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Late Holocene climate change inferred from a lacustrine sedimentary sequence in southern Inner Mongolia, China

Fei Tian [a], Yong Wang [a, *], Jin Liu [a, b], Wenkun Tang [a], Nan Jiang [a]

[a] Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China
[b] School of Earth Sciences and Resources, China University of Geosciences, Beijing 100081, China

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A B S T R A C T

This study presents a series of paleoenvironmental results from a radiocarbon-dated 154-cm-long lacustrine sedimentary sequence from Qrdin Nuur (115°51′20″E, 42°36′20.06″N; elevation 1290 asl), in southern Inner Mongolia, China. Measurements of grain size, magnetic susceptibility (MS), total nitrogen (TN), total organic carbon (TOC), total inorganic carbon (TIC), atomic TOC/TN (C/N) and carbonate content were conducted in order to reconstruct the climate since ~3700 cal a BP. In addition to a regional drying trend in the late Holocene, closely related to the weakening of the East Asian Summer Monsoon (EASM), four distinct climatic stages can be identified. (i) From 3700 to 2909 cal a BP, a semi-arid and cool climate dominated the lake area, with a transitory climatic amelioration from 3300 to 3150 cal a BP. (ii) The interval from 2909 to 2589 cal a BP was characterized by a rising temperature and the recovery from drought. (iii) From 2589 to 1903 cal a BP, drought conditions were renewed and significantly intensified in a cold environment. (iv) After 1903 cal a BP, a warm climate with severe evaporation accelerated the shrinking of Qrdin Nuur. A comparison of our results with other paleoclimatic records, mainly from southern Inner Mongolia, reveals similar climatic trends and highlights the asynchronous nature of the regional climatic transition to increased aridity, which was reflected by the activation of the Otindag sandy land and by the dominance of steppe landscapes. Several multi-centennial temperature oscillations are recognized over the last two millennia, as inferred from fluctuations in TIC and carbonate content. We correlate the warm interval from 853 to 560 cal a BP (1097–1390 AD) with the Medieval Warm Period (MWP), and the consequent cold interval from 560 to 128 cal a BP (1390–1822 AD) with the Little Ice Age (LIA). Furthermore, the climatic reconstruction shows that the lake area was generally drier during the LIA than in the MWP.

1. Introduction

Knowledge of late Holocene climate change is important for understanding current climatic dynamics, for exploring human-climate interactions, and for improving predictions of future environmental responses to these various influences. Paleoclimatic studies from the East Asian monsoon (EAM) domain highlight the occurrence of significant late Holocene climatic deterioration in the form of greatly increased aridity and/or colder temperatures (Wang et al., 2005; Herzschuh, 2006; Cosford et al., 2008; Zhao et al., 2009; Wang et al., 2010; Zhang et al., 2011; Wang and Feng, 2013). However, the onset of climate shifts and millennial- and centennial-scale climate events during the late Holocene, reconstructed from various types of paleoclimatic archive such as loess–paleosol sequences (Liu et al., 2015), cave deposits (Hu et al., 2008), lake sediments (Chen et al., 2015a; Jia et al., 2015), and peats (Zhao et al., 2014), have a strong regional expression. In addition, climatic episodes within the last two millennia, especially the Medieval Warm Period (MWP; Graham et al., 2011) and the Little Ice Age (LIA; Ogilvie, 2001), vary in duration, amplitude and humidity in China (PAGES 2k Consortium, 2013; Chen et al., 2015b), and had a profound impact on human societies (Zhang et al., 2008).

The monsoonal margin of China, referring to a strip along the present summer monsoon limit, as shown in Fig. 1 (Gao, 1962), is considered to be sensitive to climate change (Wang and Feng, 2013). In this region, vast sandy lands, e.g. Otindag and Horqin sandy lands, and numerous lakes and paleolakes, e.g. Daihai and Dali Lake, provide excellent archives for paleoclimatic

* Corresponding author.
E-mail address: wangyong@cags.ac.cn (Y. Wang).

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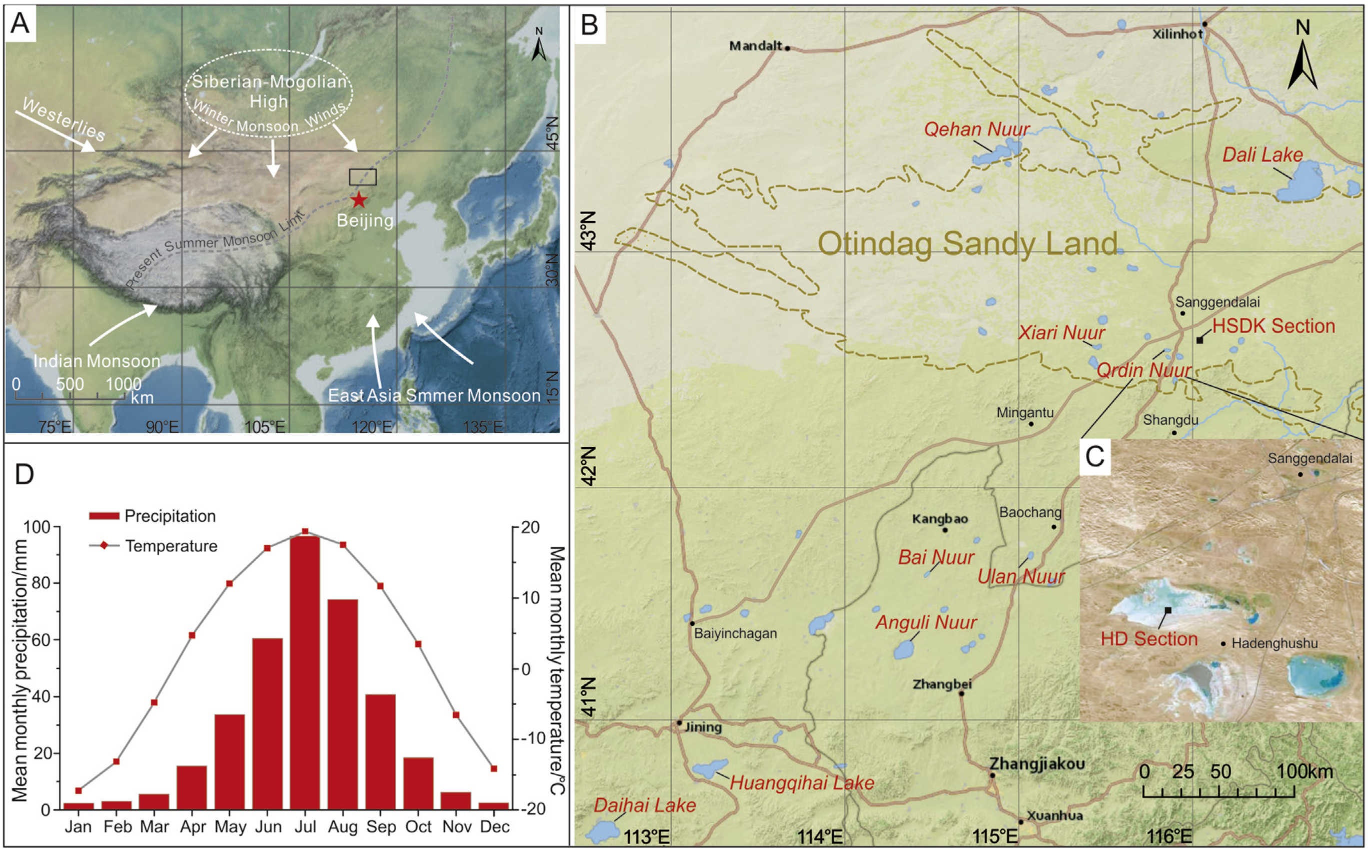

Fig. 1. (A) Map of East Asia showing the location of the study region and trajectories of major monsoonal and wind systems. (B) Map of Qrdin Nuur showing the location of the various sites mentioned in the text. (C) Satellite photograph showing the location of the HD section. (D) Mean monthly precipitation and temperature (1981–2010) (http://data.cma.gov.cn/).

reconstructions. Multi-proxy climatic reconstructions have tended to focus on Holocene climate change, and merely emphasize an overall drying trend during the late Holocene, indicated by the shrinking of lakes (Xiao et al., 2008) and the reworking of sandy lands (Zhou et al., 2008; Yang and Ye, 2013). In addition, significant variations in the grain-size and accumulation rates of aeolian sedimentary sequences in the late Holocene, especially during the last millennium, are probably indicative of increased anthropogenic influences (Yang and Ye, 2013). As the late Holocene was characterized by an increased intensity of human activity, and culminated in the onset of the Anthropocene epoch (Waters et al., 2016), high-resolution paleoclimatic reconstructions based on continuous records from the monsoonal margin are required to explore the effect of climate change on human activity. The lakes scatted around or in Otindag sandy land are mainly closed, with no outflowing water. Hence, lake level fluctuations have been driven by climate change, especially variations in effective moisture. In addition, the lakes possess continuous sedimentary records with little interference by human activity.

With the aim of improving our knowledge of late Holocene climate change in southern Inner Mongolia, high-resolution paleoenvironmental records were obtained from a lacustrine sediment sequence (HD) from Qrdin Nuur. Measurements of grain size, magnetic susceptibility (MS), total nitrogen (TN), total organic carbon (TOC), total inorganic carbon (TIC), atomic TOC/TN (C/N) and carbonate content were performed in order to provide a detailed reconstruction of lake conditions and climate variations over the past 3700 cal a BP. In addition, we compiled a set of published regional climate records to attempt a comprehensive evaluation of the trend of regional climate evolution during the late Holocene, and to assess the potential effect of climate change on human societies.

2. Regional setting

Qrdin Nuur (115°51′E, 42°36′N) is located in the central part of Zhenglan Qi, Inner Mongolia (Fig. 1A and B), close to the northern limit of the East Asian Summer Monsoon (EASM) (Gao, 1962); thus the area is sensitive to climatic and environmental changes (Wang and Feng, 2013). The closed lake, developed in an inter-dune depression, was described as covering an area of ~3.5 km^2 (Mu, 2003) about ten years ago. Field investigations revealed a drastic shrinkage of Qrdin Nuur to ~2.76 km^2, with a catchment area of ~10.9 km^2, calculated using Landsat imagery (Fig. 1C). Despite the lake regression, seasonal fluctuations in water level, deciphered from remote sensing data, have been mainly determined by variations in effective moisture. According to the Köppen-Geiger climatic classification system (Peel et al., 2007), Qrdin Nuur belongs to the Snow climate, characterized by a warm summer, with precipitation transported by the EASM, and by a cold and dry winter under the influence of the East Asian Winter Monsoon (EAWM). The mean monthly temperature is −17.2 °C in January and 19.4 °C in July (Fig. 1D), and the mean annual temperature (MAT) is 2.26 °C. A warming trend is discernable from a statistical analysis of MAT variations over the past 40 years (Li et al., 2013). The mean annual precipitation (MAP) is 359.6 mm, with July the wettest month when precipitation reaches 96.7 mm (Fig. 1 D). During summer, overland flow occurs, produced by rain falling directly onto sand