DOI: 10.1007/s11430-006-2027-4

Humid Little Ice Age in arid central Asia documented by Bosten Lake, Xinjiang, China

CHEN Fahu[1], HUANG Xiaozhong[1], ZHANG Jiawu[1], J. A. Holmes[2] & CHEN Jianhui[1]

1. CAEP, Key Laboratory of Western China's Environmental System (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China;
2. ECRC, Department of Geography, University College London, London, WC1E 6BT, UK

Correspondence should be addressed to Chen Fahu (email: fhchen@lzu.edu.cn)

Received February 14, 2006; accepted May 29, 2006

Abstract Short sediment cores retrieved from Bosten Lake, the largest inland freshwater lake in China, were used to explore humidity and precipitation variations in arid central Asia during the past millennium. The chronology of the cores was established using ^{137}Cs, ^{210}Pb and AMS ^{14}C dating results. Multi-proxy high-resolution analysis, including pollen ratios of *Artemisia* and Chenopodiaceae (A/C), carbonate content and grain size, indicates that the climate during the past millennium can be divided into three stages: a dry climate between 1000—1500 AD, a humid climate during the Little Ice Age (LIA) (*c.* 1500—1900 AD), and a warm dry period after 1900 AD. On centennial timescales, the climate change in northwestern China during the past 1000 years is characterized by oscillations between warm-dry and cold-humid climate conditions. All the proxies changed significantly and indicate increased precipitation during the LIA, including increased pollen A/C ratios and pollen concentrations, decreased carbonate content and increased grain size. The humid period during the LIA recorded by the Bosten Lake sediments is representative of arid central Asia and is supported by numerous records from other sites. During the LIA, the water runoff into the Keriya River and Tarim River in the Tarim Basin increased, while the ice accumulation in the Guliya ice core increased. Additionally, the lake levels of the Aral and Caspian Sea also rose, while tree-ring analysis indicates that precipitation increased. We hypothesize that both the lower temperature within China and the negative anomalies of North Atlantic Oscillation (NAO) during this period may have contributed to the humid climate within this area during LIA.

Keywords: multiproxy analyses, Bosten Lake, humid Little Ice Age, past millennium, arid central Asia.

The Northern Hemisphere has experienced three distinct climate phases during the past millennium ——the Medieval Warm Period (MWP); the Little Ice Age (LIA) and the recent rise in global temperatures[1−4]. The term 'Little Ice Age' was first used by Matthes[5] who documented glacial regrowth in the Sierra Nevada, California, following glacial ablation in the early Holocene Hypsithermal. Now, the term generally refers to the latest glacier expansion episode between the MWP and recent 20th century global warming[6,7]. However, the timing of the initiation and termination of the LIA is geographically asynchronous[8−11], but recent palaeoclimatic research suggests that the LIA climatic event is globally recorded[4,12−14]. Coupled with this cooling event, climate changed significantly within China and a number of records document environmental changes coincident with a LIA climate[15−17]. Although temperatures globally decreased in a similar trend, the reconstructed and modelled humidity varies significantly from region to region[13,15,18]. For example, reconstructed dust storms in eastern China suggest that the climate was dry[19], while in western China records of the LIA suggest increased moisture in the mountains[20−22], however high-resolution records fr- om the arid desert area are rare. In order to address this, we utilized lake sediments from the region, which have been shown to be reliable and sensitive palaeoenvironmental archives, having provided high- resolution palaeoclimate records on a number of timescales[23−25]. We present the results of multi-proxy analyses on sediment cores retrieved from Bosten Lake, located in the arid continental interior, to investigate the past moisture variations over the past millennium.

1 Study area and sampling strategy

Bosten Lake (41°56′N — 42°14′N, 86°40′E — 87°26′E) (Fig. 1) is located on the southern slope of Tianshan Mountains and lies in the southeastern part of Yanqi Basin between Tianshan and Taklimakan Desert in the Tarim Basin. The Yanqi Basin is bordered in the north and west by the Tianshan Mountains and by the Kuruktag Mountains in the south. Bosten Lake (1048 m a.s.l.) is the largest inland freshwater lake in northwestern China with a surface lake area of *c.* 1000 km^2, maximum water depth of 16.2 m and an average depth of 8 m[26]. Zhong *et al.*[27] investigated a Holocene profile from the western shore of the lake, which demonstrated the potential for reconstructing the past climate history of the atmospheric westerlies. Bosten Lake is hydrologically open with 13 rivers flowing into the lake, with the four major rivers accounting for 96% of the total water input. Water leaves the lake via the Kongque River, which flows to Lop Nur.

As Bosten Lake is in a continental setting, its climate reflects a typical temperate arid region[26]. Meteorological records from Yanqi County record a mean annual precipitation of 70 mm and mean annual evaporation of 2000 mm. The dry climate leads to a very simple vegetation community composed of high-altitude alpine meadow, steppe, desert steppe and desert with no distinct forest. In addition, some intrazonal vegetation is widely distributed, e.g. small areas of *Picea schrenkiana* forest stands on the shaded slopes or valleys, while some Ulmaceae trees grow in valleys and some halophyte vegetation occurs on alkaline soil. It is also notable that a large area of *Phragmites* and *Typha* plants grow in the swamp on the western side of the Bosten Lake[28,29].

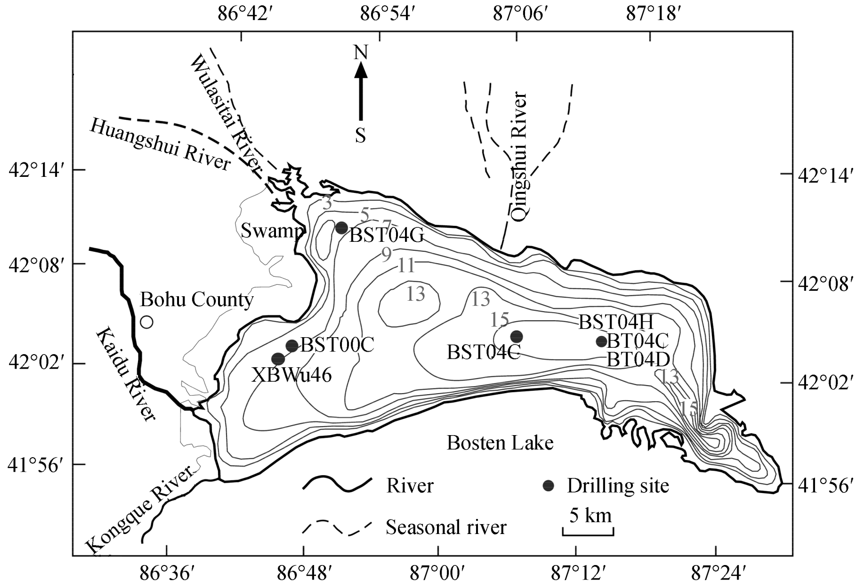

Fig. 1. The main rivers and the isobath of the Bosten Lake, the drilling sites in Bosten Lake.

Since 2000, we have retrieved a series of piston cores at different water depths from Bosten Lake[30]. The core selected for this study (BT04H) was recovered from the centre of the lake in 2004 using a Kullenberg-type piston corer and sampled at 1-cm intervals. To ensure the quality of samples for ^{210}Pb and ^{137}Cs dating, short surface sediment cores (BT04C, BT04D) with a clear mud-water interface were retrieved using a Glew corer and extruded into 0.5- and 1-cm sections in the field. In addition, to ensure the reliability of the palaeoenvironmental records archived by BST04H, an additional short core (BST04C) was taken from a water depth of 15.4 m, which shows a good general stratigraphic correlation with the previous cores.

2 Methods

Core BT04D was prepared for pollen samples at 1 cm intervals and BST04H core samples were selected for pollen analysis with intervals of 2 cm (between 20—40 cm) or 4 cm (between 0—20 cm, 40—100 cm). The pollen preparation procedures follow the standard methods[31] with minor modifications. Approximately 5 g of sediment was digested with 10% HCl, 40% HF and filtered with 7 μm sieve mesh. Before the chemical procedure, one tablet of *Lycopodium* spores (about 12, 524 spores per tablet) was added to each sample for the pollen concentration calculation. The carbonate content of the cores was measured using a Calcimeter at 1 cm intervals. The carbonate contents of the top 60 cm of both cores are shown in Fig. 2b, c, with an error of 0.74%. Grain size was measured with Malvern MS 2000 laser grainsizer after standard treatment with 10% HCL and 10% H_2O_2 and dispersed with sonication[33]. This pretreatment removes the dissolvable salt and organic matter, with the remains generally representing size of terrestrial debris. The error of the average grain size is less than 2%.

^{210}Pb and ^{137}Cs analysis was conducted on core BT04C at the Nanjing Institute of Geography and Lake Sciences, Chinese Academy of Sciences, using an ORTEC HPGe low background intrinsic germanium detector. For the long piston core, 11 AMS ^{14}C samples of TOC and plant remains were obtained after acid-alkali-acid pretreatments to make graphite targets in Lanzhou University. These targets were then measured at Kiel University and Peking University.

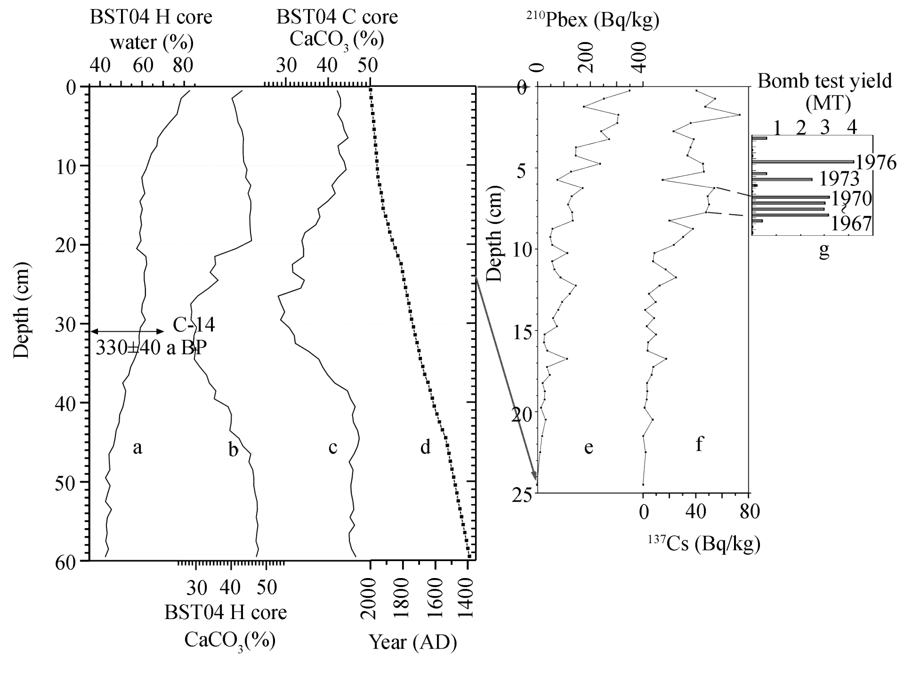

Fig. 2. Water content (a), carbonate content (b) of BST04H core; carbonate content of BST04C core (c); the age-depth model of BST04H core (d); ^{210}Pb curve (e) and ^{137}Cs curve (f) of the Glew core. The age at depth of 31 cm is the ^{14}C age after reservoir effect calibration. For comparison with the ^{137}Cs curve, a China bomb test yield curve (g, data from ref. [32]) was listed.

3 Results

3.1 Chronology

The $^{210}Pb_{ex}$ and ^{137}Cs were measured at 0.5 cm intervals on BT04C (Fig. 2). The ^{137}Cs curve can be divided into two sections. The values above 12 cm are high and variable and those below 12 cm vary around the ^{137}Cs background (Fig. 2f). The ^{137}Cs curve has several peaks, which are comparable to that of a core (BST00C) previously dated, which was taken from the western part of the lake in a water depth of 4.6 m[34]. The distribution of ^{137}Cs in the upper most sediments of Bosten Lake is very different to the widely recognized peaks caused by Chernobyl accident in 1986 and the global fallout peaks in 1963 and 1964[35]. Lin *et al.*[36] reported the effects of China bomb tests on the radioactive isotopes in the sediments of Bosten Lake, as recorded by the tritium concentration of a core retrieved from western basin in a water depth of 1 m. The ^{137}Cs curve from Bosten Lake has not only been influenced by global weapon testing, but also could be strongly influenced by regional weapon testing near the study site. The nuclear tests in China were carried out mainly in 1967—1970, 1973 and 1976[32] (Fig. 2g). There five peaks in ^{137}Cs activity, with the first peak (2 cm) probably relating to the Chernobyl accident in 1986. The following two peaks are thus likely to be related to China weapon testings and the peak in ^{137}Cs at 8.75 cm is possibly a result of the global bomb weapon tests that centred around 1963 and 1964 AD. The small variations below 12 cm could result from biological disturbance and chemical diffusion, which has been observed in other studies[37,38]. The large variations in the mass sedimentation rate calculated by the ^{137}Cs therefore may be a result of ^{137}Cs mobility in the lake sediments.

To avoid possible errors caused by the migration of ^{137}Cs, a ^{210}Pb chronology was developed using the CRS model for the upper 24 cm of the core. The $^{210}Pb_{ex}$ values (Fig. 2e) decrease exponentially, and reach equilibrium at *c.* 25 cm, which is similar to the profile observed by Lin *et al.*[36]. According to the ^{210}Pb CRS model, the average sedimentation above 12 cm and 24 cm are 2.45 mm/a and 1.2 mm/a, respectively, which could be an indication of mechanical compression process along the length of the core (Fig. 2a, d). The ^{137}Cs based sedimentation rate in the western part of Bosten Lake (water depth – 4.6 m) is 2.92 mm/a[34], and the sedimentation rate in the northern part of the lake (water depth –1 m) is 3.1 mm/a[36]. Since the coring site for this study is located in the centre of the lake, a number of kilometers away from any river input, the observed lower sedimentation rate in our core is reasonable. The water content of the core (Fig. 2a) decreases from 80% at the top to 40%—50% at the bottom, reaching nearly constant values until 45 cm. It suggests that the mechanical compression occurred within the top 45 cm. Therefore, the ages between 24—45 cm are calculated by the average mass sedimentation rate of the last five samples of ^{210}Pb. The ages below 45 cm were calculated by the average sedimentation rate obtained from the ^{14}C AMS datings.

There were a total of eleven ^{14}C AMS dates from BST04H and comparison of radiocarbon dates based on total organic carbon (TOC) and plant remains from the same depth intervals indicate a difference of 1140 years. As a result, a 1140-year age correction was applied to the remaining TOC dates. The AMS ^{14}C ages at 31 cm and 145 cm, are 330 ±40 a BP and 1270 ±40 a BP respectively, which gives a calculated average sedimentation rate of 1.04 mm/a, which is not too dissimilar to that calculated using the ^{210}Pb model (1.2 mm/a). Therefore, the age below 45 cm was calculated with a sedimentary rate of 1.04 mm/a, giving an age of 1000 AD at 100 cm. The chronology of the top 60 cm is shown in Fig. 2d.

3.2 Pollen assemblage

Pollen was counted for cores BT04 D and BST04H, with an average of 721 grains identified. The pollen assemblage data indicate a simple vegetation composition with only 30 different families/genera identified, but there are only 11 families/genera whose maximum percentages exceeded 1%, e.g. Chenopodiaceae, *Artemisia*, Gramineae, *Ephedra*, Compositae, Cyperaceae, Ulmaceae, *Nitraria*, Rhamnaceae, *Typha*, *Polypodium* (Fig. 3). The dominant pollen types in the assemblage are the Chenopodiaceae (33.8%—56.4%), *Artemisia* (21.0%—34.5%) and Gramineae (< 22%), which infer plants that are capable of persisting in an

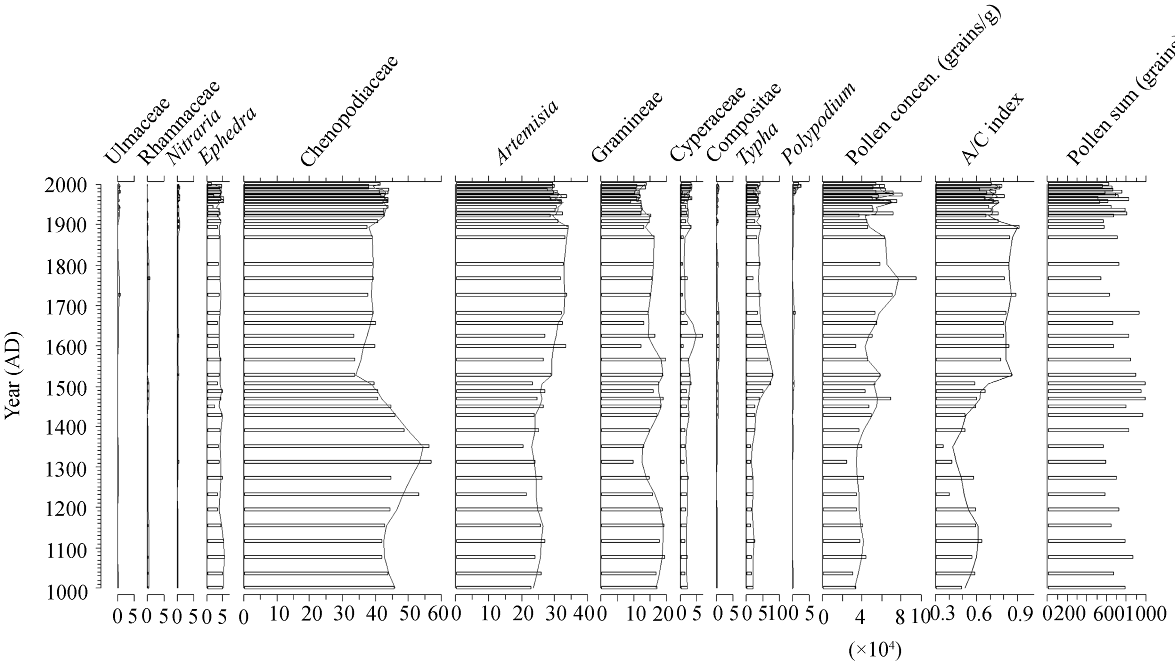

Fig. 3. Pollen assemblages, A/C ratio and pollen concentration of BST04H core (>1%).

arid environment. This is in general agreement with pollen assemblages identified in the Bosten Lake's surface sediments[29]. The pollen of other typical arid land plants such as *Nitraria* and *Ephedra* also occurs but at low percentages, while the aquatic plant *Typha*, does not exceed 9%.

Chenopodiaceae, which grows in the arid desert and alkaline soil, has higher percentages in both the lower and the upper parts of the sequence, while *Artemisia* has an increasing trend towards the top of the core. Gramineous pollen percentages change in an opposite trend to that of Chenopodiaceae. The overall pollen concentrations increase after 1450 AD and the variations are similar to the A/C ratios (Fig. 3). The A/C ratio is regarded as an effective indicator of humidity in arid and semi-arid environments, particularly when Chenopodiaceae and *Artemisia* are dominant species in the pollen assemblage[39−41]. Investigations on the pollen assemblage of the surface sediments within Bosten Lake also suggest that A/C ratios reflect the aridity of the area[29]. The pollen assemblage of surface soil samples within the Bosten Lake drainage basin also suggests that the A/C ratio averages 0.53 in desert zone and at 3.2 in a desert-steppe zone[28]. As a result of humidity increasing with altitude in an arid environment, the increase of A/C ratios from desert zone to desert-steppe zone in the Bosten Lake catchment indicates a likely correlation between the A/C ratio and humidity. Three zones in the A/C ratio profile can be distinguished during the past 1000 years. From 1000 AD to1500 AD, it was relatively low, with peaks in the ratio occurring between 1500 AD and 1900 AD. After 1900 AD, it began to decline but was still higher than that before 1500 AD (Fig. 3).

3.3 *Other proxies*

The results of multi-proxy analyses on core BST04H show obvious variations at different periods in the past 1000 years (Fig. 4). From 1000 to 1500 AD, the carbonate content was high (above 45%) and the mean grain size was small. The content of coarser grains (>30 μm) was also low but increased gradually. The mean grain size and the content of coarse grains peaked between 1500 and 1900 AD, meanwhile, the carbonate content was at its lowest during this period. After 1900 AD, the mean grain size and coarse grains decreased and the carbonate content increased again. The carbonate content is generally high during the last 1000 years, showing a declining trend except for theincrease at the upper most part of the core (Fig. 4a). The carbonate content of core BST04C (top 60 cm) is similar to that of BST04H (Fig. 2b, c), indicating that

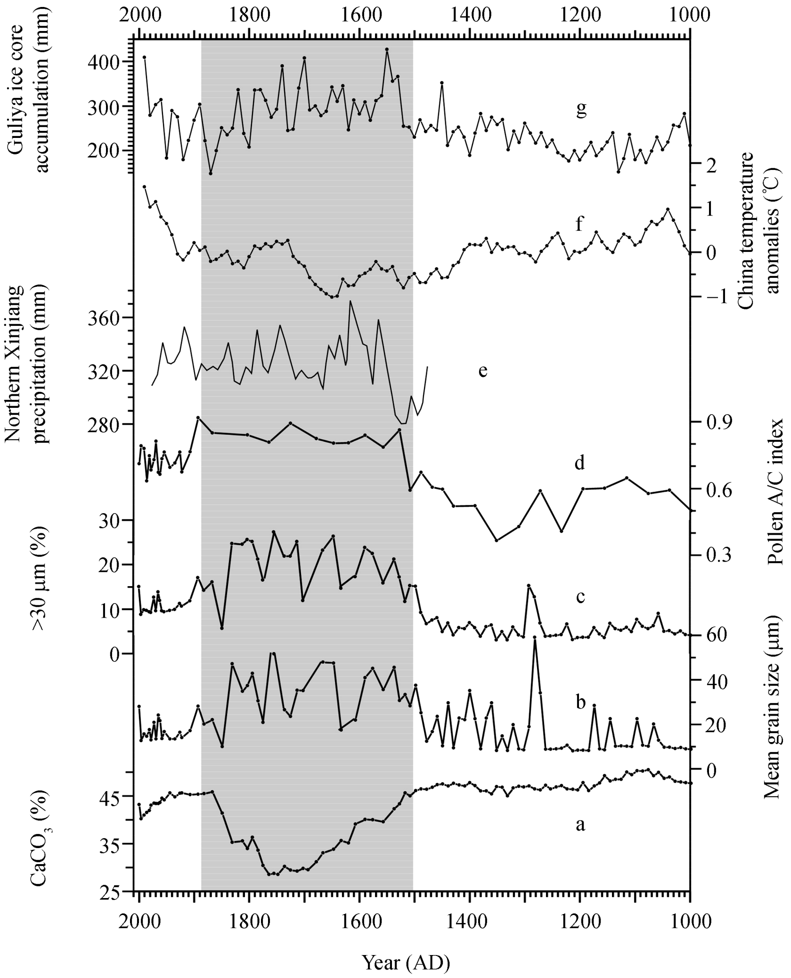

Fig. 4. Variations of the proxies along BST04H core (a: carbonate content; b: mean grain size; c: content of coarse grains (> 30 μm); d: A/C ratios) and their comparison with other records. In the figure, e: tree-ring reconstructed precipitation in northern Xinjiang[22]; f: China temperature anomalies[42]; g: ice accumulation in Guliya ice core[20].

the BST04H core is representative and a reliable record.

4 Discussion and conclusion

4.1 Multi-proxy records of climate change during the past millennium

The climatic significance of pollen A/C ratios in arid and semiarid area is relatively clear and it indicates regional humidity. The higher A/C ratios correlate to higher effective humidity, higher percentage of grassland plants and lower percentage of desert plants, and vice versa. The grain size of the terrestrial debris within the lake sediments generally relates to both lake level and river runoff (e.g. water dynamics). Generally the more precipitation in the catchment, the coarser grains will be carried into the lake and be incorporated into the lake sediments, especially when variations of lake level are small[43]. For Bosten Lake, the water area is relatively large, and coarse grains derived from an eolian source are unlikely to be a major influence on the grain size of lake sediments in the center of the lake. In addition, Bosten Lake is an open lake and no obvious palaeo-shorelines are found above the current lake level, suggesting the lake level has been quite stable. Therefore, the grain size of BST04H in the center of the lake is largely determined by the lake water dynamics and the runoff from the drainage basin. For example, the coarsening of the grain size in the upper sediments corresponds to the flood events documented in the late 1990s (see Fig. 4b, c). Similarly, results from other open- and closed-lakes, Erhai Lake[44], Qinghai Lake[45] and Daihai Lake[33] support the hypothesis that the grain size of sediments in the center of lakes reflects water dynamics and runoff, which is related to the variations in precipitation. As no aquatic plants grow on the sediment surface and Bosten Lake is frozen from November to April, the carbonate content is influenced by the very strong seasonal evaporation processes indicative of the regional humidity and temperature, for example, the lake sediments of the Aral Sea suggest that high carbonate content correlates to lower lake levels and more arid climate[46].

Three distinct climate stages can be identified from the proxies in Bosten Lake for the past millennium. Stage 1 is between 1000 AD and 1500 AD, where pollen A/C ratio is low, accompanied with fine grain sediments. The percentage of coarse grains is very low and the carbonate content is high. Stage 2 covers the period form 1500 AD to 1900 AD. All proxies changed inversely compared with stage 1. Stage 3 is the period since *c*. 1900 AD. The A/C ratio decreased but is still higher than that of stage 1. The grains size of terrestrial debris become smaller and the carbonate content increases. Before 1500 AD, pollen concentration and A/C ratios indicate a dry climate with a high percentage of *Ephedra* and low percentage of *Typha*. The high carbonate content and the small grain size support low humidity. From 1000 to 1200 AD, in the late Medieval Warm Period (MWP), the temperatures are higher than any climate preceding or following this event[47]. Although the pollen A/C ratio suggests a smaller increase in humidity than that seen at 1400 AD, it was still much drier than that after 1500 AD. Therefore, the regional climate was warm and dry during the MWP. After 1400 AD, the climate became wetter, which can be inferred from the lake sediment proxies (Fig. 4).

During stage 2 (1500—1900 AD), all the proxies suggest a more humid regional climate. During this epoch, the percentage of Gramineae is generally high, indicating the expansion of desert steppe and the reduction of desert. Increased mean grain size and coarse grains content indicate increased precipitation and river runoff feeding the lake (Fig. 4). The carbonate content and grain size suggest that the regional climate gradually transferred from the former warm and dry regime to cold and humid. Highest humidity appeared during 17—18th century and then became dry again. The period from 1500 to *c*. 1900 AD is the typical global LIA stage, during which a decrease in temperature is witnessed in most regions of the globe[13,48] and the cooling in China is also seen[7,15,17,42]. Lowered temperatures could lead to lower evaporation and thus higher humidity. Even if the water input did not change too much, the lake would become fresher, and the carbonate content decreases in such a climate regime. As the lake is frozen during the winter season and the runoff during the winter accounts for a minor proportion of the total water input, the increased grain size of the terrestrial debris in the center of the lake may indicate increased summer precipitation during the LIA. Previous research has shown that the runoff of the Tarim River, south to Bosten Lake, increased during 1450—1850 AD[49] and a river terrace formed during LIA along the Keriya River at the southern edge of the Tarim Basin[50]. In summary, our result supports the inference that the LIA in this region was characterized by a cool, humid climate with increased precipitation.

In the past *c*. 100 years (since 1900 AD), the A/C ratios decreased, indicating that the effective humidity decreased relative to the LIA period, but more humid than that of MWP. The relatively high carbonate content and finer grains contrast to those in the former period, suggesting that the evaporation process has been strengthening and the input river water has decreased. Generally, the regional climate has been relatively dry for the past 100 years. We also note that the carbonate content has been decreasing during the past 100 years and the humidity indicator, A/C ratios, increases at the top of core, which might indicate that the climate is becoming more humid under the background of dry climate. Continuous observations of lake level since 1959 AD show that the lake level of the Bosten Lake has dropped gradually by more than 3 m from 1959 to 1987 AD, before rising again after 1987 AD and by 1999 the lake level exceeded that of 1959 AD. The lake level variation is generally is correlated to the runoff of the Kaidu River, the major water input for the lake[51]. Global warming has also been a feature of the climate during the past 150 years[52]. This warming trend is also evident in Xinjiang, China, and is even more evident than that in eastern China[53]. Therefore, under the background of warming during the past 150 years, the climate in the drainage of Bosten Lake was warm and dry compared to the LIA. In recent years, there has been evidence of lake level rise, increased river runoff and precipitation in mountains of arid regions in NW China. Shi *et al.*[54] highlight that the climate of arid China might have shown a transition from warm and dry to a warm and humid climatic regime. However, the climate change during the past 1000 years recorded in Bosten Lake suggests that the recent change toward a more humid trend is still within the natural variation of the warm and dry regional climate. Further research is needed to identify whether this humidification trend could reach a similar extent of humidity to that documented in the LIA.

The records from Bosten Lake demonstrate that warm-dry and cold-humid climate variations have occurred on centennial time scales, most likely related to known climatic events that have occurred during the last 1000 years, e.g. MWP, LIA and recent global warming. On glacial-interglacial time scales, however, the climate in the inland area of central Asia changed similarly to that of eastern China. The records from loess-paleosoil sequences in central Asia are comparable to those on the Chinese Loess Plateau[55], where the climate was dry in glacials and wet in interglacials, indicating that the main climatic pattern is a cold-dry and warm-humid pattern. However, on millennial to multi-millennial time scales it is not clear whether the climate patterns remain cold-dry and warm-humid during these climatic events.

4.2 Regional comparison and possible mechanism

The multi-proxy record from Bosten Lake indicates that the climate regime has been warm-dry and cold-humid within the central Asian region during the last millennium. Ice accumulation on the Guliya ice cap, an alpine glacier to the south of Xinjiang on the western Tibetan Plateau increased during the LIA[20], which corresponds well with the larger grain size of terrestrial debris into Bosten Lake sediments (Fig. 4), indicating increased precipitation during the LIA. Additionally, tree-ring-based precipitation reconstructions show that the precipitation in northern Xinjiang has increased since 1530 AD[22] (Fig. 4e), though the tree rings mainly record high frequency climatic signals. Historical documents recorded great floods that were frequent during the Qing Dynasty (e.g. 1716, 1837, and 1883 AD)[56]. The Keriya River, a river originating from the high Kunlun Mountains (south of the Tarim Basin), could flow through the Taklimakan Desert into the Tarim River[49], and a terrace formed along the Keriya River during the LIA[50]. Historical documents also recorded that the Lop Nur expanded in the early Qing Dynasty (around 1782 AD)[57], suggesting that the climate was humid in southern Xinjiang during LIA.

The reconstructed lake level variations of Aral Sea show that the lake level was 20 m higher than present and the runoff of the Amu Darya River and the Syr Darya River increased, which are recorded by historical documents during the 14—16th century[58]. The lake level of the Caspian Sea rose rapidly and remained high during the LIA after a low stand from 2500 to 800 aBP[59]. During the past 150 years, it has declined persistently and risen since 1980s as documented by historical records. The lake level history of Caspian Sea is similar to the lake level variations documented at Bosten Lake during the past 40 years. Lake levels of some other lakes in central Asia, such as Daihai Lake, Lake Dalai Nur，Lake Ubusu Nur and Lake Baikal, rose or were stable during LIA[60]. These records suggested that the humid LIA climate recorded by Bosten Lake is a feature of the climate history of arid central Asia.

The high accumulation rate of Guliya ice core (Fig. 4) during 1500—1880 AD indicates increased precipitation at high altitudes[20], while the A/C ratios and pollen concentration in the Dunde ice core increased during LIA, supporting a humid climate[61]. Ma *et al.*[62] found that the groundwater recharge of Badain Jaran Desert also increased during the LIA by using the method of chloride mass balance in the unsaturated zone. Yang *et al.*[63] reconstructed salinity variation of Chencuo Lake using a diatom transfer function and howed the lake water freshened during 1700—1900 AD. Grain size data from the same lake also indicated that the input water increased during this period[64].

This evidence suggests that during the LIA, precipitation increased in the area dominated by both westerlies region and the marginal area influenced by monsoons.

The humid climate during the LIA as recorded by the Bosten Lake sediments is supported by evidence from other palaeoenvironmental archives in the central Asian region, but also possibly on the Tibetan Plateau. Records from lakes, ice cores and the desert also suggest that during the LIA in the inland arid area of the Asian continent, the climate was not only relatively humid, but the precipitation may have increased. The humid LIA climate in the inland arid Asia might be related to the cooling effect resulting from reduced solar activity[65] and volcanic eruptions[66,67], which may have caused global cooling. Lowered temperatures would also lead to inefficient evaporation both on the surface of water and land, resulting in increased effective humidity. On the other hand, the north Atlantic oscillation (NAO) anomaly was in a negative phase during the LIA[68]. The low frequency of NAO may have affected both the internal interactions of the climate system and external forcing[69]. Statistical analysis on the relationship between NAO anomalies and precipitation variations from more than one hundred stations in mid-latitudes of central Asia showed that the negative NAO anomalies correspond to increased precipitation in the inland area of the mid-latitude Asia influenced by westerlies[70]. When the NAO was in a negative phase, the sea surface temperature (SST) of the Azores region in the mid-latitudes increased, leading to enrich moisture in the air mass transported to central Asia by the westerlies and increased precipitation when the air mass encountered frequent cool air masses from the north. Therefore, the negative NAO anomalies may have contributed to the increased precipitation in central Asia during the LIA. Lowered temperatures and increased precipitation therefore may have led to humid conditions during the LIA in arid central Asia.

Acknowledgements We would like to thank Prof. John Dodson and Dr. Anson Mackay who provided help in pollen identification; Dr. Xia Weilan discussed the ^{137}Cs and ^{210}Pb dating results; Dr. Zhang Chengjun, Shang H M, Yang X L, Lei Y B, and Zhou A F. participated the field work. University College London and China Scholarship Council funded Huang Xiaozhong's study in UK. We especially thank three anonymous referees for constructive suggestions on the manuscript. Thanks also go to Dr. Andy Henderson who improved the English of the draft. This work was supported by the NSFC Key Project (Grant No.90502008) and the NSFC Innovation Team Project (Grant No. 40421101). And part of the lab work was funded by NSFC (Grant No.40301050).

References

1 Jones P D, Osborn T J, Briffa K R. The evolution of climate over the last millennium. Science, 2001, 292: 662—667
2 Jones P D, Mann M E. Climate over past millennia. Rev Geophys, 2004, 42: 1—42
3 Mann M E, Jones P D. Global surface temperatures over the past two millennia. Geophys Res Lett, 2003, 30(15), 1820, doi:10.1029/2003GL017814
4 Keigwin L D. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. Science, 1996, 274(5292): 1503—1508
5 Matthes F E. Report of the Committee on Glaciers, April 1939. Transactions of the American Geophysical Union, 1939, 20: 518—523
6 Bradley R S, Jones P D. Climate since A D 1500. London: Routledge, 1992. 649—655
7 Wang S W, Ye J L, Gong D Y. Climate in China during Little Ice Age. Quater Sci (in Chinese), 1998, 1: 54—64
8 Mann M E, Bradley R S, Hughes M K. Global-scale temperature patterns and climate forcing over the past six centuries. Nature, 1998, 392: 779—787
9 Bradley R S, Jones P D. Little Ice Age's summer temperature variations: their nature and relevance to recent global warming trends. Holocene, 1993, 3: 367—376
10 Grove J M. Little Ice Ages: Ancient and Modern. London: Routledge, 2004. 1—10
11 Grove J M. The initiation of the "Little Ice Age" in regions round the North Atlantic. Climatic Change, 2001, 48(1): 53—82
12 Thompson L G, Mosley-Thompson E, Dansgaard W, et al. The Little Ice Age as recorded in the stratigraphy of the tropical Quelccaya Ice Cap. Science, 1986, 234(4774): 361—364
13 Mayewski P A, Rohling E E, Stager J C, et al. Holocene climate variability. Quaternary Res, 2004, 62: 243—255
14 Yu K F, Zhao J X, Wei G J, et al. $\delta^{18}O$, Sr/Ca and Mg/Ca records of Porites lutea corals from Leizhou Peninsula, northern South China Sea, and their applicability as paleoclimatic indicators. Palaeogeogr Palaeoclimatol Palaeoecol, 2005, 218(1-2): 57—73
15 Wang S M, Liu J, Zhou J. The Little Ice Age maximum in China. J Lake Sci (in Chinese), 2003, 15(4): 369—376
16 Ge Q S, Zheng J Y, Man Z M, et al. Key points on temperature change of the past 2000 years in China. Prog Nat Sci, 2004, 14(8): 730—737
17 Yao T D, Xie Z C, Wu Y L, et al. Climatic change since Little Ice Age recorded by Dunde Ice Cap. Sci China Ser B-Chem, 1991, 34(6): 760—767

18 Liu J, Chen X, Wang S M, et al. Palaeoclimate simulation of Little Ice Age. Prog Nat Sci, 2004, 14(8): 716—724
19 Zhang D E. Analysis of dust rain in the historic times of China. Chin Sci Bull, 1983, 28: 361—366
20 Yao T D, Jiao K Q, Tian L D, et al. Climatic variations since the Little Ice Age recorded in the Guliya Ice Core. Sci China Ser D-Earth Sci, 1996, 39 (6): 587—596
21 Yao T D, Shi Y F, Thompson L G. High resolution record of paleoclimate since the Little Ice Age from the Tibetan ice cores. Quat Int, 1997, 37: 19—23
22 Yuan Y J, Han S T. Features of dry and wet changes for 500 years in the northern of Xinjiang. J Glaciol Geocryol (in Chinese), 1991, 13(4): 315—322
23 Wang S M, Zhang Z K. New progress of lake sediments and environmental changes research in China. Chin Sci Bull, 1999, 44(19): 1744—1754
24 Battarbee R W. Palaeolimnological approaches to climate change, with special regard to the biological record. Quaternary Sci Rev, 2000, 19: 107—124
25 Hodell D A, Brenner M, Curtis J H, et al. Solar forcing of drought frequency of Maya lowlands. Science, 2001, 292(18): 1367—1370
26 Cheng Q C. Research on Bosten Lake (in Chinese). Nanjing: Hehai University Press, 1995. 1—7
27 Zhong W, Shu Q. Palaeoclimatic and Palaeohydrologic oscillations since about 12.0 ka B.P. at Bosten Lake, southern Xinjiang. Oceanol & Limnologia Sin (in Chinese), 2001, 32(2): 213—220
28 Xu Y Q, Yan S, Jia B Q, et al. Numerical relationship between the surface spore-pollen and surrounding vegetation on the southern slope of Tianshan Mountains. Arid Land Geography (in Chinese), 1996, 19(3): 24—30
29 Huang X Z, Zhao Y, Cheng B, et al. Modern pollen analysis of the surface sediments from the Bosten Lake , Xinjiang , China. J Glaciol Geocryol (in Chinese), 2004, 26(5): 602—609
30 Wünnemann B, Chen F H, Riedel F, et al. Holocene lake deposits of Bosten Lake, southern Xinjiang, China. Chin Sci Bull, 2003, 48(14): 1429—1432
31 Moore P D, Webb J A, Collinson M E. Pollen Analysis. Oxford: Blackwell Science, 1991. 39—62
32 Norris R S, Burrows A S, Fieldhouse R W. British, French, and Chinese nuclear weapons. Boulder: Westview Press, 1994. 333—336
33 Peng Y J, Xiao J L, Nakamura T, et al. Holocene East Asian monsoonal precipitation pattern revealed by grain-size distribution of core sediments of Daihai Lake in Inner Mongolia of north-central China. Earth Planet Sci Lett, 2005, 233: 467—479
34 Zhang C J, Cao J, Lei Y B, et al. The chronological characteristics of Bosten Lake Holocene sediment environment in Xinjiang, China. Acta Sedimentol Sin (in Chinese), 2004, 22(3): 494—499
35 Pennington W, Cambray R S, Fisher E M. Observation of lake sediments using fallout ^{137}Cs as a tracer. Nature, 1973, 242: 324—326
36 Lin R F, Wei K Q, Cheng Z Y, et al. Distribution of ^{210}Pb, ^{228}Th, ^{239,240}Pu and ^{3}H and their implications in sediment core from Bosten Lake, Xinjiang, China. Geochimica (in Chinese), 1992, 1: 63—69
37 Oldfield F, Appleby P G. Empirical testing of ^{210}Pb dating models. In: Haworth E Y, Lund J W G, eds. Lake sediments and Environmental History: studies in palaeolimnology and palaeoecology in honour of Winifred Tutin. Leicester: Leicester University Press, 1984. 93—124
38 Appleby P G. Chronostratigraphic techniques in recent sediments. In: Last W M, Smol J P, eds. Tracking environmental changes using lake sediments. Dordrecht: Kluwer Academic Publishers, 2001. 171—203
39 Gasse F, Arnold M, Fontes J C, et al. A 13000 year climate record from Western Tibet. Nature, 1991, 353: 742—745
40 Sun X J, Du N Q, Weng C Y, et al. Paleovegetation and paleoenvironment of Manasi Lake, Xinjiang, N.W. China during the last 14000 years. Quaternary Sci (in Chinese), 1994, 3: 239—248
41 Liu H Y, Cui H T, Tian Y H, et al. Temporal-Spatial variances of Holocene precipitation at the marginal area of East Asian monsoon influences from pollen evidence. Acta Botan Sin, 2002, 44(7): 864—871
42 Yang B, Braeuning A, Johnson K R, et al. General characteristics of temperature variation in China during the last two millennia. Geophys Res Lett, 2002, 29(9), doi:10.1029/2001GL014485
43 Häkanson L, Jansson M. Principles of Lake Sedimentology. Berlin: Springer, 1983. 1—316
44 Chen J A, Wan G J, Zhang F, et al. Environmental records of lacustrine sediments in different time scales: Sediment grain size as an example. Sci China Ser D-Earth Sci, 2004, 47 (10): 954—960
45 Zhang J W, Jin M, Chen F H, et al. High resolution precipitation variations in the Northeast Tibet Plateau over the last 800 years documented by sediment cores of Qinghai Lake. Chin Sci Bull, 2003, 48(14): 1451—1456
46 Callonnec L L, Person A, Renard M, et al. Preliminary data on chemical changes in the Aral Sea during low-level periods from the last 9000 years. C. R. Geoscience, 2005, 337: 1035—1044
47 Yang B, Braeuning A, Shi Y F, et al. Temperature variations on the Tibetan Plateau over the last two millennia. Chin Sci Bull, 2003, 48(14): 1446—1450
48 Soon W, Baliunas S. Proxy climatic and environmental changes of the past 1000 years. Climate Res, 2003, 23: 89—110
49 Yang B, Braeuning A, Shi Y F, et al. Evidence for a late Holocene warm and humid climate periodand environmental characteristics in the arid zones of northwest China during 2.2－1.8 kyr B.P. J Geophys Res, 2004, 109, doi:10.1029/2003JD003787
50 Yang X P, Zhu Z D, Jaekel D, et al. Late Quaternary palaeoenvironment change and landscape evolution along the Keriya River, Xinjiang, China: the relationship between high mountain glaciation and landscape evolution in foreland desert regions. Quat Int, 2002, 97-98: 155—166
51 Xia J, Zuo Q T, Shao M C. Sustainable use of water resources in Bosten Lake. -Theory·Method·Practice. Beijing: Science Press (in

Chinese), 2003. 42—85
52 Jones P D, New M, Parker D E, et al. Surface air temperature and its changes over the past 150 years. Rev Geophys, 1999, 37(2): 173—199
53 Qian W H, Zhu Y F. Climate change in China from 1880-1998 and its impact on the environmental condition. Climatic Change, 2001, 50: 419—444
54 Shi Y F, Shen Y P, Hu R J. Preliminary study on signal, impact and foreground of climatic shift from warm-dry to warm-humid in Northwest China. J Glaciol Geocryol (in Chinese), 2002，24(3): 219—226
55 Ding Z L, Han J M, Yang S L, et al. A brief introduction of loess deposits in southern Tajikistan. Quaternary Sci (in Chinese), 2000, 20(2): 171—177
56 Tian W C. ed. Bohu County Annals. Urumchi: Xinjiang University Press (in Chinese), 1993. 73
57 Mahpir J, Tursunov A A, eds. An introduction to the hydro-ecology in the central Asia. Urumchi: Xinjiang Science, Technology and Hygiene Press (in Chinese), 1996. 149
58 Boomer I, Aladin N, Plotnikov I, et al. The palaeolimnology of the Aral Sea: a review. Quaternary Sci Rev, 2000, 19: 1259—1278
59 Hoogendoorn R M, Boels J F, Kroonenberg S B, et al. Development of the Kura delta, Azerbaijan; a record of Holocene Caspian sea-level changes. Mar Geol, 2005, 222-223: 359—380
60 Qin B Q, Shi Y F. Changes of the inland lakes of Asia since Holocene. In: Shi Y F, ed. Advances on studies of climate in China and sea level variation (I). Beijing: Ocean Press (in Chinese), 1992. 134—135
61 Liu K B, Yao Z J, Thompson L G. A pollen record of Holocene climatic changes from the Dunde ice cap, Qinghai-Tibetan Plateau. Geology, 1998, 26(2): 135—138
62 Ma J Z, Li D, Zhang J W, et al. Groundwater recharge and climatic change during the last 1000 years from unsaturated zone of SE Badain Jaran Desert. Chin Sci Bull, 2003, 48(14): 1469—1474
63 Yang X D, Wang S M, Kamenik C, et al. Diatom assemblages and quantitative reconstruction for paleosalinity from a sediment core of Chencuo Lake, southern Tibet. Sci China Ser D-Earth Sci, 2004, 47(6): 522—528
64 Wang J B, Zhu L P. Grain size characteristics and their paleoenvironmental significance of Chen Co Lake sediments in Southern Tibet. Prog Geog (in Chinese), 2002, 21(5): 459—467
65 Bard E, Raisbeck G, Yiou F, et al. Solar irradiance during the last 1200 years based on cosmogenic nuclides. Tellus Ser B, 2000, 52(3): 985—992
66 Briffa K R, Jones P D, Schweingruber F H, et al. Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. Nature, 1998, 393: 450—455
67 Silva S D, Zielinski G A. Global influence of the AD 1600 eruption of Huaynaputina, Peru. Nature, 1998, 393: 455—458
68 Chapron E, Desmet M, De Putter T, et al. Climatic variability in the northwestern Alps, France, as evidenced by 600 years of terrigenous sedimentation in Lake Le Bourget. Holocene, 2002, 12(1): 59—68
69 Gong D Y, Zhou T J, Wang S W. Advance in the studies on North Atlantic Oscillations. Adv Earth Sci (in Chinese), 2001, 16(3): 413—420
70 Aizen E M, Aizen V B, Melack J M, et al. Precipitation and atmospheric circulation patterns at mid-latitudes of Asia. Int J Climatol, 2001, 21: 535—556