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The onset of Neoglaciation 6000 years ago in western Mongolia revealed by an ice core from the Tsambagarav mountain range

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ABSTRACT

Glacier highstands since the Last Glacial Maximum are well documented for many regions, but little is known about glacier fluctuations and lowstands during the Holocene. This is because the traces of minimum extents are difficult to identify and at many places are still ice covered, limiting the access to sample material. Here we report a new approach to assess minimal glacier extent, using a 72-m long surface-to-bedrock ice core drilled on Khukh Nuru Uul, a glacier in the Tsambagarav mountain range of the Mongolian Altai (4130 m asl, 48°39.338′N, 90°50.826′E). The small ice cap has low ice temperatures and flat bedrock topography at the drill site. This indicates minimal lateral glacier flow and thereby preserved climate signals. The upper two-thirds of the ice core contain 200 years of climate information with annual resolution, whereas the lower third is subject to strong thinning of the annual layers with a basal ice age of approximately 6000 years before present (BP). We interpret the basal ice age as indicative of ice-free conditions in the Tsambagarav mountain range at 4100 m asl prior to 6000 years BP. This age marks the onset of the Neoglaciation and the end of the Holocene Climate Optimum. The ice-free conditions allow for adjusting the Equilibrium Line Altitude (ELA) and derive the glacier extent in the Mongolian Altai during the Holocene Climate Optimum. Based on the ELA-shift, we conclude that most of the glaciers are not remnants of the Last Glacial Maximum but were formed during the second part of the Holocene. The ice core derived accumulation reconstruction suggests important changes in the precipitation pattern over the last 6000 years. During formation of the glacier, more humid conditions than presently prevailed followed by a long dry period from 5000 years BP until 250 years ago. Present conditions are more humid than during the past millennia. This is consistent with precipitation evolution derived from lake sediment studies in the Altai.

1. Introduction

The Holocene can be divided into three phases; the early deglaciation period (11,600–9000 years BP), the Holocene Climate Optimum (HCO, 9000 to 6000–5000 years BP) and the Neoglaciation period (6000–5000 years BP to preindustrial time). Discussions about amplitude, duration, and causes of the different phases have initiated numerous studies and generated new paleoclimatic records. The hypothesis of a relative stable Holocene climate (Johnsen et al., 1997) compared to glacial interglacial changes has been contested and recurring cold events (so called “Bond cycles”) with a periodicity of 1470 ± 500 years have been proposed for the Holocene (Bond et al., 1997; Mayewski et al., 2004). However, Wanner et al. (2011) did not observe periodic cold relapses during the last 10 ka and contradicts the occurrence of “Bond cycles” for the Holocene. Additionally, the current debate about anthropogenic climate change raises the question if during the past 10 ka temperatures higher or similar than today may have occurred. Generation and analysis of proxy data covering the Holocene epoch is thus of major importance in order to better understand the current climate change. In this context, glacier

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fluctuations can be used to study trends of temperature and precipitation during the Holocene (Oerlemans, 2005; Solomina et al., 2008; Davis et al., 2009; Owen, 2009). Most approaches rely on distinctive features such as terminal moraines or exposure dating to reconstruct maximum glacier extents. The current retreat of glaciers provides a unique opportunity to collect ancient embedded organic particles (Miller et al., 2012), wood fragments (Ivy-Ochs et al., 2009), or archeological remnants (Grosjean et al., 2007; Nesje et al., 2012). Artifacts exposed at the front of the glacier tongues are dated and allow for reconstructing glacier fluctuation chronologies.

However, for inferring minimum extent of glaciers such specific features are difficult to identify and the access to potential sample material is often hindered by ice coverage. Consequently, little is known about glacier lowstands and the discussion is ongoing which high-mountain glaciers and ice caps have persisted throughout the Holocene and which have disappeared at some point. A promising approach to overcome the lack of evidence is the use of high-resolution ice core records extracted from alpine glaciers. They may provide insight in former climate conditions (e.g. Thompson et al., 1998; Eichler et al., 2011) and may give access to datable material in the basal ice itself or from the bedrock.

The Intergovernmental Panel on Climate Change (IPCC, 2007) projection of total disappearance of Himalayan glaciers by 2035, a statement finally recalled, had the merit to increase the public awareness about glacier changes in Asia, their importance, and impacts on society. Most investigations dealing with Asian Quaternary glacier fluctuations have focused on the Himalaya and the Tibetan Plateau (Lehmkuhl and Owen, 2005; Davis et al., 2009), likewise the ice core drilling projects. The adjacent mountain ranges including the Pamir, Tien Shan, and Altai have received less attention and were thereby investigated in less detail. For a complete understanding of glacier fluctuations in Asia, more research in these regions is required. Here we date an ice core from the Altai Mountains to examine glacier behavior and reconstruct accumulation rates during the Holocene. This work is a step toward an improvement in understanding the climate of Central Asia. We present a multi-proxy approach using an ice core covering approximately the last 6000 years and provide a larger perspective on the Holocene climate in the Mongolian Altai, than has been provided up to now.

2. Regional setting

The Altai Mountains, a complex mountain system in Central Asia, form the borders between Russia, Kazakhstan, China, and Mongolia. The maximum elevation is 4500 m asl and the range extends over approximately 1200 km (Rudaya et al., 2009). According to the Randolph Glacier Inventory (RGI, Arendt et al., 2012) and Landsat imagery used to manually correct the RGI, the Altai has a glaciated area of roughly 1300 km^2 including, approximately 500 km^2 of Mongolian glaciers. From northwest (Russian Altai) to southeast (Mongolian Altai) where the foothills reach the Gobi desert, the mountain range serves as watershed between the Arctic Ocean and the basin of central Asia. The location and extent imply a major role in the Asian climate system and thus, requires thorough paleoclimate investigations, all the more since instrumental data is limited and spatially sparse.

The mountain chain acts like a barrier and intercepts air masses originating from the west, leading to a strong northwest to southeast precipitation gradient. In the Russian Altai, mean annual precipitation is around 800 mm and decreases to less than 200 mm in the floor of the intermountain depressions of the Mongolian Altai (Klinge et al., 2003). The Siberian High controls the winter climate with cold and dry conditions. Most of the precipitation is related to the Westerlies and occurs mainly during the months June, July, and August (Klinge et al., 2003).

Glacier fluctuation studies dealing with the Altai mountain range are mainly limited to the late Pleistocene (Lehmkuhl et al., 2011), whereas knowledge for the Holocene period is rare. A detailed discussion of glacier fluctuations from Agatova et al. (2012) refutes the former general concept of a gradual retreat of the Würm glaciers in the Russian Altai by summarizing former work and presenting new data. For the period 7000 years BP to present, temperature and humidity reconstructions are presented based on lichenometry, geomorphological methods, and further radiocarbon dates from formerly buried pieces of wood. Forest regrowth in presently glaciated areas during interstage mild periods suggest strong glacier retreat or even complete disappearance especially during the HCO. Additionally, the recovery of wood fragments originating from the HCO above the modern tree line indicates warmer temperatures than nowadays. After a glacier-hostile climate, glaciers started to regrow around 5000 years BP. Periods of glacier advances (8300, 5700, 4000, and 400 years BP) have been proposed for western China (Zhou et al., 1991) adjacent to the Mongolian Altai. Glacier advances detected around 5700 years BP in western China, occurred slightly earlier than in the Russian Altai and can be interpreted as the end of the HCO and the onset of the Neoglaciation.

Lake sediment cores collected in Hoton-Nur lake (northwestern Mongolia, Fig. 1) show distinct variations in the precipitation. A major shift from wet to present dry conditions occurred 5000 years BP (Rudaya et al., 2009; Mackay et al., 2012). Information about glacier fluctuations and past temperature is, however, not available. Long-term Holocene climate records for the Mongolian Altai are thus incomplete and biased toward lake sediment data.

For the Mongolian Altai, high-resolution climate reconstructions on a millennial scale are based on tree-ring chronologies. Most studies provide records for few centuries only, the longest currently available covers 1700 years (D'Arrigo et al., 2001; Loader et al., 2010). The reconstruction suggests that the coldest and warmest conditions of the last millennia occurred during the 19th and 20th century. Further back in time the different records show less coherent behavior and thus require more data for accurate past climate information. The only alternative reconstructions originate from an ice core drilled in the Russian Altai spanning 750 years (Eichler et al., 2009a, 2009b). For the Siberian Altai, a correlation between solar forcing and temperature was found for the period 1250 to 1850 AD. In addition, the biogenic emissions from the Siberian forests are closely related to temperature changes. However, no long-term reconstructions of Holocene glacier fluctuations in the Mongolian Altai exist.

3. Experimental methods

3.1. Ice core drilling

In July 2009 a joint Russian–Swiss expedition collected a 72 m surface-to-bedrock ice core and an adjacent 52 m parallel core in the Tsambagarav mountain range situated in the Mongolian Altai (4130 m asl, 48°39.338′N, 90°50.826′E). This mountain range is dominated by small ice caps, with the ice margin varying between 3000 and 3800 m asl (Fig. 1) strongly depending on the orientation. The total glaciated area in 2008 was 73.2 km^2 (Demberel, 2011). The equilibrium line altitude (ELA) is estimated to be at 3700 m asl (Lehmkuhl et al., 2011). Prior to the expedition, the drill site was selected based on satellite imagery (Landsat 7/8.8.2002/http://landsat.usgs.gov/index.php) and the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM, 90 m horizontal resolution). Two peaks of similar elevation dominate the mountain