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Environmental variability in the monsoon–westerlies transition zone during the last 1200 years: lake sediment analyses from central Mongolia and supra–regional synthesis

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ABSTRACT

A high resolution multi–proxy (pollen, grain size, total organic carbon) record from a small mountain lake (Lake Khuisiin; 46.6°N, 101.8°E; 2270 m a.s.l.) in the south–eastern Khangai Mountains of central Mongolia has been used to explore changes in vegetation and climate over the last 1200 years. The pollen data indicates that the vegetation changed from dry steppe dominated by Poaceae and *Artemisia* (ca AD 760–950), to *Larix* forest steppe (ca AD 950–1170), *Larix–Betula* forest steppe (ca AD 1170–1380), meadow dominated by Cyperaceae and Poaceae (ca AD 1380–1830), and *Larix–Betula* forest steppe (after ~ AD 1830). The cold-wet period between AD 1380 and 1830 may relate to the Little Ice Age. Environmental changes were generally subtle and climate change seems to have been the major driver of variations in vegetation until at least the early part of the 20th century, suggesting that either the level of human activity was generally low, or the relationship between human activity and vegetation did not alter substantially between AD 760 and 1830. A review of centennial–scale moisture records from China and Mongolia revealed that most areas experienced major changes at ca AD 1500 and AD 1900. However, the moisture availability since AD 1500 varied between sites, with no clear regional pattern or relationship to present–day conditions. Both the reconstructions and the moisture levels simulation on a millennium scale performed in the MPI Earth System Model indicate that the monsoon–westerlies transition area shows a greater climate variability than those areas influenced by the westerlies, or by the summer monsoon only.

1. Introduction

The past millennium is one of the most important periods for studying environmental changes, as it covers both naturally–driven environmental changes and changes resulting from human influences (Buttler et al., 1996). Investigations covering this period therefore have the potential to differentiate between the influences that climate has had on ecosystems and those due to localized human activities, thus enabling improved predictions of future environmental responses to these various influences. Climate information covering this period has relied on modeling studies (Bauer et al., 2003) and climate reconstructions based, for example, on tree ring analyses (Briffa et al., 1990; D'Arrigo et al., 2000, 2001), and on lake sediment investigations (Chen FH et al., 2010). Previous studies have indicated that ecosystems have been affected by recent climatic warming relative to the background pre–1850 temperatures, particularly in the mountainous regions of Europe (Granados and Toro, 2000; Leonelli et al., 2011), North America (Hughen et al., 2000), and the northern high-latitudes (Mackay et al., 2005; Bjune et al., 2009). In contrast, however, pollen and

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diatom analyses from two lakes on the Tibetan Plateau have indicated only minor environmental changes (Wischnewski et al., 2011a, b), in agreement with studies from low latitude mountains (Ryves et al., 2011; Wang et al., 2011). The question therefore arises whether mountainous ecosystems in Asia are particularly resilient, or particularly sensitive, to climatic changes on centennial to decadal time scales.

The present–day Mongolian climate is influenced by a number of atmospheric circulation systems. In addition to the year–round influence of the westerlies, the winter climate is primarily controlled by the intense Siberian high pressure system and the summer climate by north part of the Asian low pressure system (Gong et al., 2001; Tudhope et al., 2001; Wang et al., 2009). These complex climatic systems render Mongolia a climatically sensitive area, as has been confirmed through climate–proxy studies on various time scales (D'Arrigo et al., 2000; Pederson et al., 2001; Fowell et al., 2003; An et al., 2008). However, the climatic history of Mongolia and the adjacent areas of northern China still have many controversies and uncertainties. For example, many researchers have assumed that the Mongolia and northern China region was arid during the early Holocene (Grunert et al., 2000; Herzschuh et al., 2004; Wang et al., 2004; Feng et al., 2005; Chen et al., 2008; Liu et al., 2008; Yang and Scuderi, 2010; Yang et al., 2011; Zhang et al., 2012), but also a wet early Holocene has been suggested by some records from that region (Prokopenko et al., 2007; Rudaya et al., 2009; Murakami et al., 2010; Xu et al., 2010). Although some studies suggest that temperatures decreased during the Little Ice Age (LIA), reconstructed and modeled moisture levels and hydrological conditions do not show consistent variations across different parts of Mongolia and northern China (Wang et al., 2003; Liu et al., 2004; Mayewski et al., 2004). Global–scale reconstructions indicate that the LIA was followed by a warming trend in the latter part of the 19th century and during the 20th century (IPCC, 2007), but high resolution environmental records from the Asian mid–latitude region are rare and dating problems, together with the marked variability in climate and orography, may be responsible for inconsistencies in climate change interpretations between the various studies. The complex spatial differences in climatic variations during the history of the Asian mid-latitude region on centennial to decadal time scales is thus only poorly understood, which means that the future effects of climate change on Mongolian ecosystems cannot be reliably projected and indicates the urgent need for further research into spatial variations in climate patterns.

Mongolian steppes form one of the largest continuous pasture–lands in the world, with approximately one third of today's population relying on herding as a primary source of livelihood (Chuluun and Ojima, 2002; Asner et al., 2004). The grazing history of these Mongolia grasslands is believed to extend back over at least 4000 years (Shinneman et al., 2009), and in particular since about 2000 years ago, starting with the Scythians and then followed by the Huns and the Mongolian Empire (Zaitseva et al., 2004; van Geel et al., 2004; Rösch et al., 2005). Mongolia was probably continuously inhabited, but details on the herding economy and nomadic life–style of its inhabitants before the 20th century are scarce. Between 1918 and 1990, the livestock comprised predominantly monospecific herds of sheep, but since that time the proportion of goats and cattle in the herds has increased. These animals are considered to be more destructive to trees and shrubs than sheep because of their different plant preferences (Vallentine, 2001; Sankey et al., 2006, 2009; Wang et al., 2009). The contemporary Mongolian vegetation is thus assumed to have been modified, at least to some extent, by human activities (Gunin et al., 1999; Rösch et al., 2005), and in mountain steppes grazing can lead to substantial floristic and edaphic changes (Zemmrich et al., 2010). However, evidence from northern Mongolia suggests that the present–day vegetation pattern has been primarily influenced by climate and relief (Schlütz et al., 2008). It therefore remains unclear to what extent the Mongolian steppe ecosystem is entirely natural.

Despite the clear need for information on environmental changes over centennial to decadal time scales, no records focusing on these time scales have hitherto been published from Mongolia. We therefore present herein new information on environmental variations that have occurred over approximately the last 1200 years, based on multi–proxy analyses of sediment core from a small lake in the Khangai Mountains of central Mongolia. Our investigations focused on the following questions: (1) How has the vegetation changed during the last ~1200 years? (2) When – if at all – did humans become the main driver of regional–scale vegetation dynamics? (3) How are global climate signals from the last millennium, such as the Medieval Warm Period (MWP), the LIA, and the Current Warm Period (CWP), reflected in Mongolia's environment? (4) How did the climate history of the Asian mid–latitude region vary between the areas controlled by the different climate systems?

2. Regional settings

The Khangai mountain system is one of the main elements of the Inner Asian mountain belt. It was formed by the Caledonian Orogeny during the late Silurian and early Devonian, and consists mainly of basalt (Yarmolyuk et al., 2007). The present–day climate in the southern part of the Khangai Mountains is a typical temperate continental climate, with cold–dry winters dominated by the Siberian/Mongolian high pressure system, and warm–wet summers influenced by the Asian low pressure system (Wang et al., 2009). Moisture from the Asian summer monsoon rarely reaches the area (Gunin et al., 1999; Sato et al., 2007) and hence the westerlies are the dominant moisture supply for this montane area (Chen FH et al., 2010). The region receives most of its precipitation during the summer (Angerer et al., 2008). Precipitation increases zonally with increasing latitude, and varies azonally with altitude in the mountainous areas in Mongolia (Sato et al., 2007). The precipitation gradient in Mongolia is reflected in the north–south vegetation transition through five zones (Fig. 1a): (1) taiga, consisting mainly of *Larix sibirica*, sometimes mixed with *Pinus sibirica*, *Abies*, *Cedrus* and *Picea*; (2) mountain/forest steppe, characterized by *Larix sibirica*–*Betula* forest in combination with a Poaceae–dominated herb layer; (3) steppe/dry steppe, in which Poaceae grow together with *Caragana* and *Artemisia*; (4) desert steppe, which is mainly a mixture of Poaceae, *Artemisia* and Chenopodiaceae; (5) desert, dominated by low shrubs and semi–shrubs, most of which belong to the Chenopodiaceae, Asteraceae, Polygonaceae, Zygophyllaceae, Tamaricaeae, Fabaceae, Rosaceae and Convolvulaceae (Hilbig, 1995; Gunin et al., 1999). In the Khangai Mountains, plant communities change with increasing altitude from dry steppe to wetter mountain steppe, forest steppe, and alpine meadow (Hilbig, 1995).

The soils beneath the forests of the Khangai Mountains have been described as permafrost–affected taiga soils (Sharkhuu, 2003; Krasnoshchekov, 2010). The lower limit of continuous permafrost on south–facing slopes ranges from altitudes of 2200–3200 m, and its average thickness ranges between 100 and 250 m. The lower limit of sporadic permafrost is at altitudes of between 600 and 700 m (Sharkhuu, 2003), and the active layer has a thickness of about 1.5 m (Krasnoshchekov, 2010).

Lake Khuisiin is located in the south–eastern part of the Khangai Mountains (Fig. 1a), in an area characterized by deeply-etched relief that has been exaggerated by the action of glaciers. The lake basin is separated from the nearby valley by a dam of lateral moraine that