 2014; Li et. al., 2017a). Genggahai Lake is fed mainly by groundwater. Loose, porous fluvio-lacustrine sediments of the Gonghe Formation (Perrineau et al., 2011) and surficial fluvial-fan sediments largely constitute the catchment substrate of groundwater. In addition, the deep incision of the Yellow River in the eastern Gonghe Basin led to a steep hydraulic gradient of the basin (Craddock et al., 2010). Therefore, the catchment of groundwater was highly permeable, and hence precipitation can infiltrate rapidly into the ground and feed the lake. The evaporation losses during the infiltration process were most likely low. In addition, the catchment area of the groundwater feeding the lake is far larger than the lake's surface area (Fig. 1B). Therefore, evaporation may play a minor role in the water balance of the lake, and hence the lake-level fluctuations can be interpreted as indicating changes in regional precipitation, reflecting the strength of the ASM in the study area. The pattern of water-level fluctuations at Genggahai Lake largely coincides with that of other lakes in the marginal regions dominated by the ASM (e.g., Qinghai, Kuhai, Dali, Dabusu and Chagan Nur) (Fig. 4B–F). This consistent pattern suggests a weak ASM during 15.4–11.3 cal kyr BP, a significantly intensified ASM during 11.3–8.6 cal kyr BP, and a gradually weakening ASM thereafter. In addition, the results of a modeling study of water level changes at Qinghai Lake also reveal an early Holocene high-stand (Fig. 4C) (Li et al., 2020b).

The evolution of terrestrial vegetation is generally the integrated reactions to multiple environmental factors, including temperature, precipitation and the available water capacity of the soil (Prentice et al., 1992). The sparse terrestrial vegetation in the marginal regions dominated by the ASM during 15.4–11.3 cal kyr BP and 5.5–0 cal kyr BP mainly resulted from low monsoonal precipitation and low temperatures (Lu et al., 2011). In addition, the relatively low total terrestrial pollen concentration (Fig. 4I) during the early Holocene (11.3–8.6 kyr cal BP) suggests that the terrestrial vegetation did not respond to the significantly ameliorated environmental conditions, although the monsoonal precipitation increased sharply. Significantly, changes in terrestrial vegetation are modulated mainly by effective moisture rather than by precipitation (Prentice et al., 1992). Furthermore, changes in effective moisture do not always respond linearly to variations in precipitation, but rather they depend on the balance between precipitation and evaporation. Therefore, the relatively low terrestrial vegetation cover in the study area during the early Holocene mostly likely reflects a low level of effective moisture. Notably, the low effective moisture during this interval is also documented by the widespread

sand dune mobility in both the NETP and NE China (Fig. 4K, 4L) (Li et al., 2014; Qiang et al., 2013a). Given that the enhanced monsoonal precipitation during the early Holocene may have infiltrated rapidly into the ground due to the porous nature of the soils and the steep hydraulic gradient of the catchment, the water retained in the soils probably could not compensate for the intense evaporation loss as a consequence of the high temperatures (Li et. al., 2017a) and high summer insolation. This may have led to a low level of effective moisture and further restricted the development of both the terrestrial vegetation and paleosols (Mason et al., 2009; Qiang et al., 2013a, 2016). In addition, the strong ASM during this period would have resulted in the strong release of latent heat by water (Herzschuh et al., 2014), which may have further increased temperatures and evaporation. By contrast, decreased temperatures (Li et. al., 2017a), due to the reduction in both summer insolation and release of latent heat by water vapor during the period from 8.6 to 6.9 cal kyr BP, likely resulted in the weakened evaporation of soil water and hence led to the widespread development of vegetation (Fig. 3) and palaeosols (Li et al., 2014; Qiang et al., 2013a) in the marginal regions dominated by the ASM. In addition, given that the terrestrial vegetation has a lagged response to precipitation changes, the different response rates of the lake water and terrestrial vegetation to climate change may also have contributed to the occurrence of different hydroclimatic conditions between Genggahai Lake and its catchment (Zhao et al., 2017).

The diverse proxies derived from sediments of Genggahai Lake clearly reveal the synchronous occurrence of high lake levels and relatively low terrestrial vegetation cover, which are correlative with evidence for widespread sand dune mobility in the marginal regions dominated by the ASM during the early Holocene. These features do not reflect different climatic patterns, but rather they reflect different aspects of monsoonal climate change. The consistent high-stand of the lakes from these monsoon margin areas suggests increased monsoonal precipitation during the early Holocene, providing compelling evidences for the spatial consistency of ASM evolution documented by oxygen isotopic records from Chinese cave deposits (Cheng et al., 2019; Dykoski et al., 2005; Hu et al., 2008; Wang et al., 2005). The strong ASM and the increased monsoonal precipitation in the marginal regions dominated by the ASM during the early Holocene are ascribed to the enhanced thermal contrast between land and sea in spring and summer due to the increased orbitally-induced summer insolation (Fig. 4G, 4H). The relatively low terrestrial vegetation cover during the early Holocene, as well as the widespread dune sands in eolian sections in both the NETP and NE China, most likely reflect low effective moisture conditions due to high evaporation, and hence they cannot be interpreted as evidence of a weak monsoon.

4 Conclusions

The water-level fluctuations of Genggahai Lake and the vegetation conditions in its catchment were reconstructed from the aquatic biota and pollen preserved in the lake sediments. The results suggest a higher lake level and a stronger ASM during 11.3–5.5 cal kyr BP, compared to the intervals of 15.4–11.3 cal kyr BP and 5.5–0 cal kyr BP. However, the total terrestrial pollen concentration indicates relatively lower terrestrial vegetation cover during the early Holocene (11.3–8.6 cal kyr BP), compared with the period from 8.6 to 6.9 kyr cal BP. In contrast to the lake-level fluctuations, the vegetation cover in the catchment cannot be used as a proxy for variations in monsoonal precipitation and thus ASM strength. Rather, the relatively low vegetation cover mainly reflects a low level of effective moisture conditions, as a result of intense evaporation due to high temperatures during the early Holocene.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure and table captions

Fig. 1. Location and modern environmental context of Genggahai Lake. (A) Overview map showing locations of the paleoclimatic sites referenced in the text, and the dominant circulation systems of the westerlies and the Asian monsoon. Genggahai Lake is indicated by a star. Lakes Qinghai (Shen et al., 2005), Kuhai (Mischke et al., 2010), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Chagan Nur (Li et al., 2020a), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010), Dabusu Lake (Li and Lv, 2001) and Dongge Cave (Dykoski et al., 2005) are indicated by circles. The modern Asian summer monsoon limit is shown by a green dashed line (after Gao et al., 1962). (B) Physical environment of the Gonghe Basin. Mountain areas above 4,500 m a.s.l. and the potential catchment area of groundwater-fed Genggahai Lake are delineated by the white dashed line and the blue dashed line (after Qiang et al., 2017), respectively. (C) Vegetation (after Qiang et al., 2013b.) and coring sites.

Fig. 2. Records of plant macrofossils (A–F), Cladocera (G, H), and diatoms (I, J, K) from the sediments of Genggahai Lake and the reconstructed lake level (L). (G, I, J) Relative abundance of Cladocera, planktonic diatoms and non-planktonic diatoms, respectively. (H, K) Total counted individuals of Cladocera and diatoms, respectively. In (A, C, E) green and red bars denote *Potamogeton pectinatus* (or *Myriophyllum spicatum*) and *Chara* encrustations, respectively. Macrofossil stem encrustations are identified in the stratigraphy. *Chara* gyrogonites are presented as individuals/dm^2 per year.

Fig. 3. Comparison of the synthesized tree pollen index (J, this study) and pollen records from the marginal regions dominated by the ASM. (A, B) Total terrestrial pollen concentration from lakes Genggahai (this study) and Qinghai (Shen et al., 2005), respectively. (C−I) Tree pollen percentages from lakes Genggahai (this study), Qinghai (Shen et al., 2005), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010), respectively. The gray bar indicates the optimal vegetation conditions during 8.6–6.9 cal kyr BP.

Fig. 4. Comparison of the lake-level record (A) and total terrestrial pollen concentration (I) from Genggahai Lake and other paleoclimatic records. (B) Asian summer monsoon (ASM) index based on the sedimentary carbonate and TOC content of the sediments of Qinghai Lake (An et al., 2012). (C) Simulated water level of Qinghai Lake (Li et al., 2020b). (d) Mz (φ) grain-size record from Dabusu Lake (Li and Lv, 2001). (E, F) Water level of Chagan Nur (Li et al., 2020a) and Dali Lake (Goldsmith et al., 2017), respectively. (G) Summer insolation at 35°N (Berger and Loutre, 1991). (H) $\delta^{18}O_c$ record from Dongge Cave (Dykoski et al., 2005). (J) Synthesized tree pollen index (this study). (K) Probability density plot of the OSL ages of eolian sand samples from the NETP (Qiang et al., 2013a). (L) Synthesized sand percentages in eolian deposits in northeast China (Li et al., 2014).

Lateglacial and Holocene climate change in the NE Tibetan Plateau: Reconciling divergent proxies of Asian summer monsoon variability

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Abstract

The nature of Holocene Asian summer monsoon (ASM) evolution documented by diverse natural archives remains controversial, with a contentious issue being whether or not a strong Asian summer monsoon prevailed during the early Holocene. Here we present sequences of multiple proxies measured in sediment cores from Genggahai Lake in the NE Tibetan Plateau (NETP). The results suggest that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. This finding clearly reflects the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms. The early Holocene high stand of the lake, as demonstrated by the stratigraphic variability of the remains of aquatic biota, may have responded to the strengthened ASM and increased monsoonal precipitation; the relatively low vegetation cover in the marginal region of the Asian monsoon during the early Holocene, and the coeval widespread active sand dune mobility in both the NE Tibetan Plateau and NE China, most likely resulted from a low level of effective moisture due to high evaporation, and hence they cannot be interpreted as evidence of a weak ASM. Our results potentially reconcile the current divergent interpretations of various proxy climate records from the region. Our findings suggest that the ASM evolution was characterized by a consistent pattern across the monsoonal regions, as indicated by the oxygen isotope record of Chinese speleothems.

Key words: Holocene; monsoon; China; Micropaleontology; lake level; vegetation.

1 Introduction

The Asian monsoon system affects more than half of the world's population and the associated ecosystems (Webster et al., 1998). Understanding the variability of the Asian monsoon has significant implications for the social and ecological systems in the region (Hansen and Lebedeff, 1987; Mishra et al., 2019). Precipitation in the marginal regions dominated by the Asian summer monsoon (ASM) is highly dependent on the strength of the ASM: a stronger ASM circulation can transport more water vapor, leading to higher precipitation, and vice versa (Zhou et al., 2009). Therefore, precipitation in these marginal regions can directly reflect the strength of the ASM (Chen et al., 2015). Over the past two decades, numerous studies of the Holocene evolution of the ASM have been conducted based on diverse natural archives from the region (e.g., Chen et al., 2015; Dykoski et al., 2005; Goldsmith et al., 2017; Hu et al., 2008; Li et al., 2014; Wang et al., 2005; Wei et al., 2020). However, the nature of ASM evolution during the Holocene still remains controversial, with a contentious issue being whether or not a strong Asian summer monsoon prevailed during the early Holocene. For example, the early Holocene high-stand of lakes in the marginal regions dominated by the ASM (Fig. 1A), including lakes Dali (Goldsmith et al., 2017), Dabusu (Li and Lv, 2001) and Kuhai (Mischke et al., 2010), reflects an intensified ASM which is consistent with monsoonal records from Chinese speleothems (Dykoski et al., 2005; Hu et al., 2008; Wang et al., 2005). However, records of pollen assemblages and/or pollen-based precipitation from the lakes in the region (Fig. 1A), including lakes Gonghai (Chen et al., 2015), Dalianhai (Cheng et al., 2013), Daihai (Xiao et al., 2004), Dali (Wen et al., 2017) and Hulun (Wen et al., 2010), together with evidence for widespread sand dune mobility in NE China (Li et al., 2014), indicate the occurrence of dry terrestrial conditions at this time, possibly related to a weak ASM. Furthermore, even diverse proxies generated from the same study site may exhibit divergent patterns of Holocene climate change and ASM evolution. For example, at Qinghai Lake, the geochemical proxies (An et al., 2012; Jin et al., 2015; Lister et al., 1991) generally suggest a high lake level and a strong ASM during the early Holocene. In contrast, the shoreline deposits (Liu et al., 2015) and the pollen assemblages (Shen et al., 2005) suggest that the lake level probably was low at this time, induced by high evaporation or a weak ASM. These seemingly contradictory interpretations, especially those from the same site (e.g., Qinghai Lake), cannot be explained by the spatial and temporal differentiation of ASM evolution, or by chronological uncertainties. Therefore, a comprehensive analysis of the driving mechanisms of these proxies and their linkage to the ASM are essential for reconciling the controversy.

Genggahai Lake is a small, shallow lake in the NE Tibetan Plateau (NETP) (Fig. 1A), located in the marginal region dominated by the ASM. The sediments are rich in the remains of aquatic biota and terrestrial pollen, which provide the opportunity to conduct multi-proxy investigations of ASM evolution. Qiang et al. (2013b) have discussed the lake-level fluctuations over the past 16 kyr based mainly on plant macrofossil assemblages in the sediments from a single core (GGH-A) recovered from the lake. However, the early Holocene high-stand of the lake was indirectly inferred by geochemical variables (total organic carbon, total nitrogen and carbon isotopic composition of bulk sediment organic matter), due to the absence of plant macrofossils (Qiang et al., 2013b). In addition, the evolution of lake bathymetry may also lead to lake-level fluctuations on a long timescale (Hilton, 1985; Lehman, 1975), which was not differentiated from the influence of climatic factors in the previous study (Qiang et al., 2013b). Therefore, comprehensive analyses of diverse bioindicators (e.g., plant macrofossils, Cladocera, diatoms) from multiple cores are essential not only for the reliable reconstruction of lake-level fluctuations, but also for assessing the influence of the evolution of lake bathymetry on the lake-level fluctuations, and for understanding regional hydroclimatic changes (Dearing, 1997). Moreover, the evolution of the regional terrestrial vegetation and its potential linkages to the ASM remain unclear.

Here we present sequences of aquatic (plant macrofossils, Cladocera, diatoms) and terrestrial (terrestrial pollen) proxies derived from multiple sediment cores from Genggahai Lake. Combined with hydrological and ecological investigations of the modern lake, and with reference to independent climatic records from the marginal regions dominated by the ASM, our aims were to reconstruct the regional ASM variability during the Lateglacial and the Holocene, and to reconcile the current divergent results of proxy indicators of ASM evolution.

2 Materials and Methods

Genggahai Lake (36°11′N, 100°06′E) is located in the central Gonghe Basin (Fig. 1B) at an altitude of 2,860 m a.s.l. The lake is small (surface area, ~2 km^2) and shallow (maximum water depth, ~1.8 m) and has an elevated salinity (~1.2 $g\ L^{-1}$) and pH (~9.1). *Potamogeton pectinatus*, *Myriophyllum spicatum*, and *Chara* spp. dominate the submerged macrophyte communities in the current lake. The lake is mainly fed by groundwater. Sever small spring-water streams flow into the lake. Three sediment cores were recovered from Genggahai Lake in January 2008 and January 2013 using a modified Livingstone piston corer. Cores GGH-A (length 782 cm) and GGH-C (length 774 cm) were recovered from the center of the lake in a water depth of 170 cm (Fig. 1C), and core GGH-E (length 765 cm) was recovered from the northwest littoral area in a water depth of 110 cm (Fig. 1C). Due to the lack of terrestrial plant remains, samples of

the leaves of aquatic macrophytes were picked from the sediments for accelerator mass spectrometry (AMS) ^{14}C dating, conducted by Beta Analytic Inc. (Miami, USA) (Table S1). The reservoir age of the lake was estimated at 1,010 ^{14}C years on average, based on the AMS ^{14}C dating results of the dissolved inorganic carbon of the lake water, macrophyte remains in the lake's surface sediments and living *P. pectinatus* (Li et al., 2017b). A total of 26 ^{14}C ages from cores GGH-A (cited from Qiang et al. 2013b), GGH-C, and GGH-E (Table S1), which are in stratigraphic order, were calibrated to calendar years (Calib 6.0.1, Reimer et al., 2009) after subtracting an average reservoir age (1,010 yr). The age-depth models of the three cores were generated by the Bacon Bayesian age-modeling software (Blaauw and Christen, 2011), using the calibrated radiocarbon ages. The age versus depth profiles of the three cores agree well with each other, which supports their reliability (Fig. S1).

Plant macrofossils, including *Chara* gyrogonites (Fig. 2B, 2D, 2F) and encrustations of *Chara* spp. and *P. pectinatus* (or *M. spicatum*) (Fig. 2A, 2C, 2E), were picked from cores GGH-A (cited from Qiang et al. 2013b), GGH-C, and GGH-E. Cladocera (Fig. 2G) and diatom (Fig. 2I, 2G) analyses were conducted on core GGH-C using standard methods (Korhola and Rautio, 2001; Weckström et al., 1997). In addition, fossil pollen (Fig. 3A, 3C) was extracted from core GGH-A following the methods of Fægri and Iversen (1989). In order to comprehensively depict the terrestrial vegetation conditions in the marginal regions dominated by the ASM, we compiled six lacustrine tree pollen records from the region, including from lakes Qinghai (Shen et al., 2005), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010). Since the changes in the tree pollen content of these records show a similar trend, a synthesized tree pollen index covering the past 12 kyr (obtained by taking the average of the normalized tree pollen contents from the six lakes) was used to portray changes in tree cover in the marginal regions dominated by the ASM (Fig. 3). Further details about the method are given in the supplements.

3 Results and discussion

3.1. Patterns of hydroclimatic evolution indicated by lake level and pollen sequences

In general, submerged macrophytes, Cladocera, and diatoms in freshwater lakes are sensitive to changes in water level, and thus their fossil remains in lake sediments can be used to reconstruct past water-level fluctuations (Birks, 1993; Heggen et al., 2012). The aquatic plant macrofossils in the sediments of Genggahai Lake mainly originate from *Chara* spp., *P. pectinatus* and *M. spicatum*. These species also dominate the lake today and they are common in shallow lakes worldwide (Wilson et al., 1941). The spatial distribution of submerged macrophytes in the modern lake is mainly modulated by the water depth, and the shallow water

zone of the lake is occupied by *Chara* spp. (Fig. S2) (Qiang et al., 2013b). Therefore, the occurrence of the fossil remains of *Chara* spp. and *P. pectinatus* (or *M. spicatum*) in the lake sediments, especially the occurrence of abundant *Chara* gyrogonites, most likely reflects a shallow water environment. As for fossil Cladocera, only two littoral species (*Chydorus sphaericus* and *Coronatella rectangula*) which prefer macrophyte habitats were identified in the sediments of Lake Genggahai (Walseng, B., 2016a, 2016b). Diatoms in the sediments are relatively diverse, consisting of both planktonic (e.g., *Lindavia comta* and *Cyclotella distinguenda*) and non-planktonic species (e.g., *Gomphonema angustum* and *Achnanthes minutissima*). Based on changes in submerged macrophytes, Cladocera and diatoms in the lake sediments (Fig. 2), the history of lake-level fluctuations was divided into the following four stages:

15.4–11.3 cal kyr BP The lake sediments contain abundant submerged-macrophyte encrustations, *Chara* gyrogonites and littoral cladoceran fossils, reflecting a shallow lake. In addition, the diatom assemblages are dominated by both planktonic (e.g., *L. comta* and *C. distinguenda*) and non-planktonic species (e.g., *G. angustum*). Notably, *C. distinguenda* is a *tychoplanktonic species* which can adapt to shallow water conditions. Therefore, the lake level most likely was low during this period.

11.3–8.6 cal kyr BP Submerged macrophytes and Cladocera largely disappear from the sediments. In addition, the diatom assemblages are dominated by an euplanktonic species (i.e., *L. comta*). Thus we conclude that the lake level was high during this period, and it may have exceeded the depth limit for submerged macrophytes, resulting in the absence of Cladocera macrophyte habitats and increasing the abundance of planktonic diatoms.

8.6–5.5 cal kyr BP Submerged macrophyte encrustations occur episodically and *Chara* gyrogonites are relatively scarce. Cladocera fossils largely disappear from the sediments, probably in response to the scarcity of macrophyte habitats. The diatom assemblages are dominated by both planktonic (e.g., *L. comta* and *C. distinguenda*) and non-planktonic species. Thus we conclude that the lake level during this period was probably high overall, but lower than during the previous stage.

5.5 kyr cal BP to the present The lake sediments contain abundant submerged-macrophyte encrustations, *Chara* gyrogonites, littoral Cladocera fossils, and non-planktonic diatoms, reflecting a shallow lake.

The terrestrial pollen in lake sediments is mainly derived from the catchment and hence it reflects the local and regional terrestrial vegetation conditions (Pennington, 1979). Changes in total terrestrial pollen concentrations (Fig. 3A) and tree pollen contents (Fig. 3C) in the

sediments of Genggahai Lake are largely in agreement with those at nearby Qinghai Lake (Fig. 3B, 3D) and the synthesized tree pollen index (Fig. 3J), showing that optimal vegetation conditions occurred during 8.6–6.9 cal kyr BP. Overall, the aquatic and animal fossils (macrophytes, Cladocera, diatoms) and terrestrial pollen in the sediments of Genggahai Lake indicate that a higher lake level and relatively lower terrestrial vegetation cover occurred synchronously during the early Holocene (11.3–8.6 kyr cal BP), compared with the period from 8.6 to 6.9 kyr cal BP. This implies the occurrence of different hydroclimatic conditions between the lake and its catchment (Fig. 4A, 4I). This apparent contradiction is also reflected in proxy sequences from other lakes in the marginal regions dominated by the ASM: e.g., at Lakes Qinghai (An et al., 2012; Shen et al., 2005), Dali (Goldsmith et al., 2017; Wen et al., 2017) and Chagan Nur (Li et al., 2020a).

3.2. Implications for the evolution of the Asian summer monsoon

The early Holocene high lake levels and low total pollen concentrations (or tree percentages) recorded by lake sediments from the margins of the regions dominated by the ASM are mutually contradictory in terms of their interpretation as evidence for ASM strength (e.g., An et al., 2012; Chen et al., 2015), or as evidence for the spatial differentiation of ASM evolution (Zhang et al., 2019). However, these seemingly contradictory patterns most likely reflect the existence of different hydroclimatic conditions between the lake and its catchment due to diverse driving mechanisms (cf., Wilson et al., 2015), and they cannot simultaneously be interpreted as proxies of ASM strength.

In general, lake-level fluctuations are controlled by the water balance of the lake. However, previous studies have demonstrated that the evolution of lake bathymetry on a long timescale may also result in lake-level fluctuations (Hilton, 1985; Lehman, 1975). Increased allochthonous input of detrital materials will enhance the sedimentation rate in the deepest parts of the lake due to gravity (i.e., the “sediment-focusing effect”) which will lead to decreases in water depth (Hilton, 1985). However, at Genggahai Lake, the AMS ^{14}C dating results show that the sedimentation rate of the central cores (GGH-A and GGH-C) was largely consistent with that of the littoral core (GGH-E) during the Lateglacial and Holocene (Fig. S1), indicating that changes in lake bathymetry since the Lateglacial were probably minor, exerting little effect on the lake level. This could be ascribed to the flat lake basin morphometry and the dense growth of submerged macrophytes, which largely restricted re-suspension and transport of sediments to the depocenter (cf. Dearing, 1997). Therefore, lake-level fluctuations mainly represent the balance between water inflows and losses. Currently, there are no large glaciers on the summits of the mountains surrounding Genggahai Lake. In addition, the Lateglacial glaciers on these mountains

were mainly distributed in areas above 4,500 m a.s.l. (Fig. 1B) (Li et al., 1991) and therefore their total extent was relatively small. Thus they are unlikely to have continuously contributed meltwater which could sustain the high lake level during the early Holocene (11.3–8.6 cal kyr BP), given the temperature increase of ~3 °C at the onset of the Holocene (Herzschuh et al., 2014; Li et. al., 2017a). Genggahai Lake is fed mainly by groundwater. Loose, porous fluvio-lacustrine sediments of the Gonghe Formation (Perrineau et al., 2011) and surficial fluvial-fan sediments largely constitute the catchment substrate of groundwater. In addition, the deep incision of the Yellow River in the eastern Gonghe Basin led to a steep hydraulic gradient of the basin (Craddock et al., 2010). Therefore, the catchment of groundwater was highly permeable, and hence precipitation can infiltrate rapidly into the ground and feed the lake. The evaporation losses during the infiltration process were most likely low. In addition, the catchment area of the groundwater feeding the lake is far larger than the lake's surface area (Fig. 1B). Therefore, evaporation may play a minor role in the water balance of the lake, and hence the lake-level fluctuations can be interpreted as indicating changes in regional precipitation, reflecting the strength of the ASM in the study area. The pattern of water-level fluctuations at Genggahai Lake largely coincides with that of other lakes in the marginal regions dominated by the ASM (e.g., Qinghai, Kuhai, Dali, Dabusu and Chagan Nur) (Fig. 4B–F). This consistent pattern suggests a weak ASM during 15.4–11.3 cal kyr BP, a significantly intensified ASM during 11.3–8.6 cal kyr BP, and a gradually weakening ASM thereafter. In addition, the results of a modeling study of water level changes at Qinghai Lake also reveal an early Holocene high-stand (Fig. 4C) (Li et al., 2020b).

The evolution of terrestrial vegetation is generally the integrated reactions to multiple environmental factors, including temperature, precipitation and the available water capacity of the soil (Prentice et al., 1992). The sparse terrestrial vegetation in the marginal regions dominated by the ASM during 15.4–11.3 cal kyr BP and 5.5–0 cal kyr BP mainly resulted from low monsoonal precipitation and low temperatures (Lu et al., 2011). In addition, the relatively low total terrestrial pollen concentration (Fig. 4I) during the early Holocene (11.3–8.6 kyr cal BP) suggests that the terrestrial vegetation did not respond to the significantly ameliorated environmental conditions, although the monsoonal precipitation increased sharply. Significantly, changes in terrestrial vegetation are modulated mainly by effective moisture rather than by precipitation (Prentice et al., 1992). Furthermore, changes in effective moisture do not always respond linearly to variations in precipitation, but rather they depend on the balance between precipitation and evaporation. Therefore, the relatively low terrestrial vegetation cover in the study area during the early Holocene mostly likely reflects a low level of effective moisture. Notably, the low effective moisture during this interval is also documented by the widespread

sand dune mobility in both the NETP and NE China (Fig. 4K, 4L) (Li et al., 2014; Qiang et al., 2013a). Given that the enhanced monsoonal precipitation during the early Holocene may have infiltrated rapidly into the ground due to the porous nature of the soils and the steep hydraulic gradient of the catchment, the water retained in the soils probably could not compensate for the intense evaporation loss as a consequence of the high temperatures (Li et. al., 2017a) and high summer insolation. This may have led to a low level of effective moisture and further restricted the development of both the terrestrial vegetation and paleosols (Mason et al., 2009; Qiang et al., 2013a, 2016). In addition, the strong ASM during this period would have resulted in the strong release of latent heat by water (Herzschuh et al., 2014), which may have further increased temperatures and evaporation. By contrast, decreased temperatures (Li et. al., 2017a), due to the reduction in both summer insolation and release of latent heat by water vapor during the period from 8.6 to 6.9 cal kyr BP, likely resulted in the weakened evaporation of soil water and hence led to the widespread development of vegetation (Fig. 3) and palaeosols (Li et al., 2014; Qiang et al., 2013a) in the marginal regions dominated by the ASM. In addition, given that the terrestrial vegetation has a lagged response to precipitation changes, the different response rates of the lake water and terrestrial vegetation to climate change may also have contributed to the occurrence of different hydroclimatic conditions between Genggahai Lake and its catchment (Zhao et al., 2017).

The diverse proxies derived from sediments of Genggahai Lake clearly reveal the synchronous occurrence of high lake levels and relatively low terrestrial vegetation cover, which are correlative with evidence for widespread sand dune mobility in the marginal regions dominated by the ASM during the early Holocene. These features do not reflect different climatic patterns, but rather they reflect different aspects of monsoonal climate change. The consistent high-stand of the lakes from these monsoon margin areas suggests increased monsoonal precipitation during the early Holocene, providing compelling evidences for the spatial consistency of ASM evolution documented by oxygen isotopic records from Chinese cave deposits (Cheng et al., 2019; Dykoski et al., 2005; Hu et al., 2008; Wang et al., 2005). The strong ASM and the increased monsoonal precipitation in the marginal regions dominated by the ASM during the early Holocene are ascribed to the enhanced thermal contrast between land and sea in spring and summer due to the increased orbitally-induced summer insolation (Fig. 4G, 4H). The relatively low terrestrial vegetation cover during the early Holocene, as well as the widespread dune sands in eolian sections in both the NETP and NE China, most likely reflect low effective moisture conditions due to high evaporation, and hence they cannot be interpreted as evidence of a weak monsoon.

4 Conclusions

The water-level fluctuations of Genggahai Lake and the vegetation conditions in its catchment were reconstructed from the aquatic biota and pollen preserved in the lake sediments. The results suggest a higher lake level and a stronger ASM during 11.3–5.5 cal kyr BP, compared to the intervals of 15.4–11.3 cal kyr BP and 5.5–0 cal kyr BP. However, the total terrestrial pollen concentration indicates relatively lower terrestrial vegetation cover during the early Holocene (11.3–8.6 cal kyr BP), compared with the period from 8.6 to 6.9 kyr cal BP. In contrast to the lake-level fluctuations, the vegetation cover in the catchment cannot be used as a proxy for variations in monsoonal precipitation and thus ASM strength. Rather, the relatively low vegetation cover mainly reflects a low level of effective moisture conditions, as a result of intense evaporation due to high temperatures during the early Holocene.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure and table captions

Fig. 1. Location and modern environmental context of Genggahai Lake. (A) Overview map showing locations of the paleoclimatic sites referenced in the text, and the dominant circulation systems of the westerlies and the Asian monsoon. Genggahai Lake is indicated by a star. Lakes Qinghai (Shen et al., 2005), Kuhai (Mischke et al., 2010), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Chagan Nur (Li et al., 2020a), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010), Dabusu Lake (Li and Lv, 2001) and Dongge Cave (Dykoski et al., 2005) are indicated by circles. The modern Asian summer monsoon limit is shown by a green dashed line (after Gao et al., 1962). (B) Physical environment of the Gonghe Basin. Mountain areas above 4,500 m a.s.l. and the potential catchment area of groundwater-fed Genggahai Lake are delineated by the white dashed line and the blue dashed line (after Qiang et al., 2017), respectively. (C) Vegetation (after Qiang et al., 2013b.) and coring sites.

Fig. 2. Records of plant macrofossils (A–F), Cladocera (G, H), and diatoms (I, J, K) from the sediments of Genggahai Lake and the reconstructed lake level (L). (G, I, J) Relative abundance of Cladocera, planktonic diatoms and non-planktonic diatoms, respectively. (H, K) Total counted individuals of Cladocera and diatoms, respectively. In (A, C, E) green and red bars denote *Potamogeton pectinatus* (or *Myriophyllum spicatum*) and *Chara* encrustations, respectively. Macrofossil stem encrustations are identified in the stratigraphy. *Chara* gyrogonites are presented as individuals/dm^2 per year.

Fig. 3. Comparison of the synthesized tree pollen index (J, this study) and pollen records from the marginal regions dominated by the ASM. (A, B) Total terrestrial pollen concentration from lakes Genggahai (this study) and Qinghai (Shen et al., 2005), respectively. (C−I) Tree pollen percentages from lakes Genggahai (this study), Qinghai (Shen et al., 2005), Dalianhai (Cheng et al., 2013), Gonghai (Chen et al., 2015), Dali (Wen et al., 2017), Daihai (Xiao et al., 2004) and Hulun (Wen et al., 2010), respectively. The gray bar indicates the optimal vegetation conditions during 8.6–6.9 cal kyr BP.

Fig. 4. Comparison of the lake-level record (A) and total terrestrial pollen concentration (I) from Genggahai Lake and other paleoclimatic records. (B) Asian summer monsoon (ASM) index based on the sedimentary carbonate and TOC content of the sediments of Qinghai Lake (An et al., 2012). (C) Simulated water level of Qinghai Lake (Li et al., 2020b). (d) Mz (φ) grain-size record from Dabusu Lake (Li and Lv, 2001). (E, F) Water level of Chagan Nur (Li et al., 2020a) and Dali Lake (Goldsmith et al., 2017), respectively. (G) Summer insolation at 35°N (Berger and Loutre, 1991). (H) $\delta^{18}O_c$ record from Dongge Cave (Dykoski et al., 2005). (J) Synthesized tree pollen index (this study). (K) Probability density plot of the OSL ages of eolian sand samples from the NETP (Qiang et al., 2013a). (L) Synthesized sand percentages in eolian deposits in northeast China (Li et al., 2014).

Fig. 1

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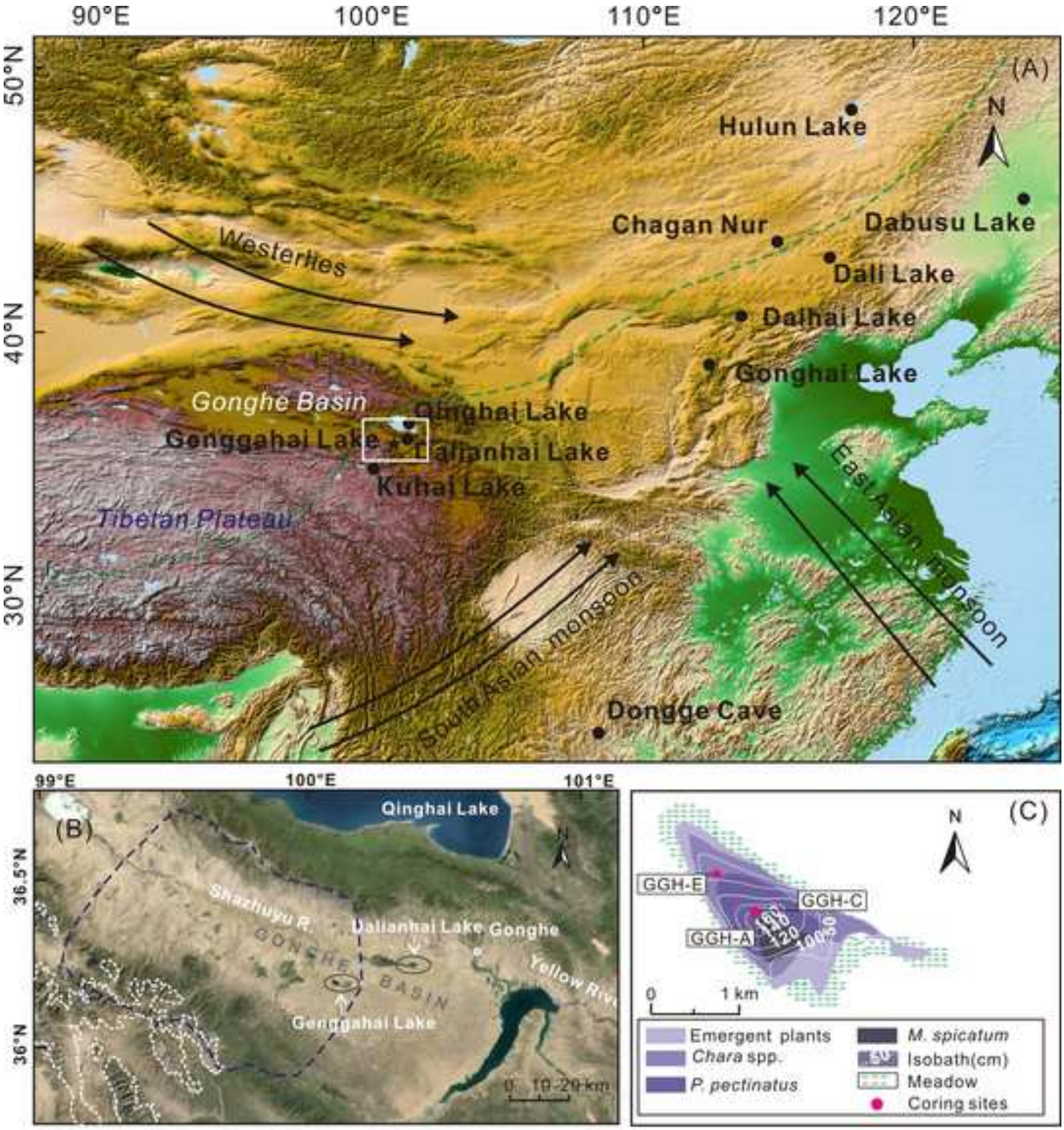

Fig. 2

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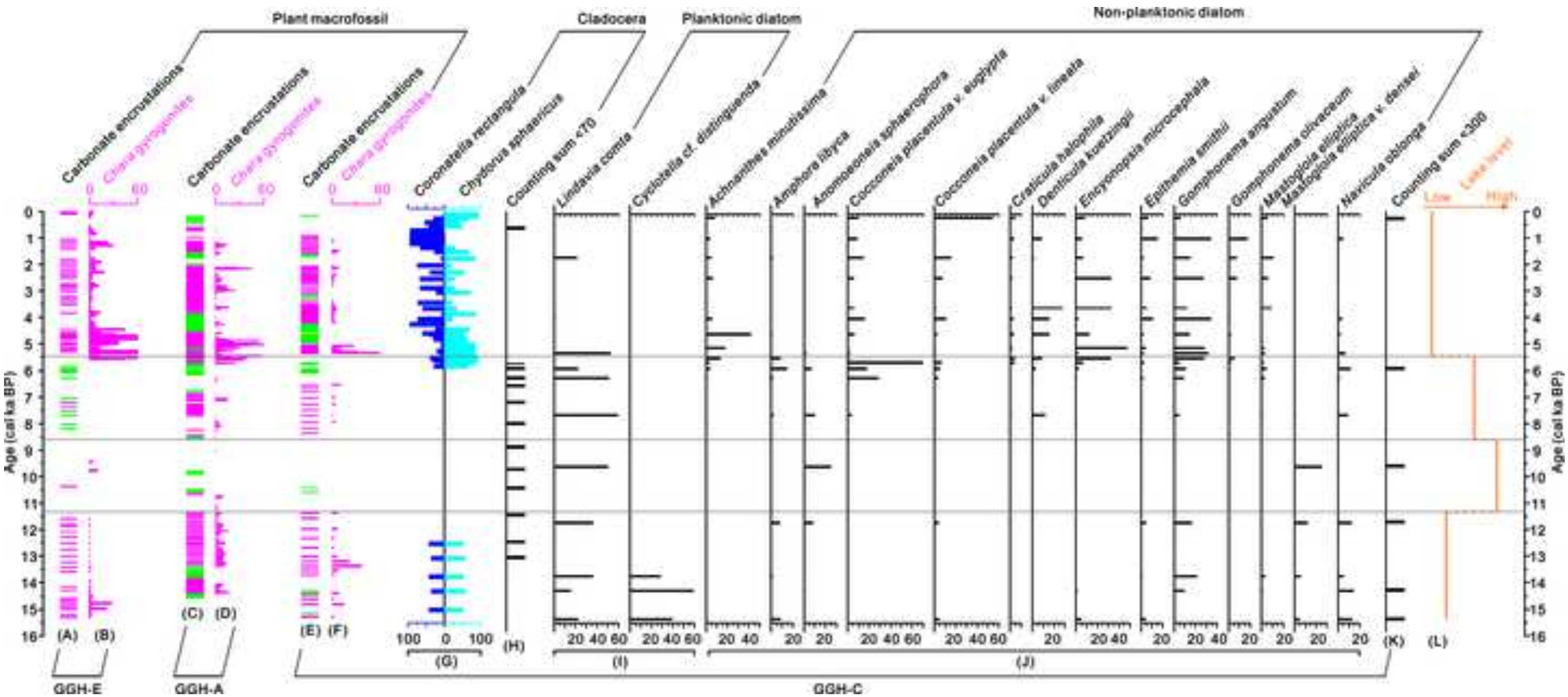
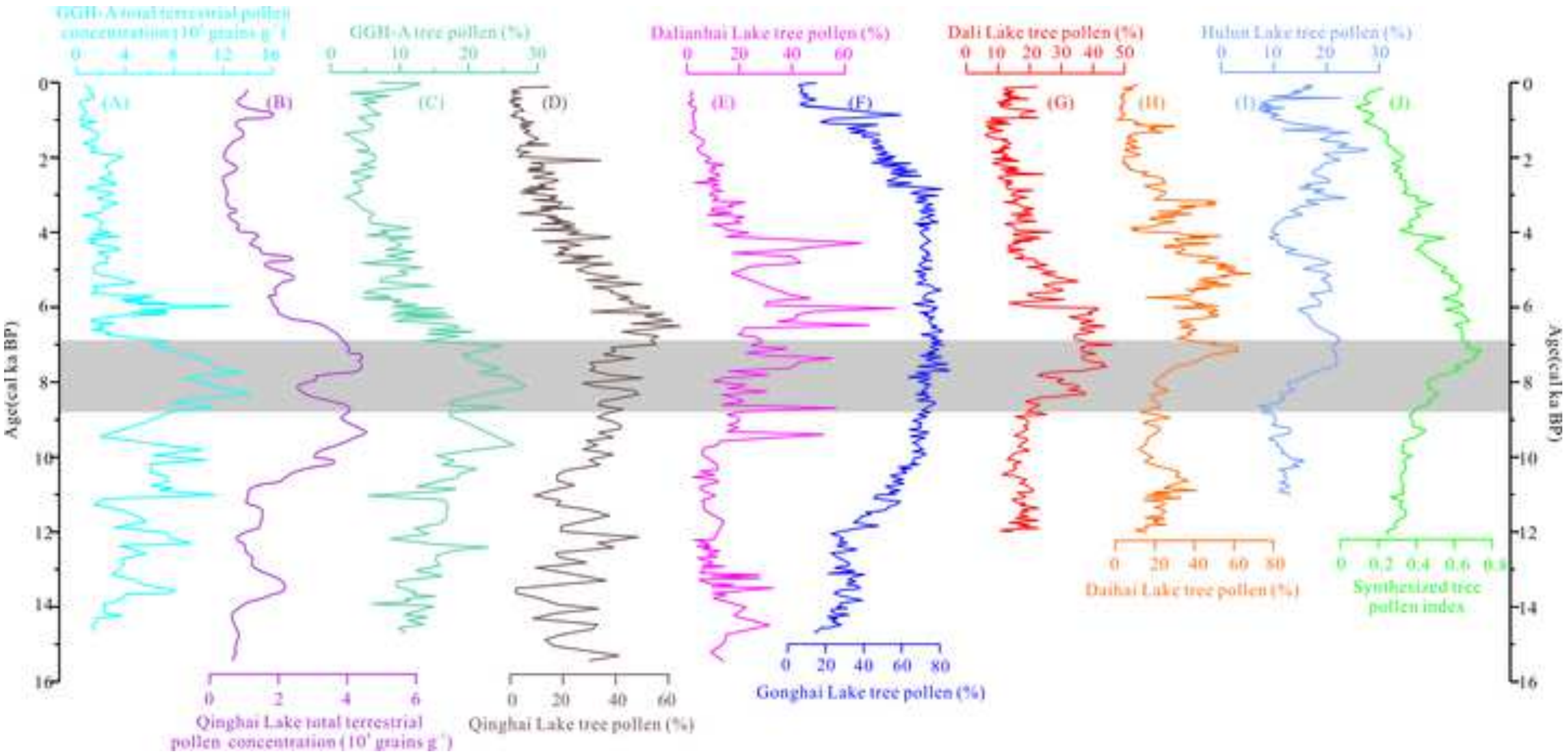
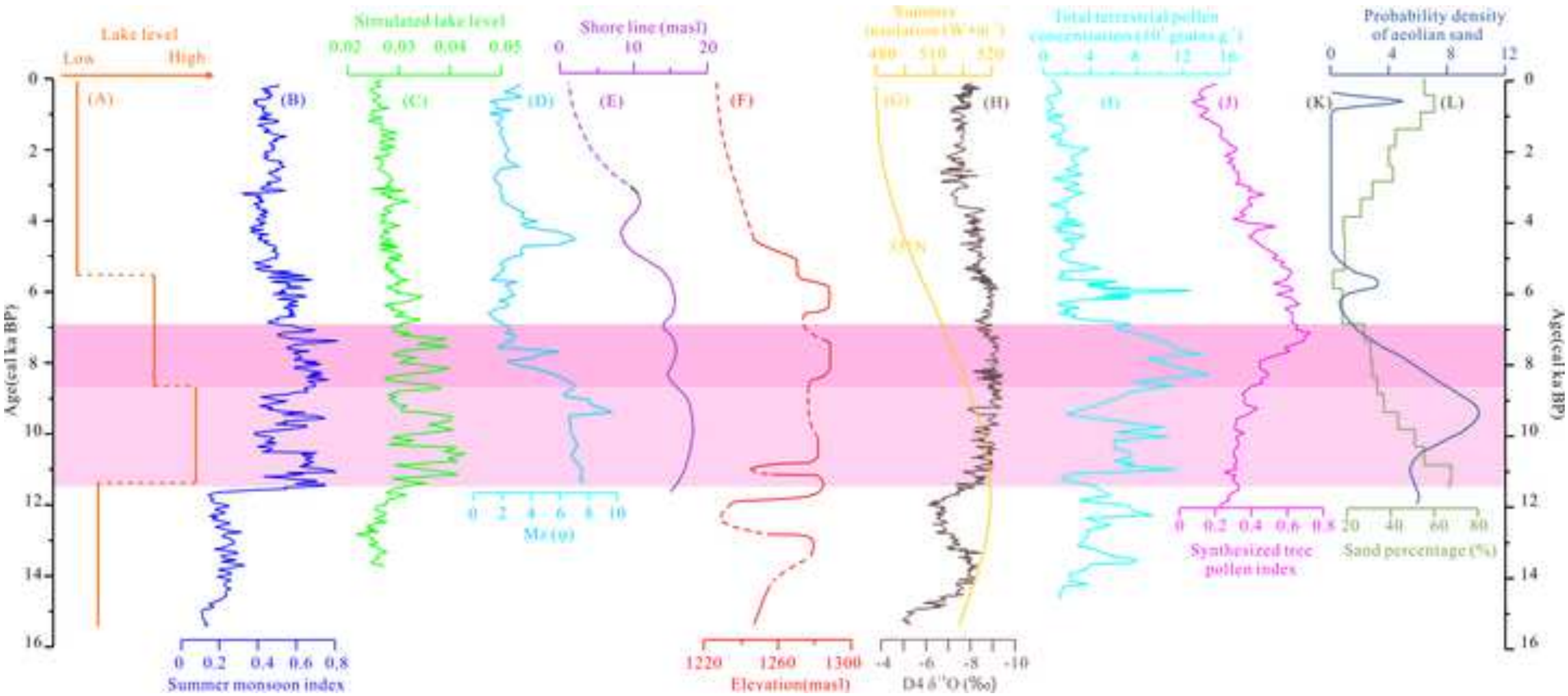


Fig. 3



Dalianhai Lake tree pollen (%)
Dali Lake tree pollen (%)
Hulun Lake tree pollen (%)
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(I)
(J)
Age(cal ka BP)
Age(cal ka BP)
Daihai Lake tree pollen (%)
Synthesized tree pollen index
Gonghai Lake tree pollen (%)
Qinghai Lake total terrestrial pollen concentration
Qinghai Lake tree pollen (%)

Fig. 4


Lake level
Low
High
(A)
(B)
Summer monsoon index
Simulated lake level
(C)
(D)
Mz (φ)
Shore line (masl)
(E)
(F)
Elevation(masl)
(G)
(H)
D4 δ18O (‰)
(I)
(J)
Synthesized tree pollen index
Probability density of aeolian sand
(K)
(L)
Sand percentage (%)
Age(cal ka BP)

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Declaration of interests

☑The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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