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Climate and environmental changes over the past 150 years inferred from the sediments of Chaiwopu Lake, central Tianshan Mountains, northwest China

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Abstract We used a 55-cm sediment core from shallow Chaiwopu Lake in the central Tianshan Mountains of Xinjiang, northwest China, to investigate climate and environmental changes in this arid region over the past ~150 years. The core was dated using ^{137}Cs. We compared temporal changes in several sediment variables with recent meteorological and tree-ring records. Organic matter had a positive correlation with the Palmer Drought Severity Index in the central Tianshan Mountains, and the δ^{13}C of organic matter had a positive correlation with regional temperature. We applied constrained incremental sum-of-squares cluster analysis to element concentrations in the core and identified three distinct zones: (1) 55–46 cm, ~1860–1910, (2) 46–26 cm, ~1910–1952, and (3) 26–0 cm, 1952–present. Between 1880 and 1910 AD, following the Little Ice Age (LIA), the sediment environment was relatively stable, climate was cold and dry, and the lake water displayed high salinity, in contrast to conditions during the LIA. During the LIA, westerlies carried more water vapor into Central Asia when the North Atlantic Oscillation was in a negative phase, and encountered the enhanced Siberia High, which probably led to increased precipitation. In the period 1910–1950 AD, the lake was shallow and the regional climate was unstable, with high temperatures and humidity. In the last ~15–20 years, human activities caused an increase in sediment magnetic susceptibility, and heavy metal and total phosphorus concentrations in the sediment were substantially enriched. Mean annual temperature displays a warming trend over the past 50 years, and the lowest temperature was observed in the 1950s. There has been an increase in annual total precipitation since the 1990s. The combined influences of climate and human activity on the lake environment during this period were faithfully recorded in sediments of Chaiwopu Lake. This study provides a scientific basis for environmental management and protection.

Keywords Lake sediment · Climate and environmental change · Chaiwopu Lake · China

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Introduction

The average surface temperature on Earth has increased since 1861, and current climate instability is greater than during any previous period (IPCC 2007). Arid regions are predicted to be among the ecosystems most affected by global climate change (Melillo et al. 1993). Evaluation of the responses of arid environments to global climate requires further data collection, experimental work, modeling, and interdisciplinary exchange to improve our understanding of climate–ecosystem interactions at various spatial and temporal scales (Lioubimtseva 2004). In recent years, records of climate change for the past few centuries and millennia have been the focus of attention of many geoscientists (Bradley 2000; Crowley 2000; Wu et al. 2009), and several well-dated, high-resolution paleo-moisture records have been obtained across the arid region of central Asia (Chen et al. 2006; Sorrel et al. 2006; Austin et al. 2007; Ma et al. 2011a). Chen et al. (2010) developed a synthesized moisture index curve over the past

millennium, which shows a relatively dry Medieval Warm Period, a moist Little Ice Age, and increasing humidity during the recent period of global warming. Instrumental records indicate that aridity has increased across the entire Central Asian region over the past century, especially in the western region, and that decreases in precipitation are accompanied by temperature increases (Lioubimtseva and Henebry 2009). It is, however, difficult to determine whether climate changes over different timescales are analogous. The past century is the key for understanding climate variability because it marks the period of change from a climate system dominated by natural influences to one dominated by anthropogenic activities (Brönnimann et al. 2007). Unfortunately, in arid northwest China, there are instrumental records for regional climate and environmental change for only the past ~50 years. Li et al. (2006a) reconstructed moisture variations for the central Tianshan Mountains using tree-ring data from the past 100 years, but the limited number of paleo-climate data and instrumental records are insufficient to provide a complete picture of climate change in this region. It is crucial to extend the record of climate variability beyond the era of instrumental measurements to understand the range of natural climate variability and the rate at which climate change may occur.

Lake sediments are composed of allochthonous materials derived from the watershed and autochthonous materials from the lake itself and can provide information pertaining to lake evolution and environmental change in the surrounding watershed (Engstrom and Wright 1984; Ma et al. 2011b). Chaiwopu Lake is located in the central area of the Tianshan Mountains, Xinjiang, northwest China, and possesses a sensitive ecological zone. The Chaiwopu Basin is the airflow exchange channel between the north and south Xinjiang. In the past 30 years, the lake has undergone great changes in water surface area, resulting in some serious environmental impacts on this ecologically vulnerable, continental, arid region (Ma et al. 2011c). Shi et al. (1990) inferred Quaternary climate and hydrological changes in this lake by analyzing a 500-m sediment record. Wang and Jiao (1989) reconstructed lake-level variations and regional climate change during the Holocene. Both studies focused on climate and environmental change over very long timescales. In this study, we developed a sediment age–depth model using ^{137}Cs. High-resolution sampling and measurement of sediment variables enabled us to explore the trajectory of recent climate and environmental change, which will assist in providing a scientific basis for environmental management and protection.

Environmental setting

Chaiwopu Basin is a small, inter-montane structural basin in the central Tianshan Mountain area, northwest China.

Yilianhabierga Mountain lies south of the basin and has an elevation of 4,483 m above sea level (a.s.l.), and to the north is Bogeda Mountain (5,445 m a.s.l.). Chaiwopu Basin is connected with the Junggar Basin to the west, and the Baiyanggou River links it with the Turpan Basin to the southeast. Chaiwopu Lake is situated in Dabancheng District, approximately 45 km southeast of Urumqi, Xinjiang, northwest China (Fig. 1a). The lake is fairly round in shape and approximately 5–6 km in diameter. The lake water level was 1,903.86 m a.s.l. with a lake area of 30 km^2 in 1971, but fell to 1,901.66 m a.s.l. with an area of 27 km^2 in 2008. The average water depth is ~2 m with a maximum depth of ~4 m (Fig. 1b). The lake is brackish, with a salinity of 6.8 g/l. It has a transparency of 18 cm, a pH of 9.04, and an average conductivity of 0.867 S/m. Chaiwopu Lake is covered with ice from mid-November to late March or early April. It is a natural cold-water lake that receives water from several streams running from Bogeda Mountain. The lake and its surroundings have been officially protected since 2009, when Urumqi Chaiwopu Lake National Wetland Park was created by the State Forestry Administration of China.

The meteorological stations of Dabancheng (43.3627°N, 88.3116°E; 918.7 m a.s.l.) and Urumqi (43.8259°N, 87.6174°E; 1,105.3 m a.s.l.) have recorded the mean
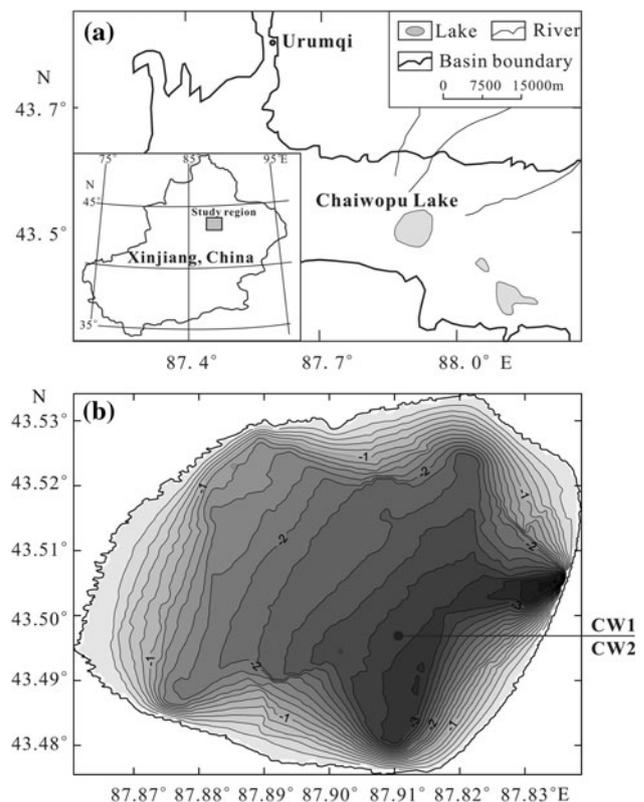

Fig. 1 Maps showing the study site (**a**) and bathymetry of Chaiwopu Lake with core location (**b**)

annual temperature and the annual total precipitation during the past 50 years (Fig. 2). Mean annual temperature rose gradually since the late 1950s, and stable higher temperatures have been maintained in recent years. Annual total precipitation increased since 1980 AD, whereas it has decreased over the last 10 years.

Materials and methods

Sediment cores were obtained from the center of Chaiwopu Lake (43.49445°N, 87.90087°E) (Fig. 1b) in July 2008 with a piston-percussion corer (Reasoner 1993) fitted with 60-mm-internal-diameter Perspex tubes. The parallel sediment cores were designated CW1 (47 cm) and CW2 (55 cm). The cores were extruded vertically in the field. CW1 was sampled at 0.5-cm intervals to a depth of 20 cm and at 1-cm intervals below 20 cm. Core CW2 was sampled at 1-cm intervals from the surface to the base. Each sample was sealed in a labeled plastic bag. CW1 was used for radiometric measurements of ^{137}Cs, and CW2 was used for analysis of multiple sediment variables. All analyses were carried out at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences.

Subsamples of dried sediments were analyzed for ^{137}Cs by direct gamma spectrometry using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al. 1986). ^{137}Cs was measured by its emissions at 662 keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low-energy gamma rays within the sample (Appleby et al. 1992).
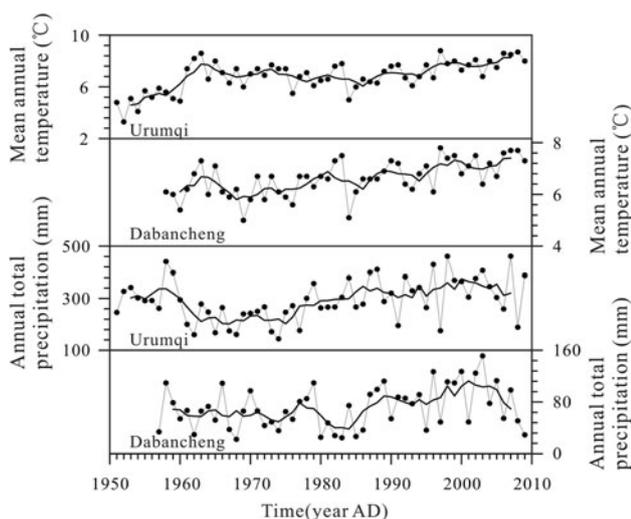

Fig. 2 Curves of mean annual temperature and annual total precipitation with 5-year moving average (*solid lines*) in the region of Chaiwopu Lake

Grain size distribution of the samples was determined with a Malvern Mastersizer 2000 analyzer with a measurement range of 0.02–2000 μm. Samples were pretreated with 10–20 ml of 30 % H_2O_2 to remove organic matter and then with 10 ml of 10 % HCl to remove carbonates. Approximately 2,000 ml of deionized water was added, and the sample solution was stored for ~24 h to remove acidic ions. Finally, the sample residue was treated with 10 ml of 0.05 M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 min, to facilitate dispersion before grain size analysis. The Mastersizer 2000 automatically yields the median diameter and percentages of the related size fractions of a sample with a relative error of <1 %.

Organic matter determined by loss-on-ignition (OM-LOI) was measured by sequential heating of the samples in a muffle furnace. After oven drying the sediment to constant weight (usually 12–24 h at ~100 °C), it was combusted at a temperature of 600 °C. Percent OM-LOI was calculated using the following equation: OM-LOI = $((D_{100} - D_{600})/D_{100}) \times 100$, where D_{100} represents the dry weight of the sample before combustion and D_{600} the dry weight of the sample after heating to 600 °C.

The geochemical element contents were analyzed with a Leeman Labs Profile ICP-AES for samples treated with HF–HNO$_3$–HClO$_4$ in a Berghof MWS-3 microwave digester. The relative error scale of parallel samples was determined to be <5 %. Magnetic susceptibility (MS) of each sample was determined with a Bartington MS2 susceptibility meter (Bartington Instruments, Oxford, England). Magnetic susceptibility was measured in the laboratory with a Bartington MS2 meter linked to a MS2B dual-frequency sensor (Bartington Instruments Ltd.). The sensor operates with an alternating current producing an alternating magnetic field (80 A/m, Bartington Instruments Ltd., 2000). The MS2B dual-frequency sensor is used with 10-ml sample containers. In this study, low frequency is selected, three measures of MS were taken from each sample and the average was found.

Samples dried for isotopic analysis of organic matter were leached with HCl (~3N) to dissolve carbonate, rinsed copiously with distilled water to remove chloride, dried at low temperature (at 80 °C), and ground into fine powder (<100 mesh). Each prepared sample was packed in tinfoil boats (150 μg of carbon) and combusted in excess of oxygen at 1,050 °C using an elemental analyzer (NA 1500, Fisons Instruments). The resulting CO_2 was isotopically analyzed online using a Finnigan MAT-251 multi-collector stable isotope ratio mass spectrometer. Isotope ratios are expressed in per milliliter (‰) relative to the international standard, Vienna Peedee Belemnite (V-PDB). The average reproducibility for ^{13}C of organic matter was 0.05 ‰.

Constrained incremental sum-of-squares cluster analysis (CONISS) (Grimm 1987) was applied using the program

ZONE, version 1.2, written by Juggins (2002), to identify statistically different zones in the core.

Results

Radiometric dating

The ^{137}Cs dating method uses ^{137}Cs activity in lake sediments, which originated from nuclear tests and nuclear plant accidents, as time horizon markers (Ritchie et al. 1973). In the Northern Hemisphere, ^{137}Cs first began to accumulate in 1952 AD, with the beginning of atmospheric atomic bomb testing. ^{137}Cs was first detected in the Chaiwopu Lake core at the depth of 26 cm, which was assigned a date of 1952 AD (VandenBygaart et al. 1998). Peak activity at 20 cm depth is associated with peak testing of nuclear weapons in 1963 AD (Miller and Heit 1986), which produced considerable atmospheric ^{137}Cs fallout. The surface layer corresponds to the time of sampling in 2008 AD. Assuming that 26–20 cm corresponds to 1952–1963 AD, 20–0 cm corresponds to 1963–2008, and the entire period from 26 to 0 cm represents sedimentation from 1952 to 2008, we can calculate linear sedimentation rates for the periods of 5.5, 4.4, and 4.6 mm/a, respectively. The bottom of the core (55 cm) corresponds to about 1880 AD by downward extrapolation of the average linear sedimentation rate. The age model for the Chaiwopu Lake sediment core was established using these values and appears in Wu and Ma (2010) (Fig. 3).

Element content

The content of elements varied throughout the core (Fig. 4). Trends in element content fall into three categories: (1) Concentrations of Al, Na, K, Ba, and Ti are lowest at the core base and increase sharply at 45 cm depth, (2) Ca, Sr, and Mg showed similar trends in variation and are negatively correlated with elements in the first group, and (3) stratigraphic variations in all heavy metals are similar and display concentration differences above and below 46 cm. They are relatively low and stable from 55 to 46 cm depth and then increase in the upper part of the core, particularly above 9 cm. The lowest value was found at 45 cm.

The geochemical composition of the lake sediment is related to the lake water chemistry and is also influenced by the geological and geochemical background and weathering intensity. Regional humidity changes were inferred from the ratio of immobile to mobile elements [C index; $C = \sum(Fe + Al + Mn + Cr + Co + Ni)/\sum(K + Na + Ca + Mg + Sr + Ba)$] (Chen et al. 1990; Wu 1995). Increases in the Sr/Ca ratio indicate desiccation of the lake and enhanced lake salinity (Chen et al. 1999).
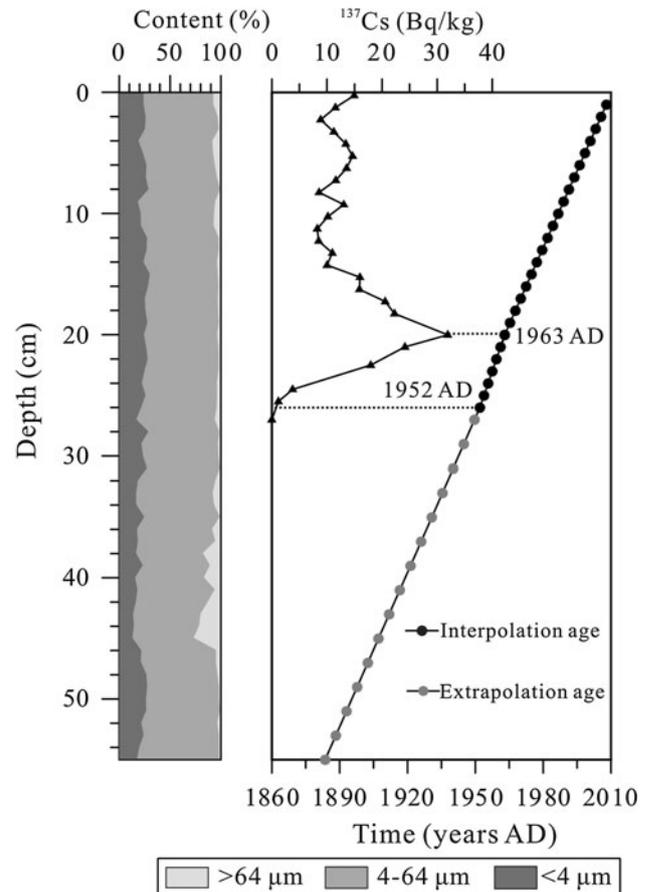

Fig. 3 Distribution of ^{137}Cs-specific activity and age–depth relations based on ^{137}Cs dating. *Column* on the *left* shows the grain size distribution of the sediment core

CONISS was applied to multiple variables in the sediment core to examine major changes during the past ~150 years. The core was divided into three sections: below 46 cm (prior to 1909), 46–26 cm (1909–1952), and 26–0 cm (1952–2008) (Fig. 4).

Sedimentology

Sediment grain size fractions of (<4 μm), (4–64 μm), and (>64 μm) were generally about 22.6, 71.7, and 5.7 %, respectively, throughout the sediment core. Maximum grain size was measured at depths from 45 to 33 cm, where the percent of the >64 μm fraction increased to an average of ~12.6 %, with a notable peak value of 26.9 % at 45 cm (Fig. 3). Generally, surface runoff is high, and its erosion force is strong enough to carry coarse terrestrial particles to the lake's deep-water area, where they are deposited (Chen et al. 2004). Under extremely dry conditions, the smaller lake area decreased the distance required for the transport of large particles to the core site, resulting in an increased grain size. But the size–frequency distribution curves did

Fig. 4 Vertical distribution of element contents in Chaiwopu Lake sediment core with CONISS results
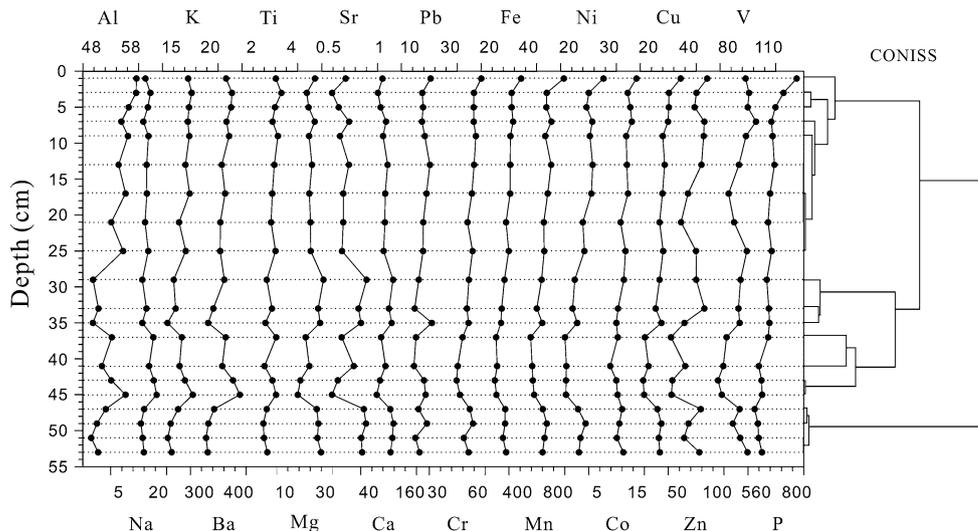

not approach a normal distribution in the whole Chaiwopu Lake sediment (Fig. 5a), which suggests that at least two different factors influenced the composition of lake sediments. So the changes in sediment environment cannot simply be explained using the aforementioned issues.

Subpopulations of sediment grain size were identified by calculating the standard deviation (Boulay et al. 2003; Liu et al. 2005; Guan et al. 2010); standard deviation values for each grain size class are displayed in Fig. 5b. The peak values of standard deviation correspond to the modal grain sizes of each environmentally sensitive grain size population. Two peaks occur, at 7 and 60 μm, and the boundary of

the fine/coarse grain size populations is around 20 μm (Fig. 5b). The >209 μm size fraction of Core CW2 is not shown in Fig. 5 because the proportions of this population are generally <1 %. Figure 5 shows variations in the content and average particle size of the fine and coarse grain size populations versus depth. At depths of 45, 11, and 4 cm (Fig. 5), the proportions of the two populations display marked variability attributed to two environmental events. Average particle size of the fine and coarse grain size populations is consistent with the Loess of the Urumqi River Basin (Gao and Liu 1990), suggesting the coarse grain size populations are carried by

Fig. 5 a Grain size distribution curves of typical sediments. **b** Standard deviation values versus grain size of sediment core CW2. **c** The content of separated fine grain size populations. **d** The content of separated coarse grain size populations. **e** The average particle size of fine grain size populations. **f** The average particle size of coarse grain size populations
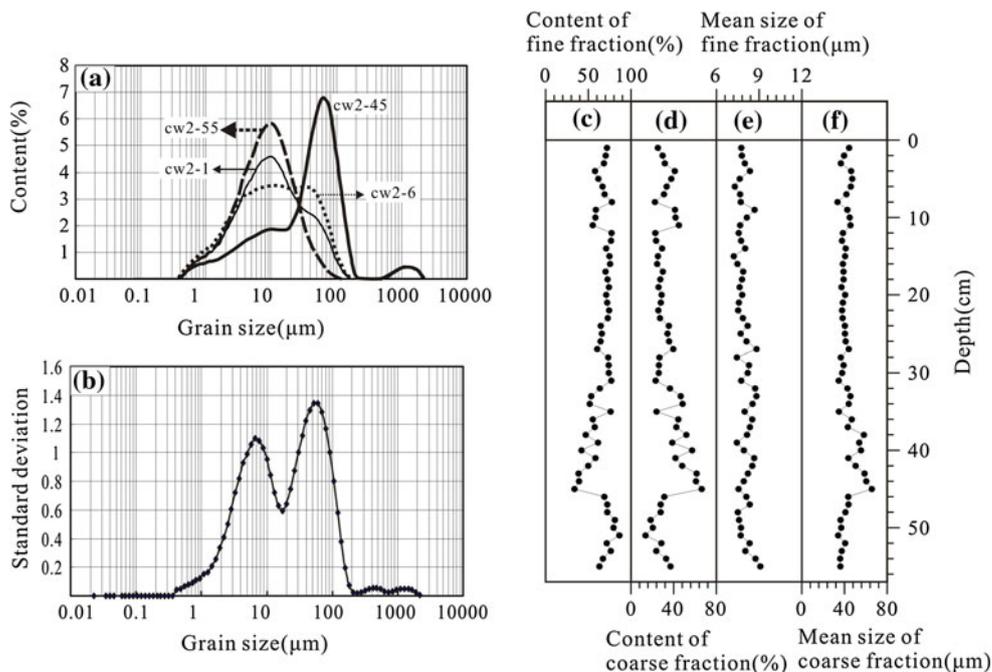
wind. Smaller variability in the grain size records from 55–45 to 33–10 cm indicates that the sedimentary environment was relatively stable during the deposition of this material.

Organic matter in the lake sediment is a mix of aquatic and terrestrial plant debris, the latter resulting from watershed erosion (Meyers and Teranes 2001). The organic matter content can thus be used to reconstruct paleoenvironments of lakes and their watersheds and to infer past regional climate change (Brenner et al. 1999). In arid/semi-arid areas, regional moisture is the main factor influencing plant growth (Ma et al. 2011a). In humid climates, plants grow vigorously, leading to a higher content of organic matter in lake sediments, whereas under arid conditions, plant growth is limited and organic matter content in lake sediments is lower. The lower OM-LOI content indicates drier climate period, while the higher reflects wetter climate interval (Liu et al. 2002; Wu et al. 2009; Oldfield et al. 2010; Zhong et al. 2010). The OM-LOI variations are consistent with Palmer Drought Severity Index (PDSI) of the central Tianshan Mountain area in northwest China (Fig. 6e) (Li et al. 2006a). The OM-LOI indirectly reflects humidity variation in Chaiwopu Lake region. OM-LOI analysis showed values between 3.7 and 6.3 %. The OM-LOI below 35 cm is relatively low, with an average of ∼4.3 %, whereas above 35 cm, it increases to an average of ∼5.4 % (Fig. 6f).

Magnetic minerals in the sediment mainly originate from basin surface material. High MS values are considered to be a sign of stronger erosion (Hu et al. 2002). The average MS value is approximately 1.8×10^{-8} m^3 kg^{-1}. Below 26 cm, the MS is low, with an average

0.9×10^{-8} m^3 kg^{-1}. In the upper 26 cm, the MS increases to 2.8×10^{-8} m^3 kg^{-1}, the highest value in the entire section (Fig. 6d).

The carbon isotope of bulk organic matter depends on several factors, such as sources of organic matter, biological productivity, intensity of photosynthesis, hydrological conditions, sediment environment, reservation of lake sediment and so on (Hayes 1993; Kump and Arthur 1999; Wu et al. 2007). Chaiwopu Lake is a natural cold-water body, so the aquatic biological activities are more closely related to the water temperature. It was revealed that organic carbon isotopes reflected the regional temperature change in accordance with the sediment records for Xingcuo Lake, located on the Tibet Plateau (Wu et al. 2007). The $\delta^{13}C_{org}$ correlated with the mean annual temperature in Urumqi. It is also positively correlated with the Northern Hemisphere temperature (Fig. 6h) (Jones and Moberg 2003). In the Chaiwopu Lake sediment, $\delta^{13}C_{org}$ ranges from −24.2 to −26.5 ‰, with a mean value of −25.5 ‰. There are three large negative shifts occurring at 1890 AD, 1910 AD, and 1960 AD. The $\delta^{13}C_{org}$ curve shows a gradual increase to −24.2 ‰ at the top of the core (Fig. 6g). The implied climate and environmental changes were proved using instrumental data, which indicates that environmental information was effectively preserved in the lake sediment.

Discussion

CONISS analysis of element and other sediment data enabled division of the Chaiwopu Lake core into three

Fig. 6 a The content of coarse grain size populations. b The molar ratio of Sr/Ca. c The value of C index. d The values of magnetic susceptibility (MS). e The values of Palmer Drought Severity Index (PDSI). f The organic matter content determined by loss-on-ignition (OM-LOI). g $\delta^{13}C$ values in organic matter ($\delta^{13}C_{org}$). h The Northern Hemisphere temperature anomalies
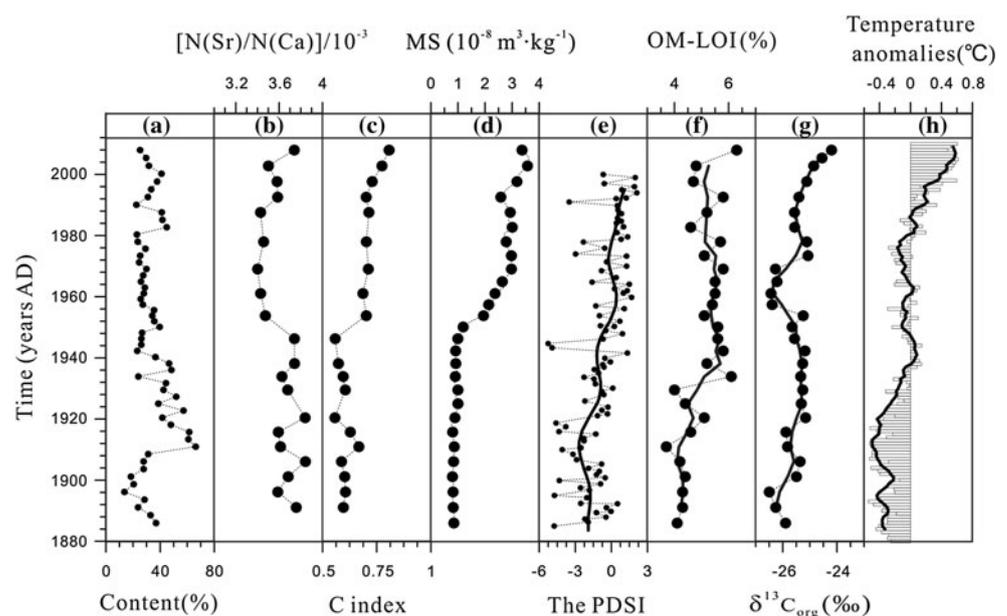
zones, which reflect three distinct climate and environmental periods:

1. The first period was from about 1880 to 1910 AD. The average particle size, element content, OM-LOI, and MS were relatively constant, which reflects a relatively stable sediment environment. The $\delta^{13}C_{org}$ values were relatively low, indicating that the climate was quite cold at this time. During this period, the lake sediment consisted mainly of fine-grained particles (Fig. 6a). There is no significant variation in the median grain size, which reflects the stable hydrodynamic conditions. Values of the C index were relatively low (Fig. 6c) and Sr/Ca was relatively high (Fig. 6b), suggesting that regional climate was dry and lake water salinity was high. These data indicate a relatively stable aquatic environment, with high salinity, under cold and dry climate conditions, after the Little Ice Age.

2. The period from 1910 to 1950 was the second stage. In this period, geochemical indicators OM-LOI and grain size fluctuated significantly. $\delta^{13}C_{org}$ increased. In this period, values of the C index were low and Sr/Ca remained high, suggesting that lake water was shallow and the regional climate was unstable, with generally higher temperature and humidity. Contents of mobile elements (Mg, Ca, and Sr) are lower (Fig. 4), which suggests that the chemical weathering intensity was still weak.

3. In the last 50 years, which correspond to the upper 25 cm in the core, and the 50-year instrumental data from the Urumqi meteorological station, the MAT displays a warming trend, and the lowest temperature was observed in the 1950s. The $\delta^{13}C_{org}$ also decreased. Variations in annual total precipitation were more complex, and there was a significant increase in ATP since the 1990s. According to satellite images collected at different times, along with respective topographic maps, Chaiwopu Lake has remained stable, with fluctuations in total area of <2 km^2 (Ma et al. 2011c). The grain size remained relatively constant, so the water body was relatively stable. MS is very different from that measured in previous periods, indicating greater erosion of the Chaiwopu Basin, perhaps caused by human activity. The high value of the C index suggests a high moisture condition in the watershed during this period, a better soil-vegetation environment, and more surface runoff. The low molar Sr/Ca supports this interpretation. Increases in heavy metal and total phosphorus (TP) concentrations were likely influenced by enhanced human activity.

Xinjiang is a unique dry area where atmospheric circulation is dominated today by westerlies. It is one of the arid regions that will likely be strongly affected by global warming. Climate change in northwest arid China has shown characteristics similar to the global warming trend over the last 1,000 years reconstructed from lake sediments (Chen et al. 2010; Wu et al. 2009) and ice cores (Yao et al. 1996), but precipitation here possesses a distinct regional characteristic: dry during warm periods and humid in cold periods. In this study, we found that the climate in this area was cold and dry during the period 1880–1910 AD. Climate and environmental patterns at 100-year timescales, however, are not consistent with the millennial timescale inferred from the Ebinur Lake sediment records. The isotope records from Lake Ebinur were inversely correlated with the Siberia High record during the Little Ice Age, perhaps reflecting the possibility that the westerlies carried more water vapor into Central Asia during the cold period when the North Atlantic Oscillation was in a negative phase (Ma et al. 2011a). When this moisture-rich air mass encountered the enhanced Siberia High, it would have led to increased precipitation (Ma et al. 2011a).

Global warming will have a large impact around the globe, causing differences in precipitation distribution, hydrological cycles, and effective moisture changes. In the Chaiwopu region, the climate became warmer and moister beginning about 1950 AD. Shi et al. (2007) considered that a warm–moist transition may occur in northwest China, based on the instrumental data and glacier and lake changes over the last 50 years. Global warming enhanced the water cycle during this period, and the atmospheric water vapor from the Indian Ocean, the south of the Arabian Sea, and portions of the west and northern parts of the Atlantic Ocean and the Arctic Ocean increased as a consequence of these changes in climate. In recent years, however, increasingly warmer and drier climate raises great uncertainty concerning future climate trends in arid regions. Climate instability, with strong moist/dry fluctuations in recent years, was the most apparent feature of climate change in Xinjiang.

Around 1910 AD, particle size showed a sudden change, and the organic carbon isotopes and OM-LOI element content underwent significant fluctuations. Coarse aeolian sands became part of the lake sediment composition. The CONISS results show a boundary at 45 cm ($\sim$1910) (Fig. 4), which indicates that a sudden climate and environmental change occurred. Global and Northern Hemisphere temperature experienced a significant change about 1910 (Jones and Moberg 2003; Brohan et al. 2006), and in the arid region of northwest China, PDSI also showed the central Tianshan Mountain area was dry at this time (Li et al. 2006a), consistent with the hypothesis that dry climate provides abundant material basis for sand storms, and explaining how the aeolian sands increased the sediment grain size in Chaiwopu Lake. Periods of high dust flux were also recorded in 1906, 1915, and 1919 from an

ice-core record in Chongce Ice Cap (6,350 m a.s.l.), west Kunlun Mountains, China (Li et al. 2006b). The Malan ice-core record also shows that the period 1910–1915 was a period of active dust events (Wang et al. 2007). All these data reflect the fact that climate and environment changed abruptly about 1910.

Conclusions

In the 150-year Chaiwopu Lake sediment record, organic matter content reflects the regional total annual precipitation, and the stable carbon isotopes of organic matter correlates with regional temperatures. We compared these findings with results from previous studies and found that the organic matter variations are consistent with PDSI in the central Tianshan Mountains of northwest China.

We analyzed grain size, organic matter content, $\delta^{13}C$ in organic matter, and magnetic susceptibility and conducted a CONISS analysis of element content, to infer regional climate and environmental change in the area over the past 150 years. Lake level was high, and climate was cold and dry between 1880 and 1910. During the period 1910–1950, multiple sediment variables indicate increased regional temperature and humidity but relatively weak chemical weathering. Lake conditions remained similar to those of the former period, but with higher salinity. In particular, an abrupt climate and environmental event occurred about 1910.

Human impacts on lake environment over the past 50 years have caused an increase in magnetic susceptibility and led to greater concentrations in the sediment of heavy metals and total phosphorus. Variations in the stable carbon isotope values of organic matter are consistent with the instrumentally recorded temperature changes. This will enable the calibration of the isotope record to climate data and provide a quantitative basis for inferring historical climate and environmental change.

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