Grain size of Lake Qinghai sediments: Implications for riverine input and Holocene monsoon variability

Xingxing Liu^{a,b}, Jef Vandenberghe^c, Zhisheng An^a, Ying Li^a, Zhangdong Jin^a, Jibao Dong^a, Youbin Sun^{a,*}

^a State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China

^b College of Earth Science, University of Chinese Academy of Sciences, Beijing 100049, China

^c Institute of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands

*Corresponding author (sunyb@ieecas.cn)

Abstract: Grain-size compositions of lake sediments can provide direct information on changes in transporting mechanism and sedimentary environment. Various grain-size parameters have been employed to reconstruct hydrological conditions within the lake and dust influx from outside the lake. Here we present the grain-size results of a 5-m core retrieved from Lake Qinghai, northeastern Tibetan Plateau in order to address the links between Holocene depositional process and climatic change. Our results indicate that two parameters (skewness and grain-size ratio of $8\sim 50/2\sim 8\ \mu\text{m}$) are sensitive to hydrodynamic changes in Lake Qinghai, which are further linked to the strength of the Asian summer monsoon. Variations of these two parameters reveal that summer monsoon intensity weakened gradually from early to late Holocene, superimposed by persistent centennial variability with dominant periods at 0.35, 0.23 and 0.12 kyr. Comparison of grain-size variations with solar activities and North Atlantic cooling events reveals that solar forcing likely plays an important role in driving centennial monsoon variability.

Keywords: Lake Qinghai; Grain size; Holocene; Asian summer monsoon; Solar activities

1. Introduction

The northeastern Qinghai-Tibetan Plateau is highly sensitive to climatic changes due to its high altitude and transitional position between arid and semiarid zones (Zhao et al., 2010; Henderson et al., 2010; An et al., 2012). During the past decades, many lakes in this region have been investigated extensively to infer environmental and climatic changes, such as Hurleg Lake (Zhao et al., 2007), Chaka Salt Lake (Liu et al., 2008), Gahai Lake (Zhao et al., 2008), Koucha Lake (Herzschuh et al., 2009), Hala Lake (Wünnemann et al., 2012), and Dalianhai Lake (Chen et al., 2012; Cheng et al., 2013). Lake Qinghai, as the largest brackish lake in inland China, has attracted great attention from the paleoclimate community due to its sensitivity to changes in past monsoon and westerly circulations (Lister et al., 1991; Shen et al., 2005; Ji et al., 2005; Colman et al., 2007; Liu et al., 2007; An et al., 2012; Liu et al., 2014a, b). Multiple proxies including pollen (Shen et al., 2005; Colman et al., 2007), contents of inorganic and organic carbon (An et al., 2012), elemental and isotopic geochemistry (Ji et al., 2005; Liu et al., 2007; Liu et al., 2011; Thomas et al., 2014; Jin et al., 2015), and grain size (Zhang et al., 2003; An et al., 2012) have been generated from Lake Qinghai sediments to reconstruct the environmental and paleoclimatic changes in this region. These results indicated that the Holocene monsoon trend is similar to those revealed by speleothem records (Fleitmann et al. 2003; Dykoski et al. 2005; Wang et al. 2005; Cai et al., 2010), whereas centennial variability between different archives is difficult to directly match due to uncertainty in the chronologies and varied sensitivity of proxy indicators to monsoon intensity. It is necessary to generate sensitive proxies with robust chronology to decipher centennial monsoon variability and dynamics.

Clastic materials transported into lakes are mainly supplied by riverine and/or eolian inputs (e.g., Colman et al., 2007). Grain-size distribution of clastic sediments can provide direct information on changes in transporting dynamics and sedimentary environment (Friedman and Sanders, 1978, Peng et al., 2005; Prins and Weltje, 1999; Xiao et al., 2009; Vandenberghe, 2013). Usually, the grain-size distribution of lake sediments is characterized by a polymodal pattern, which may be affected by various factors such as the source of clastic materials, specific depositional processes and

environments, shape and size of the lake and hydraulic dynamics of lake waters (Inman, 1949; Folk and Ward, 1957; Sun et al., 2002; Qiang et al., 2014; Xiao et al., 1995, 2013). To retrieve grain-size proxies sensitive to different dynamics, mathematical methods were widely adopted to partition the grain-size components of polymodal sediments (Sun et al., 2002, 2004; Qin et al., 2005; Weltje and Prins, 2007; Xiao et al., 2009, 2015). Since coarse-grained particles might either reflect strong wind intensity associated with eolian transport (Tsoar and Pye, 1987; Pye, 1987) or relate to heavy precipitation-induced riverine input (Lerman, 1978; Chen et al., 2003), linking grain size parameters to climatic factors is highly dependent on the local characteristics of individual lakes (Friedman and Sanders, 1978; Lerman, 1978; Håkanson and Jansson, 1983; Talbot and Allen, 1996).

As to Lake Qinghai, Zhang et al. (2003) suggested that the content of the coarse fraction can be regarded as a proxy for precipitation, with high amounts of coarse material corresponding to increased surface runoff during wet climatic conditions over the last 800 years. In contrast, coarse grain-size population was employed to reflect the eolian inputs over the past 32 ka (An et al., 2012). Since the lithology of Lake Qinghai sediments changed significantly from eolian-dominated facies during the last glacial maximum to lacustrine-dominated facies during the Holocene, implications of grain-size parameters should be addressed accordingly in association with different sedimentary environment. In this study, we tried to combine the basic grain size parameters (e.g., mean and skewness) with grain size ratio (8~50/2~8 μm) and Weibull fitting results to address the dominant transport dynamics of Holocene sediments in Lake Qinghai. Two sensitive grain-size proxies (skewness and grain-size ratio) were then employed to infer riverine input linked to summer monsoon variability. Finally, by comparing the grain-size results with regional and global climate records, we addressed the plausible driving forces of orbital-to-centennial variability of Holocene summer monsoon intensity.

2. Setting of Lake Qinghai

Lake Qinghai (36°32' to 37°15'N, 99°36' to 100°46'E) is situated at an altitude of 3194 m above the sea level on the northeastern Qinghai-Tibetan Plateau (Fig.1A), with a surface area of 4,260 km² and a catchment area of 29,660 km² (LZBCAS, 1994). From 1958 to 2013 the mean annual

temperature and mean annual precipitation in Lake Qinghai was -2.5°C and 381.3 mm, respectively, with relatively heavy rainfall in summer season (Fig. 1B). Five rivers discharge into the Qinghai lake basin (Fig. 1A), and the inflowing water is mainly from the Buha River, Shaliu River, and Hargai River, which contribute 42.6%, 15.3%, and 15.0% of the total water volume, respectively (Li et al. 2007; Sun et al. 2007). Comparison of observational data including rainfall, water discharge and suspended particle material (SPM) at two hydrological stations indicates that ~80% water inflow occurred from June to September, and only a minor inflow of ~3% occurred from April to May, mainly due to the melting of ice and snow (Jin et al., 2011; Zhang et al., 2013). High values of the present-day SPM, river discharge and precipitation occurred simultaneously during the summer season, suggesting that summer rainfall contributes a dominant amount of water supply to Lake Qinghai, and also plays a key role in transporting SPM into the lake (Zhang et al., 2013).

3. Materials and methods

In 2005, two parallel cores 1A and 1F (36°48'40.7"N, 100°08'13.5"E, 3194 m above sea level) were retrieved from the deposition-center of the southern sub-basin of Lake Qinghai with the ICDP GLAD800 drilling system. To obtain a continuous sequence, lithological and grain size data of the two cores have been compared in previous study, indicating that the upper 5-m is dominated by lacustrine sediments (An et al., 2012). According to previous description of lithology and comparisons of mean grain size, CaCO₃, and total organic carbon (TOC) between cores 1F and 1A, the lithologic units of upper 5 m can be further divided into three sub-units: (1) 0-2.3 m, gray clay with thin horizontal bedding; 2.3-3.7 m, dark silty clay with thin horizontal bedding; 3.7-5.0 m, light brown lacustrine silty clay. Below 5 m, the lithology changes from gray and gray-yellowish silty clay with silt layers in the middle part (5-9 m) to light brown and gray silty clay, more homogeneous loess-like silt and fine sand layers in the lower part (9.0-18.6 m) (An et al., 2012).

To better understand the grain size results of the Holocene Qinghai lake sediments, suspended sediments from the Buha River, modern dust, surface lacustrine sediments, and Pleistocene loess deposits from the surrounding catchments were collected for grain size measurements in order to

107 evaluate the links between sensitive grain-size populations and dominant transport dynamics. 13
108 offshore surface sediment samples were collected by a 6-cm diameter piston drilling device, and the
109 top 2-cm sediments might be deposited within about 40 years (Li et al., 1996; Henderson et al., 2003;
110 Xu et al., 2006). 3 nearshore surface sediment samples were collected using a large scoop for the
111 topmost ~3-4 cm (Liu et al., 2009, 2013). Loess samples were collected from the outcrops within the
112 catchments (Fig. 1).

113 All the samples were pretreated by adding H₂O₂ and HCl to remove organic matter, carbonate,
114 and iron oxides, and were dispersed with 10% (NaPO₃)₆ and a sufficient dispersion of the suspension
115 by ultrasonic treatment before grain-size measurement (Lu and An, 1998). The grain size distribution
116 was measured by a Malvern 2000 laser diffraction instrument with 100 bins ranging from 0.02 to 2000
117 μ m at the Institute of Earth Environment, Chinese Academy of Sciences. The Mie theory is applied for
118 the particle size calculation from the diffraction pattern, which can accurately predict the light
119 scattering behavior of all materials (Grehan and Gouesbet, 1979; Wiscombe, 1980). In a previous
120 study (An et al., 2012), grain size variations in different lithologic units were interpreted as a mixing
121 of eolian and fluvial input, and the flux of >25 μ m fraction was employed as a westerly climate index.
122 In this study, however, we conduct a more comprehensive analysis of grain size data of the Holocene
123 lacustrine-dominated sediments (0-5 m), and try to provide a novel understanding of sensitive
124 grain-size parameters as indications of the riverine input.

125 The age of the entire Core 1F was determined using fifty-eight ¹⁴C dates including bulk organic
126 matter, seed and plant residue samples (An et al., 2012; Zhou et al., 2014). According to the
127 differences in lithology and total organic content, the core was divided into 3 sections for age-model
128 reconstruction using linear regressions of these ¹⁴C dates. Chronology of the upper 5-m was generated
129 by linear regression of forty dates ($Y=23.354x+135$, $R^2=0.987$) (Fig. 2). The intercept of the equation
130 was considered as the reservoir age (135 years), indicating that the contribution of “old carbon” is
131 very limited in the upper part of the core (Zhou et al., 2014). Since the dating errors in the Holocene
132 ranges from 20 to 60 years and our 1-cm sampling strategy yields a time resolution of about 23 year, it
133 is reasonable to discuss centennial-scale climatic variations based on our high-resolution grain size

results.

4. Grain size results

Many grain-size parameters have been investigated to reflect different transport dynamics, including mean grain-size, modal value, sorting coefficient (or standard deviation), skewness, kurtosis, and grain-size ratios (Vandenberghe et al., 1985, 1997; Xiao et al., 1995, 2009, 2013, 2015; Chen et al., 1999). For example, mean and modal values are linked in general to the average intensity of transport dynamics (Folk and Ward, 1957). Standard deviation is often used to quantify the grain-size populations with varied variability through time (Boulay et al., 2003; Sun et al., 2003). Skewness is found to be a slanting asymmetry in an abnormal distribution, which sensitively reflects the trace variation of the grain size distribution (Folk and Ward, 1957). Kurtosis is a descriptor of the shape of a probability distribution which reflects the changes in sedimentation dynamics (Folk and Ward, 1957). Grain-size ratio is successfully applied to indicate the proportion of medium and coarse-grained versus fine-sized silt (Vandenberghe et al., 1985, 1997). However, each of these parameters is not solely linked to a single process but always represents a mixing of different processes.

Different decomposing approaches, such as end-member modeling (EMM) method (Kranck et al., 1996; Weltje, 1997; Weltje and Prins, 2003; Dietze et al., 2012, 2013, 2014), Weibull-distribution fitting (Sun et al., 2002, 2004, 2008) and lognormal-distribution fitting (Qin et al., 2005; Xiao et al., 2009, 2013), have been widely applied to partition sensitive grain-size components of terrestrial, fluvial and eolian sediments. EMM analysis does not require any case-specific assumptions, which means that the number of end members and their shapes do not have to be specified either, so it should be particularly well suited to the unmixing of grain-size distributions (Prins and Weltje, 1999; Prins et al., 2007; Dietze et al., 2012, 2013, 2014). Fitting experiments indicated that for most hydraulic and aeolian sediments the Weibull function gives better results than other functions, since natural sediments are usually not lognormally distributed (Sun et al., 2002). Here results of Weibull fitting and EMM modeling were combined with the bulk parameters (e.g., standard deviation, skewness, and grain size ratio) to better interpret the implications of the Lake Qinghai grain-size data.

Different grain-size parameters including mean, skewness (S_k), grain-size ratio (GSR) of sediment amounts of 8~50 μm and 2~8 μm and contents of four size fractions (<2 μm , 2-8 μm , 8-50 μm , and >50 μm) are shown in Fig. 3. Grain-size distributions in core 1F are mainly composed of fine (2-8 μm) and medium (8-50 μm) silt fractions, with contributions of 25.8-64.9% and 22.5-65.0%, respectively. Down-core variations of four grain-size proxies (mean grain size, S_k , GSR, and the contents of 8-50 μm) exhibit general decreasing trends, in contrast to the increasing trends of the contents of two finer fractions (Fig. 3). The >50 μm size-fraction is characterized by very low percentages through the whole core and punctuated by several intervals (e.g., 1.8-1.4 m) of relatively high percentages. Based on subtle lithological changes, these grain size proxies can be divided into three intervals: (1) large amplitude fluctuations at 5-3.7 m; (2) moderate amplitude variability at 3.7-2.3 m; and (3) relatively small amplitude variations at 2.3-0 m, except for several remarkable peaks between 1.8-1.2 m (Fig. 3). Note that changes in the mean grain size and S_k are different from those in the percentages of <2 μm , 2-8 μm and 8-50 μm size-fractions from 1.8 to 1.4 m. This is because two former parameters are influenced by changes in the percentage of >50 μm size-fraction, whereas the percentages of three size fractions are not.

In general, lacustrine deposits are finely horizontally laminated. It is difficult to distinguish different mechanisms of transport in the lake solely by their sedimentary facies and bulk grain size. Thus, the original grain-size distributions were first unmixed using EMM method which extracts genetically meaningful end-member grain-size distributions (i.e., loadings) and percentages in each sample (Dietze et al., 2012). Weibull fitting was then applied to analyze the size, proportion and origins of all components in order to compare with the EMM results. Unmixing of grain size distributions in core 1F with EMM yielded an optimal model with four end-members (EMs) explaining 96.0% of the data variance, of which EMs 1, 2, 3 and 4 explain 3.42%, 42.66%, 21.15% and 32.77%, respectively (Fig. 4). Both EM 1 and EM 4 have a broad mode in the fine and coarse part, characterized by peaks at 20.0 and 15.9 μm at the coarse side, and 2.2 and 3.6 μm at the small side (Fig. 4A). Interesting to remark is the coarse tail at the right side in all EMs but especially in EM1, although not appearing as a separate end-member (Fig. 4A). In contrast, EM 2 and EM 3 have a narrow peak

with modal size at 4.5 and 12.6 μm , respectively (Fig. 4A). EM 2 and EM 3 are the robust end-members in modern lake surface sediments (Dietze et al., 2012), which have modal values similar to typical loess deposits transported in high suspension (Prins et al., 2007; Vandenberghe, 2013). The content of EM1 is relatively low through the whole core punctuated by several intervals of high percentages. The upper 2.3-m of 1F core is basically all dominated by EM2 and EM 4, it is consistent with our description of strata (Fig. 4B). EM 3 is generally high in the lower part of core 1F, which is also consistent well with description of strata (Fig. 4B).

Due to small difference in grain size distribution of 1F core sediment samples, standard deviation (STD) is applied here to extract sensitive grain size components from sediment samples (Boulay et al., 2003). A standard deviation close to zero indicates that the data points tend to be very close to the mean (also called the expected value) of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values. Each of these size classes represents a population of grains with the highest variability through time. Weibull-distribution function fitting was further conducted on the standard deviation curves of different types of sediments (i.e., Core 1F sediments, loess and modern dust, river SPM and lake surface sediments), revealing four significant grain-size components in each of these sediments (colored lines in Fig. 5B). However, the grain-size components of these three types of sediments are quite different in composition and point to a different origin. Two major components (C2-fine silt component, C3-medium silt component) contribute to 85% of the total volume distribution of core 1F sediments, similar to that of the SPM samples in the Buha River (Fig.5A). The contents of the ultrafine component (C1) and the coarsest component (C4) are both quite low (<8%).

The very fine component C1 in loess may be originally and genetically related to pedogenic processes (Sun et al., 2011). In lake sediment, C1 is the long-term suspension component in standing water which exists in many lakes (Xiao et al., 2009, 2013). The main sedimentary component of loess and dust is composed of C2 and C3 components, each of them transported by different atmospheric circulation processes: long-term and short-term suspension, respectively (Prins et al., 2007; Vandenberghe, 2013). C4 (156 μm) in loess and modern dust is the eolian saltation component which

transport distance is relatively limited (Vandenberghe, 2013). Obviously, C3 of core 1F is strikingly different in modal size from C3 in dust, loess and river suspension sediments: in lake core 1F it is fine background loess (17 μm), while in loess or dust sediment it is typical monsoonal loess (47 μm) and in the Buha river-transported sediment it represents the fluvial suspension load (80 μm). Likewise, C4 of core 1F (58 μm) equals C3 of modern dust and loess (47 μm), while C4 of river sediments (468 μm) is much coarser than all other components and likely represents the river-transported bedload (Vandenberghe, 2013).

The end-member analyses from the two approaches (EMM and Weibull fitting) enable a direct methodological comparison. Although at first glance the end-members derived from both approaches might look different, the results are remarkably similar when looking in detail at their sedimentary interpretation. Both methods provide 4 significant grain-size components which show a striking sedimentary correspondence between EMs (EMM) and components of core 1F (Weibull). More specifically, EM2 (4.5 μm) and the fine part of EM1 and EM4 (2-4 μm) correspond to C2 (4 μm), EM3 (12 μm) and the coarse part of EM1 and EM4 (16-20 μm) correspond to C3 (16-20 μm). Further, two fractions are visible in the EMs but not identified as separated end-members. They may be correlated with 2 components distinguished by the Weibull method: the coarse tail of EM1 corresponds to C4 (58 μm), while the very fine tail of all EMs corresponds with C1 (1 μm).

Considering the change of sedimentary facies of the whole core, 25 μm has been regarded as a threshold value for differentiating riverine components and eolian contributions in last glacial to Holocene sediments in Lake Qinghai (An et al., 2012). However, taking into consideration the results of EMM and Weibull fitting, we argue that 50 μm is a more likely boundary to distinguish the riverine and (reworked) eolian components during the Holocene when sedimentary facies is stable, and 8 μm is another important boundary size sensitive to hydrodynamic changes (Fig. 5B). As stated before, the <2 μm existing in all samples may belong to a long-term suspension component in a fluid medium (Xiao et al., 2013), and thus is considered as a background component that exclude for further interpretation. Similar to the U-ratio suggested by Vandenberghe et al (1985, 1997), the grain-size ratio (GSR) of two sensitive components C2 to C3 can be estimated from the contents of 8-50 μm to

2-8 m fractions to reflect changes in the hydrodynamics. The GSR variation fluctuates greatly between 5-2.3m, and then the amplitude decreases with depth (Fig. 3).

5. Sensitivity of Holocene grain-size distribution to riverine input

Grain-size composition of lake sediments can be regarded as a function of three main factors: (1) sources of clastic materials, (2) lake level fluctuation, and (3) hydraulic dynamics of lake waters (Håkanson and Jansson, 1983; Sly, 1989a, b; Xiao et al., 2013). Fluxes and contributions of main sources to the modern Lake Qinghai sediment are complex because of limited hydrological and observation data. According to the hydrological situation of Lake Qinghai (LZBCAS, 1994) and the mass balance calculation of annual fluvial SPM into the modern lake from the estimation of LIGCAS (1979), the ratio of fluvial particulate matter contribution and atmospheric dust input is about 3.6:1 (Xu et al., 2010). Based on geochemical properties, however, estimated dust contribution of the modern lake deposition was about 65% (Jin et al., 2009), which took the fluxes of reworked eolian dust and loess transported through rivers into account.

Water discharge and sedimentary processes can be influenced by other water sources, especially glacial melt water. However the contributions of precipitation and melt water to river discharges are spatially different in northern arid region. For example, the glaciated mountain ridges of the Shule Nanshan contribute 40% melt water to the total input at Hala Lake (Wünnemann et al., 2012; Yan and Wünnemann, 2014). In the Lake Qinghai Basin, glaciers lie mainly in the upper reaches of Buha Rivers which cover an area of 13.29 km². Glacial meltwater runoff is about $0.1 \times 10^8 \text{ m}^3/\text{y}$, accounting for 1.24% of the Buha River's annual runoff (LZBCAS, 1994; Cui and Li, 2015). Meanwhile, the application of pollen-based transfer functions yields an abrupt temperature increase at 10.4 cal kyr BP and a decrease at 5.0 cal kyr BP of about 3°C on the eastern Tibetan Plateau (Herzschuh et al., 2014). Glaciers retreated rapidly for decades at the beginning of Holocene, reducing the area and volume of glacier ice in comparison with present-day values would likely result in increased contribution of the glacier melt water to river runoff in Lake Qinghai catchments.

It's challenging to address the lake level impact on grain size variation since the lake level change of Lake Qinghai remains controversial, especially during the period of the early Holocene. The evidence of high Sr/Ca value (Zhang et al., 1989), multi-proxy investigations (Yu, 2005), and enriched $\delta^{13}\text{C}_{\text{org}}$ value (Liu et al., 2013) demonstrated that lake level was low during the early Holocene induced by intense summer insolation and high temperature (Berger and Loutre, 1991) and thus high evaporation (Lu et al., 2011; Mason et al., 2009; Liu et al., 2013). In contrast, more geochemical and isotopic evidence suggested that the lake level was high during the early Holocene, as evidenced by high CaCO_3 and TOC contents (Shen et al., 2005; An et al., 2012), negative $\delta^{18}\text{O}$ ratios of ostracod shells (Liu et al., 2007; An et al., 2012), and low Rb/Sr and high Ca/Zr (Jin et al., 2015). High lake level during the early Holocene may be attributed to an enhanced summer precipitation and hence high runoff triggered by orbital forcing of Indian/Asian monsoonal climate (Berger and Loutre, 1991; Dietze et al., 2013; Ran and Feng, 2013; Wang et al., 2014; Jin et al., 2015).

Particle grain size and S_k values in the lake are, respectively, supposed to be fine and low with high water level and weak water dynamic (Diegerfeldt et al., 1997; Chen et al., 2003). Generally, water dynamics are stronger in the nearshore zone (shallow water) than in the offshore zone (deep water) (Lerman, 1978; Sly, 1989a, b). Therefore, the high values of S_k and mean grain size during early Holocene in 1F core demonstrate either low lake level or strong water dynamic. However, the grain size results of surface sediments in Lake Qinghai show insignificant relationship ($0.02 < r^2 < 0.59$) with the changing water depth, suggesting that water depth may not be a driving force of particle size variations in Lake Qinghai. By contrast, the grain size of SPM coarsens with increasing discharge (Supplementary Fig. S1). The discharge amounts and various grain parameters are significantly correlated ($r^2 > 0.98$), implying that hydraulic dynamics of the riverine input may be a dominant factor affecting grain size variations. Meanwhile, grain-size distribution patterns of core 1F sediments are similar to those of suspended particles from the modern Buha River and of lake surface sediments, but different from those of modern dust and loess samples collected in Lake Qinghai and its surrounding catchments (Fig. 5A), implying the riverine input as the dominant transport process.

S_k may be considered as an indicator of the intensity of transport dynamics, since high S_k values

point to the presence of a ‘coarse tail’ of the grain-size distribution as representative for fluvial admixture. The modal size and content of the fine silt component increase from lower to upper intervals, in contrast to gradual decreases of the modal size and content of medium silt component (Supplement Fig. 2). In combination with the S_k , it seems that the fine silt component represents weak water dynamic conditions, whereas coarse silt component stands for strong water dynamics. Thus, we prefer to consider the grain size of the Holocene sediments in Lake Qinghai as an indicator of the transport dynamics associated with the riverine runoff, with high GSR and S_k corresponding to strong water dynamic.

Weibull fitting has been applied to link sensitive grain-size components to different depositional processes and sedimentary dynamics (Sun et al., 2002, 2004) and supplemented with EMM results. C1 is likely produced by settling from suspension in a fluid medium (in standing water) which can be called ‘lacustro-aeolian’ (Xiao et al., 2009, 2013; Vandenberghe, 2013). C4 is fine sand that typically represents fluvial transport (probably bedload), which could theoretically be confused with aeolian saltation material (Vandenberghe, 2013). In core 1F this coarse-grained fraction could also be trapped by a lake ice cover during the frozen season from November to next March, which will drop into lake sediments after ice melting (Chen et al., 2013). C2 and C3 (equivalent with all EMs except their very fine and very coarse tails) have the typical grain size of loess, but could be supplied directly by the wind or may be transported in suspension as fluvial reworking of originally aeolian loess which can be called ‘fluvio-aeolian’ sediment (Vandenberghe, 2013) (Fig. 5). It appears from many studies that the grain size of the source material is largely remaining identical when deposited in a lake or pool. For instance, loess grain size remains almost unchanged in floodplain pools or in tectonic basins (Vandenberghe et al., 2012; Licht et al. 2014). The grain size distributions of C2 and C3 maintain this inheritance, whereas the modal size becomes slightly finer after sorting and reworking in the lake. Thus, only judging from the grain-size characteristics of end-members C2-3, it is difficult to choose between both options. However, there is additional information available. First, there is a clear evidence of fluvial supply by the presence of coarse-grained fluvial bedload well visible in the coarse tail of the EM1 component (and comparable with end member C4 from the Buha river samples).

Second, there is a strong correlation between S_k (coarse tail pointing to fluvial input) and the typical loess fraction 2-32 μm (corresponding with the C2-3 fractions), and the correlation between amount of suspended sediment transport from the river to the lake and precipitation (and SMI, see below). Finally, sedimentary structures, more particularly the horizontal laminations, also point to fluvial deposition. To summarize, all these evidence point rather to fluvial reworking than to direct in-situ wind deposition of the two grain-size components C2-and 3 and the fine-grained C4 in the lake.

Correlation of these grain size proxies to the summer monsoon index (SMI) proposed by An et al (2012) was analyzed to address the sensitivity of various grain-size proxies to hydrological change. Coefficients of the SMI with S_k , contents of 8-50 and 2-8 μm fractions, and GSR are above the 99% significant level ($r^2 > 0.48$, $n=450$, $p=0.01$), implying that these four proxies are sensitive to changes in summer monsoon intensity. In contrast, correlation coefficients of the SMI with the mean grain size, and the contents of $<2\text{ }\mu\text{m}$ and $>50\text{ }\mu\text{m}$ fractions are relatively low ($r^2 < 0.29$), implying that these two proxies are less sensitive to changes in the summer monsoon intensity. Relatively high correlations of S_k and GSR with the SMI suggest that these two proxies can be regarded as sensitive indicators of the riverine discharge and thus are linked to the summer monsoon intensity. The result also shows that the riverine input is more clearly expressed by the reworking of the silt components (C2-3), which reflects the suspension load.

6. Discussion

6.1 Holocene monsoon variation

The S_k and GSR exhibit a decreasing trend similar to the SMI (Fig. 6), implying that the summer monsoon intensity was relatively strong during the early Holocene and decreased gradually afterwards. However, discrepancies among these three proxies are evident during the early Holocene (11.5-8.8 ka) and mid Holocene (5.6-3.5 ka). The high values of S_k and GSR are most likely a result of high runoff and river discharges (Jin et al., 2015), linked to strong monsoon precipitation and/or enhanced glacier melt during the onset of climate warming. In the early Holocene (11.5-8.8 ka), the SMI variation indicates three strong monsoon intervals punctuated by two weak monsoon events around 10.2 ka and

9 ka. The S_k and GSR values were relative high before 10.2 ka and during 10-8 ka, and in-between was a weak monsoon interval. In the middle Holocene (5.6-3.5 ka), a shift of the monsoon intensity is evident in these three proxies, however the timing is different from 5.6 ka for the SMI to 5 ka for the GSR and 4 ka for the S_k . In the late Holocene, while the general monsoon intensity was relatively weak compared to the early Holocene, fine-scale variability is more evident in the GSR record than that in S_k and SMI.

Orbital trend of two grain-size proxies from the Lake Qinghai generally resembles the speleothem $\delta^{18}\text{O}$ record from Dongge cave in southwest China (Dykoski et al., 2005) and the summer insolation change (Berger, 1978) (Fig. 6), suggesting a spatial similarity of the Holocene monsoon variation induced by insolation forcing. Besides the similar orbital trend, lake and speleothem records differ in three aspects. First, speleothem $\delta^{18}\text{O}$ record indicates that the summer monsoon was relatively weak during the earliest Holocene (11.5-10 ka), in contrast to relative strong monsoon intensity inferred from two grain-size proxies. This discrepancy might attribute to the impacts of lake level on grain-size records (Chen et al., 2003) and/or of the moisture sources on the speleothem $\delta^{18}\text{O}$ records (Clemens et al., 2010; Liu et al., 2015). Second, mid-Holocene monsoon weakening between 6-3 ka in the speleothem record is longer than the lake Qinghai records, likely due to the northern location and limited impacts of the summer monsoon of Lake Qinghai. Third, fine-scale variability superimposed on the orbital trend seems evident in the grain-size proxies compared to the speleothem $\delta^{18}\text{O}$ record. Asynchronous changes among these proxies are due to varied sensitivity of these proxies and archives to changes in the monsoon intensity (Caley et al., 2014; Chen et al., 2015).

Climatically, solar radiation directly determines land-ocean thermal contrast that controls the western Pacific subtropical high-pressure system (Fleitmann et al., 2003). A northward penetration of the monsoon rainfall belt is dynamically linked to the northward extension of the subtropical high, resulting in decreased precipitation in southern China and increased precipitation in northern China (Gao et al., 1962; Ding and Chan, 2005; Ding et al., 2008). Since the $\delta^{18}\text{O}$ of speleothem is influenced by seasonal changes in the amount and moisture sources of summer to winter precipitation, its implication for the monsoon intensity is rather complicated and highly dependent on the specific

locations (Wang et al. 2001; Yuan et al. 2004; Dykoski et al. 2005; Cheng et al. 2006; Kelly et al. 2006; Wang et al. 2008; Cai et al., 2015). Unlike the Dongge Cave in southwest China, Lake Qinghai is located at the northern limit of the summer monsoon front and thus sensitive to monsoon front migration (Zhao et al., 2010; Henderson et al., 2010). Similar monsoon strengthening in the earliest Holocene was also revealed by effective moisture records from the Naleng (Kramer et al., 2010), Chaka (Liu et al., 2008) and Genggahai lakes (Song et al., 2012; Qiang et al., 2013, 2014) in the northeastern Qinghai-Tibetan Plateau and the loess deposits at Duowa in the western Chinese Loess Plateau (Maher and Hu, 2006).

Furthermore, the timing of mid-Holocene monsoon shift appears to be different in the southern and northern regions of China. Early multi-proxy study indicated that the mega-thermal (Holocene Optimum) period in China was occurred from 8.5 ka BP to 3.0 ka BP (Shi et al., 1992). Based on a synthesis of lake levels, pollen profiles and loess records, An et al. (2000) proposed that the Holocene optimum was asynchronous (earlier in north and later in south) across China. Recently, the timing of mid-Holocene monsoon shift differs from 7.5 ka to 4.5 ka in speleothem records (Hu et al., 2008; Cai et al., 2010) and from 6.0 to 3.3 ka in peat and lacustrine records (Zhou et al., 2004; Zhang et al., 2011; Liu et al., 2015; Chen et al., 2015). Although chronological uncertainty and proxy sensitivity might attribute to different timing of the mid-Holocene monsoon shift, comprehensive syntheses of spatially distributed lake and speleothem records confirm the asynchronous feature of Holocene monsoon change (Cai et al., 2010; Chen et al., 2015; Liu et al., 2015), which may be related to the complicated response of the monsoon system to insolation-induced thermal forcing. The decreased summer insolation during mid-Holocene can result in significant changes in land-ocean thermal contrast, sea surface temperature in the western tropical Pacific, and Northwest Pacific subtropical High; all these factors have important impacts on the summer monsoon precipitation changes in central and northern China (Wang et al., 2003; Liu et al., 2003, Cai et al., 2010).

6.2 Centennial monsoon variability linked to solar activities

To address fine-scale climatic variability and dynamics, high-frequency components (<1 kyr) of

grain size proxies were obtained after removing the long-term trend and compared with the North Atlantic Ice-rafted detritus (IRD) events and atmospheric ^{14}C production rate (Fig. 7A). High-frequency components of three proxies from Lake Qinghai exhibit persistent large-amplitude fluctuations during the Holocene. A number of strong and weak monsoon events can be identified in the high-frequency components of three proxies from Lake Qinghai, such as weak monsoon intervals around 11.2, 10.3, 9.0, 8.2, 7.6, 7.2, 5.7, 5.4, 4.5, 3.2, 2.6, 1.2, and 0.4 ka BP. Some of these weak monsoon intervals (e.g., 7.6, 5.7, 4.5, 3.2, 1.2 ka) are well correlated with the North Atlantic cooling events. However, most of these weak monsoon events such as 11.2, 10.3, 9.0, 8.2, 7.2, 5.4, 2.6 and 0.4 ka BP correspond well to the high ^{14}C production rates (Fig. 7B).

Atmospheric ^{14}C and North Atlantic cooling are two commonly accepted drivers of centennial climate variability. The ^{14}C production rate is related to the solar winds and solar activity, with higher production rates corresponding to weaker solar winds and reduced irradiance (Stuiver et al., 1980, 1998; Masarik and Beer, 1999). Response of the East Asian summer monsoon attribute to solar changes is almost immediately associated with rapid atmospheric processes, such as shifts in mean position of the ITCZ that may control tempo-spatial variability of precipitation in East Asia (Wang et al., 2004). Rapid monsoon changes are also correlated with abrupt events in the North Atlantic region, as the ocean thermohaline circulation hypothesis is widely accepted as the mechanism responsible for the teleconnection (Broecker et al. 1992; Alley et al. 1997; Bond et al., 2001; Wang et al., 2001; Clement and Peterson, 2008). When the North Atlantic is in cold periods, significant changes in the Atlantic Meridional Overturning Circulation (AMOC) and temperature gradients across the northern hemisphere result in a southward shift of the ITCZ and weakening of the East Asian summer monsoons (Zhang and Delworth, 2005, Broccoli et al. 2006, Menviel et al. 2008, Zhang et al. 2010, Sun et al., 2012). This correlation has been confirmed by speleothem records from central and southern China (Yuan et al., 2004; Dykoski et al., 2005; Cheng et al., 2006; Kelly et al., 2006; Wang et al., 2008).

To address the possible link of centennial monsoon variability with external solar forcing and internal North Atlantic feedbacks, we compare the spectral and cross-spectral results of these proxies.

Spectral results reveal that the SMI, S_k and GSR records share the same periodicities at 0.35, 0.23, and 0.12 kyr (Fig. 7B), characterized by distinctive centennial-scale variability. Two dominant periodicities (0.35 and 0.23 kyr) are not evident in the HSG spectrum, implying that North Atlantic cooling is not the direct cause of centennial summer monsoon variability. However, the co-existence of grain size records and ^{14}C production rate at 0.35, 0.23, and 0.12 kyr indicates a plausible linkage of centennial summer monsoon variability to solar forcing. Cross spectral results indicate that the peaks at 0.35 and 0.23 kyr closely match between these two parameters. High coherence in these two periods are well above the 95% significance level (Fig. 8), providing further evidence of the close relationship between the ^{14}C production rate and GSR. These two records are strongly coherent and almost in-phase at these centennial periods, indicating that solar forcing likely plays a key role in driving centennial monsoon variability.

7. Conclusions

A comprehensive analysis of grain size data of Holocene Lake Qinghai sediments suggests that S_k and GSR can be applied to reflect the riverine input and thus be regarded as sensitive indicators of the summer monsoon intensity. Two grain-size proxies display a weakening of Holocene summer intensity punctuated by significant centennial variability, compared to the SMI from Lake Qinghai and the speleothem $\delta^{18}\text{O}$ record from Dongge Cave. Broad similarity of the orbital trend of Holocene monsoon variability indicates that solar insolation plays a key role in driving the general weakening of the summer monsoon from early to late Holocene. Evident discrepancies among these proxy variation during the earliest Holocene and mid-Holocene transition highlight that varied sensitivity of different proxies, locations and archives to the summer monsoon variation should be fully considered in regional to global paleoclimatic comparison. Centennial variability is persistent in two sensitive grain-size proxies, with dominant periods at 0.35 and 0.23 kyr. Visual comparison and cross spectral analysis of two grain-size proxies with possible driving factors (North Atlantic cooling and atmospheric ^{14}C) suggest that centennial monsoon variability was likely induced by external forcing, highlighting the potential role of solar activities in driving centennial-scale Asian monsoon variability.

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Figure Caption

Fig. 1. (A) Map showing Lake Qinghai, drainage systems and location of the 1F core (red star), lake surface sediments (blue dots) and loess deposits (black dots); (B) Monthly mean precipitation and temperature changes from 1958 to 2013 (data from Gangcha Meteorological Station). Red dots indicate the Buha (BH) and Shaliu (SL) hydrological stations. Relative discharge contributions of three large rivers (Buha, Shaliu and Hargai) discharges are derived from Li et al (2007) and Sun et al (2007).

Fig. 2. The age model for the upper 5-m of Core 1F using the linear regression (red line) of forty calibrated ^{14}C dates (blue dots) from An et al. (2012).

Fig. 3. Down-core variations of mean grain size, skewness (S_k), grain-size ratio (GSR) of 8-50 μm to 2-8 μm and contents of four size fractions ($<2 \mu\text{m}$, 2-8 μm , 8-50 μm , $>50 \mu\text{m}$) of the upper 5-m of Core 1F. Lithology and mean grain size variation were modified after An et al. (2012).

Fig. 4. EMM results of core 1F sediments: (A) End-member loadings represent sedimentologically interpretable unmixed grain-size distributions and (B) End-member scores (%) denote the proportion of variance explained by the individual end-member.

Fig. 5. (A) Grain-size distribution patterns of lake sediments, modern dust, loess, surface lacustrine samples, and suspended particles from the Buha River and (B) Weibull fitting results of the corresponding standard deviations of these samples. Estimated modal size and percentages of four grain-size components (C1-very fine fraction, C2-fine fraction, C3-coarse fraction, and C4-very coarse fraction) are shown for three types of sediments in the right panels. Gray bars around 2, 8, and 50 μm indicates the key boundaries between different transport dynamics.

Fig. 6. Comparison of Lake Qinghai proxies and other paleoclimatic records. (A) June insolation at 65°N (Berger, 1978), (B) $\delta^{18}\text{O}$ of the D4 stalagmite calcite from Dongge Cave (Dykoski et al., 2005), (C) S_k and (D) GSR (8-50/2-8 μm) of core 1F sediments, (E) summer monsoon index (SMI) of Lake Qinghai sediments (An et al., 2012), and (F) NGRIP $\delta^{18}\text{O}$ (Rasmussen et al., 2006). Red lines denote Long-term trend of these proxy records. Gray bar highlights the transitional periods in the early and middle Holocene, respectively.

Fig. 7. Comparison of (A) centennial components of GSR and S_k with the SMI (An et al., 2012), North Atlantic

ice-rafted hematite stained grains (HSG) (Bond et al., 2001), and atmosphere $\delta^{14}\text{C}$ record (Reimer et al., 2004) and (B) the corresponding spectral results of these proxy records. Left panel from top to bottom: North Atlantic ice-rafted hematite stained grains (HSG), S_k , GSR, SMI, and atmosphere $\delta^{14}\text{C}$. The blue and green bars indicate correlations of weak monsoon to high HSG and $\delta^{14}\text{C}$ values, respectively. In right panel, spectral peaks above represent the 80% confidence levels (grey lines) are marked.

Fig. 8. Cross-spectral results between atmosphere $\delta^{14}\text{C}$ (Reimer et al., 2004) (magenta) and GSR (blue). Spectral density is plotted on a log scale. The horizontal dashed lines indicate the 95% significance level of coherence. Shaded bars indicate two highly coherent spectral peaks for these two records.

Figure 1

Figure 2

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Figure 8