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Possible solar forcing of 400-year wet–dry climate cycles in northwestern China

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Abstract Here we present a multi-proxy paleolimnological record from a closed-basin lake (Ebinur Lake) in northwestern China to investigate climate change in this arid region during the last 1,500 years. The 120-cm long sediment core was dated by AMS radiocarbon and ^{210}Pb methods. The fine-grained clay sediments contain 3–17% organic matter (OM) and 9–31% carbonate, and are interrupted by multiple sand and silt layers. These sand/silt layers, having consistently low OM, were found at 700–800, 1000–1100, 1300–1400, and 1700–1750 A.D., with a time spacing of 300–400 years. We interpret that the low OM sand/silt layers were deposited during higher lake levels caused by increased river inflow from the surrounding mountains during wet climate intervals. This interpretation is supported by concurrent decreases in δ^{18}O and δ^{13}C of bulk carbonate and in carbonate content. Wet climate intervals at 700–800 A.D. and at 1700–1750 A.D. also correlate with elevated snow accumulation and low δ^{18}O from Guliya ice core on the NW Tibetan Plateau, both regions strongly

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influenced by the westerlies. This approximate 400-year periodicity of wet–dry climate oscillations appear to correlate with solar activity as shown by atmosphere ^{14}C concentration and with paleo-moisture records in interior North America. Our results suggest that solar activities might have played a significant role in driving wet–dry climate oscillations at centennial scales in the interior of Eurasian continent.

1 Introduction

It has become increasingly important to document and understand natural climate variability in the geological past using proxy records, as instrumental records are too short (<150 years) to reveal the full natural climate variability. In recent years, there have been increased efforts in studying climate changes during the Holocene (e.g., Gasse et al. 1991; Shi et al. 1993) and the last two millennia (e.g., Yang et al. 2002; Crowley 2000). However, there are few multiple proxy records available from arid region in central Asia, and as a result the forcing mechanisms of regional climatic change are poorly understood. Climate change would have major social and economic impacts in these ecologically vulnerable, continental, arid and semi-arid regions, such as in northwestern China. Understanding past climate change and forcing mechanisms will provide useful insights into projecting and mitigating the possible future climate change.

In arid region, lake hydrology and preserved sedimentary records are sensitive to environmental changes. A recent synthesis of ice-core and tree-ring records indicates that the climate over the last 2,000 years shows large variations on the Tibetan Plateau and in eastern China, including the so-called Medieval Warm Period and Little Ice Age (Yang et al. 2002). However, high-resolution records from lake sediments are lacking, especially from the arid regions of northwestern China. Sediments in high salinity lakes contain precipitated carbonates, which can be analyzed for stable oxygen and carbon isotopic composition for paleoclimate reconstructions (Kelts and Talbot 1990; Wu et al. 2004).

Here we present a high-resolution paleoclimate record from Ebinur Lake in northwest China to investigate changes in moisture conditions during the last 1,500 years. This study was built upon our previous work at the lake on climate and hydrological changes during the early and middle Holocene (Wu et al. 1993, 1996, 2005).

2 Study site

Ebinur Lake is located in northwest China near the border with Kazakhstan at 82°50′ E longitude and 45°00′ N latitude (Fig. 1). The lake is situated on a lacustrine plain at an elevation of 190 m above sea level, surrounded by Ala Mountain to its north and northwest, Boer Tala valley to its west, Jing River pluvial fan to its south, and sand dunes around Kuitun River to its east. Ala Mountain Pass to the northwest is a well-known wind passage, with a maximum wind speed of 55 m/s and on average 164 days per year having wind speed >20 m/s. The mean annual precipitation around the lake is about 95 mm, while annual evaporation amounts to 1,315 mm. Regional vegetation is temperate desert.

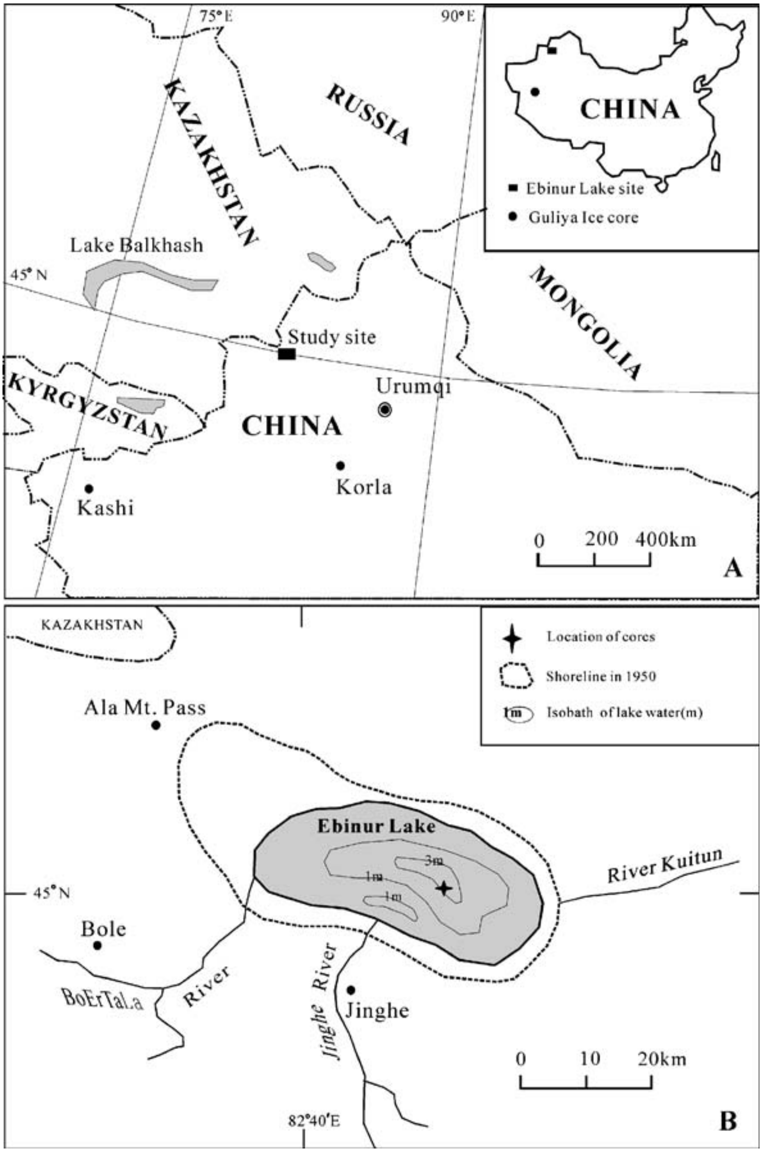

Fig. 1 Location maps. **a** Location of Ebinur Lake in northwest China (black rectangle). *Inset* shows locations of Ebinur Lake and Guliya ice core in China. **b** Bathymetry of Ebinur Lake and coring location

The lake has a surface area of 542 km^2 with a drainage area of 50,321 km^2, including 24,317 km^2 of mountainous area. Ebinur Lake is mainly supplied by Bo River and Jing River that originate from the mountain regions to the southwest and south of the lake. The lake has a maximum water depth of 3.5 m and an average depth of 1.2 m. The lake has a salinity of 85–124 g/L in total dissolved solids.

3 Methods

3.1 Field coring

Two sediment cores were extracted on 20 August 2001 from the center of the lake at 3.5 m water depth (Fig. 1) using a piston-percussion corer (Reasoner 1993), fitted with 60 mm internal diameter perspex tubes. The cores AB01 and AB02 were taken about 0.5 m apart and are 120 cm and 65 cm long, respectively. Both cores were extruded vertically in the field and subsampled at 0.5-cm intervals down to 20 cm in depth and at 1-cm intervals below 20 cm. Each subsample was sealed in a labeled plastic bag. Sediment samples from core AB01 were used for multi-proxy analyses and ^{14}C age determinations, whereas samples from core AB02 were used for ^{210}Pb dating.

3.2 Sediment geochemical analyses

Loss-on-ignition of the sediment samples was determined by combustion at 550°C for two hours to estimate organic matter (OM) content and at 1,000°C to estimate carbonate content. Based on 15 replicate analyses, analytical error of the LOI method was ±0.5%.

Organic samples for isotopic analysis were treated with 3-N HCl to remove carbonate and rinsed repeatedly with distilled water. Analysis of ^{13}C in OM was conducted using a Finnigan MAT-251 multi-collector stable isotope ratio mass spectrometer at the Nanjing Institute of Soil Science, Chinese Academy of Sciences. The reproducibility for ^{13}C of OM is 0.05‰. Authigenic carbonate samples for ^{18}O and ^{13}C analysis were reacted with 100% phosphoric acid, following the standard procedure of McCrea (1950). The evolved CO_2 was dried and purified in a gas-transfer system under vacuum. The reproducibility of the analyses was ±0.15‰ for ^{18}O and ±0.05‰ for ^{13}C.

For stable isotopic analysis of ostracode shells, the valves of dominant species *Ilyocypris bradyi* Sars were picked, cleaned with a 5% H_2O_2 solution for 15 min, rinsed in distilled water, and stored in liquid ethanol (100%). A total of 5 to 16 shells per sample (ca. 30 μg) were used to determine oxygen and carbon isotope compositions by reaction with 100% phosphoric acid at 70°C on a Finnigan MAT 252 with a Kiel Carbonate Device III, fitted with an automated Isocarb common acid bath preparation system in the Institute of Earth Environments, CAS. Analytical reproducibility is better than ±0.08‰ and ±0.2‰ for ^{13}C and ^{18}O, respectively. All isotopic results were reported in δ notation in per mil (‰) relative to the international standard Vienna Peedee belemnite (V-PDB).

3.3 Radiometric dating

Sub-samples of dried sediment from core AB02 were analyzed for ^{210}Pb and ^{226}Ra by direct gamma spectrometry using Ortec HPGe GWL series, well-type, coaxial, low background, intrinsic germanium detectors (Appleby and Oldfield 1978). ^{210}Pb activity was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV-rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known ^{210}Pb activity. Corrections were made for the effect of self-absorption of low energy-rays within the sample. Supported ^{210}Pb in each sample was assumed to be in equilibrium with in situ ^{226}Ra. Unsupported ^{210}Pb activity at each depth was calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity.

The radiocarbon (^{14}C) activity of one bulk organic matter from the 107 cm depth in core AB01 was measured by accelerator mass spectrometry (AMS) at the State Key Accelerator Mass Spectrometry Laboratory of Beijing University. Radiocarbon date was ^{13}C-corrected and calibrated to calendar ages using IntCal04 dataset (Reimer et al. 2004).

4 Results

4.1 Age model and chronology

The unsupported ^{210}Pb activity in the Ebinur core declined from 82 Bq/kg at the core surface to a constant level at 8 cm (Fig. 2a). The 8-cm horizon was assigned an age of 1850 A.D. The chronology of the top 8 cm was determined using the stratigraphic

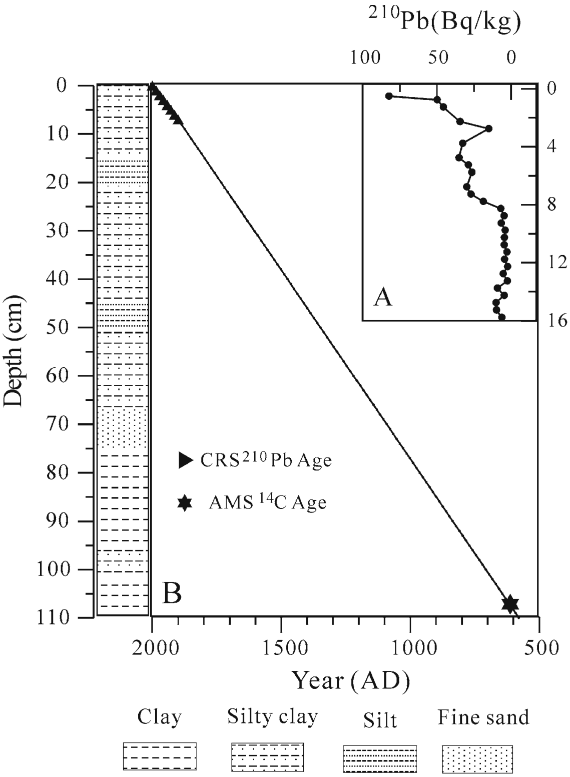

Fig. 2 Lithology and age model at Ebinur Lake. **a** ^{210}Pb versus depth in core AB02. **b** Depth–age relation based on ^{210}Pb dating and radiocarbon date. *Column on the left* shows lithological change in the core

decay profile of unsupported ^{210}Pb activity and the constant rate of supply (CRS) model of Appleby and Oldfield (1978). ^{210}Pb result confirms the presence of present-day sediment surface.

The AMS^{14}C date at 107 cm is $1,410 \pm 70^{14}$C year BP (lab # BA01149). Ages for the samples between the sediment surface and 107 cm were derived by linear interpolation between calibrated radiocarbon age of 630 A.D. (= 1320 cal year BP) and the sediment surface age (2001 A.D.). Calculated average sedimentation rate was 0.69 mm year^{-1}. Extrapolation of this age model yielded an estimated age of 580 A.D. for the bottom of the core.

4.2 Sediment lithology and composition

The sediment is dominated by grey-colored clay and silty clay, with four distinct light brown fine sand or silt layers (Fig. 2). The core contains 3–17% in organic matter and 9–31% in carbonate (Fig. 3). XRD analysis of selected samples indicates that carbonate in sediments is dominated by aragonite (>70% on average). The coarse sediment layers consistently have low OM content (3–8%).

4.3 Oxygen and carbon isotope results

Carbon and oxygen isotope results from bulk carbonate and ostracode shells and carbon isotope from organic matter are presented in Fig. 3. δ^{18}O values from bulk carbonate range from −8.1 to −2.1‰, and δ^{13}C from −1.5 to 1.6‰, both having a tendency to co-vary. The δ^{18}O values are around −4‰ before 1350 A.D., but show

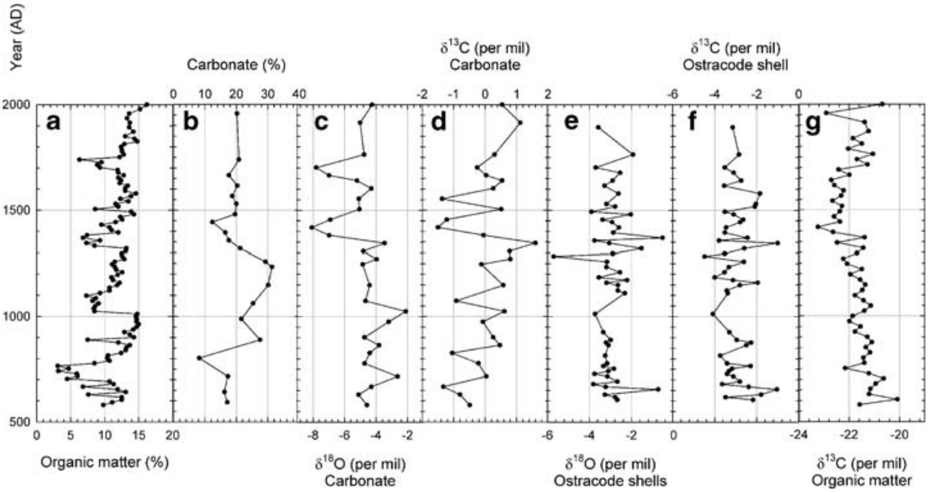

Fig. 3 Multiple proxy records from Ebinur Lake. **a** Organic matter; **b** carbonate; **c** oxygen isotope from bulk carbonate; **d** carbon isotope from bulk carbonate; **e** oxygen isotope from ostracode shells (*Ilyocypris bradyi*); **f** carbon isotope from ostracode shells (*Ilyocypris bradyi*); **g** carbon isotope from bulk organic matter

large fluctuations after 1350 A.D. between −8.1 and −3.8‰. δ^{13}C values show a fluctuating increase from −1‰ to 1‰ from 550 to 1350 A.D. before a large drop of > 3‰ at 1350 A.D. Both δ^{18}O and δ^{13}C show several large negative excursions at ca.750, 1050, 1350 and 1650 A.D.

Isotope values from ostracode shells range from –5.9‰ to –0.3‰ in δ^{18}O and from −4.5‰ to −1‰ in δ^{13}C, which do not appear to co-vary. Ostracode isotopes appear to show less clear trends than isotopes from bulk carbonate. δ^{13}C values from organic matter range from –23.2‰ to –20.1‰, showing a declining trend from −21‰ at 550 A.D. to –23‰ at 1350 A.D. An increase to –21‰ occurred afterward.

5 Discussion

5.1 Paleolimnological interpretations

The oxygen-isotope composition of carbonates precipitated at isotopic equilibrium with the ambient water is determined by water temperature and the isotopic composition of the host water. The water isotopic composition is mainly controlled by (a) the composition of inflowing water, including precipitation of the region; and (b) lake hydrology and especially evaporative enrichment. At Ebinur Lake, the ratio of precipitation to evaporation (P/E) is the primary control of lake level (Wu et al. 1993), and isotopic enrichment intensity of the lake water. A decrease in δ^{18}O values largely reflects an increase in the P/E ratio within the basin, likely under wet (and/or cool) climate conditions with high precipitation and/or low evaporation.

Carbon isotopes in carbonate are controlled by isotopic composition in DIC (dissolved inorganic carbon) of the lake water. The major processes influencing the δ^{13}C value of the DIC are (a) photosynthetic activity of aquatic plants; (b) decay of organic matter; and (c) rate of exchange of CO_2 with the atmosphere (e.g., Talbot 1990). The absence of dense macrophyte cover within this highly alkaline lake suggests that the productivity may not have played a major role, at least from macrophytes. Bulk carbonates with a lower δ^{13}C are likely deposited in diluted alkaline lake during higher lake-level stages (e.g., Mayer and Schwark 1999). Isotopic covariance between δ^{18}O and δ^{13}C in authigenic carbonates is often used to indicate closed-basin lakes (Fritz et al. 1975; Talbot 1990; Lewis and Anderson 1992). The isotopic record from Lake Manas, a closed-basin lake in the same region as Lake Ebinur, shows the same hydrological regime (Wei and Gasse 1999), which is apparently identical with our data presented here (Fig. 3).

Isotopes from ostracode shells and organic matter show changes that do not correlate well with isotopes from bulk carbonate, but they may provide information on changes in limnological conditions and lake productivity. Higher δ^{13}C in organic matter indicates enhanced lake trophic conditions (Brenner et al. 1999; Teranes and McKenzie 1999). Between ca. 550 and 750 A.D. primary productivity levels might be high, as reflected in the elevated δ^{13}C values of organic matter (Fig. 3). We do not fully understand the reasons behind the different patterns in isotopic records of various sediment components. We suspect that the variable habitat of ostracode species and possible mixture of aquatic and terrestrial organic matter might have played an important role in causing these divergences.

5.2 Regional wet–dry climate oscillations and solar forcing

We interpret that the change in lithology reflects change in inflowing water, lake levels and climate, with coarse low-OM layers indicating high lake levels and wet climate. Ebinur Lake receives 78% of its water inflow from river runoff originating from the surrounding mountains, where 65% of annual precipitation falls in summer months from May to August. The coarse sand and silt layers are likely the lithological response to increased runoff and elevated detrital input during wet climate intervals. These high lake-level intervals occurred at 700–800, 1000–1100, 1300–1400 and 1700–1750 A.D. This interpretation is supported by lower carbonate contents at 800 and 1300–1450 A.D. (Fig. 3b). The concurrent drops in both δ^{18}O and δ^{13}C in bulk carbonate around 750, 1050, 1350 and 1650 A.D. strongly support the high lake-level. The shift around 1350–1400 A.D. appears to be the most dramatic change in lake level as indicated by bulk carbonate isotopes (Figs. 3c and d).

At Ebinur Lake four wet climate intervals marked with coarse low-OM layers, especially at 700–800 A.D. and at 1700–1750 A.D., correspond to the increased snow accumulation rate in Guliya ice core on the NW Tibetan Plateau (Yao et al. 1996; Fig. 4d). At the present both Ebinur Lake and Guliya ice cap are strongly influenced by the westerlies, and instrumental climate records from both regions show similar changes (Wang et al. 1998). Among the Ebinur Lake proxy records, δ^{13}C in organic matter shows some similarity to ice accumulation rates from Guliya ice core (Figs. 4c and d). This close correlation suggests that the δ^{13}C in organic matter might have recorded certain aspects of climate changes, perhaps through changes in the coverage proportion of C3 and C4 plants. It has been documented that δ^{13}C in organic

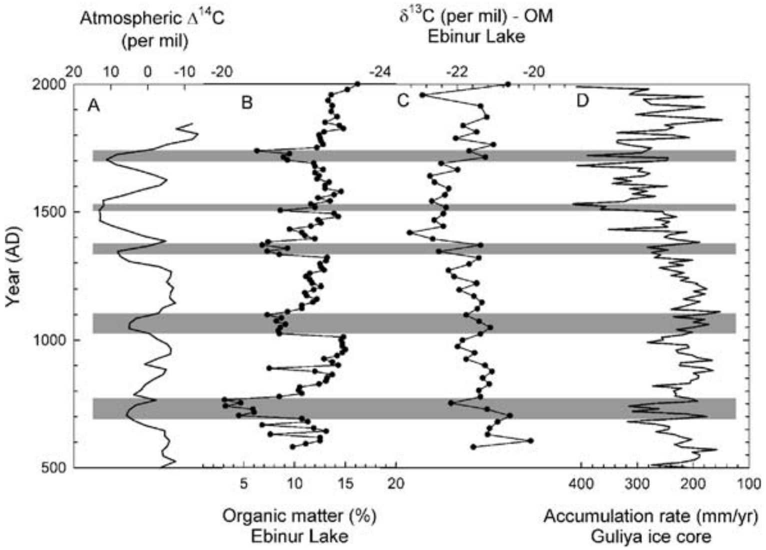

Fig. 4 Connection of records in Ebinur Lake and Guliya ice core and solar forcing. *Shaded zones* represent intervals with high lake levels at Lake Ebinur. **a** residual atmospheric radiocarbon concentration (Reimer et al. 2004); **b** organic matter at Ebinur Lake; **c** carbon isotope from bulk organic matter at Ebinur Lake; **d** snow accumulation at Guliya ice core (Yao et al. 1996)

matter from lake sediment in arid region correlates with precipitation amount (Wu et al. 2005; Huang et al. 2001). The dating uncertainty of our record and poor understanding of environmental controls of carbon isotopes in OM prevent us from detailed discussion.

Although both the Medieval period and the Little Ice Age (LIA) were hydrologically complex and neither can be characterized by uniformly wet or dry conditions, certain general structures and long-term patterns appear. The onset of the Mediaeval Warm Period (MWP) at 1000 A.D. and its transition to the LIA at 1350 A.D. appear to correspond with major wet events, as have been documented in interior North America (e.g., Yu et al. 2002). The wet events at Ebinur Lake show an average time spacing of about 300–400 years, which may correlate with decreased solar activity as shown by high atmosphere ^{14}C concentration (Fig. 4a; Reimer et al. 2004). However, the exact phasing relationship needs to be confirmed with better-dated paleoclimate records from the region. Stuiver and Braziunas (1989) identified 400 years as a fundamental periodicity of solar variations based on analysis of cosmogenic isotope analysis. Yu and Ito (2003) reviewed evidence for ∼400–year climate cycles from seven paleoclimate sites in interior North America, including Elk Lake in Minnesota (Dean 1997), Pickerel Lake in South Dakota (Dean and Schwalb 2000), and Rice Lake (Yu and Ito 1999) and Moon Lake in North Dakota (Laird et al. 1996). The dating uncertainty of our Ebinur Lake record prevents us from direct comparison with other paleoclimate records in North America. However, the similar 400-year regularity at Ebinur Lake suggests that solar activities might have played a significant role in driving wet–dry climate oscillations at centennial scales in the interior of Eurasian continent.

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