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Asynchronous glaciations in arid continental climate

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ABSTRACT

Mountain glaciers at ~26–19 ka, during the global Last Glacial Maximum near the end of the last 10^5 yr glacial cycle, are commonly considered on the basis of dating and field mapping in several well-studied areas to have been the largest of the late Quaternary and to have advanced synchronously from region to region. However, a numerical sensitivity model (Rupper and Roe, 2008) predicts that the fraction of ablation due to melting varies across Central Asia in proportion to the annual precipitation. The equilibrium-line altitude of glaciers across this region likely varies accordingly: in high altitude, cold and arid regions sublimation can ablate most of the ice, whereas glaciers fed by high precipitation cannot ablate completely due to sublimation alone, but extend downhill until higher temperatures there cause them to melt. We have conducted field studies and ^{10}Be dating at five glaciated sites along a precipitation gradient in Mongolia to test the Rupper/Roe model. The sites are located in nearby 1.875 × 1.875° cells of the Rupper/Roe model, each with a different melt fraction, in this little-studied region. The modern environment of the sites ranges from dry subhumid in the north (47.7° N) to arid in the south (45° N). Our findings show that the maximum local advances in the dry subhumid conditions predated the global Last Glacial Maximum and were likely from MIS 3. However, we also found that at ~8–7 ka a cirque glacier in one mountain range of the arid Gobi desert grew to a magnitude comparable to that of the local maximum extent. This Holocene maximum occurred during a regional pluvial period thousands of years after the retreat of the Pleistocene glaciers globally. This asynchronous behavior is not predicted by the prevailing and generally correct presumption that glacier advances are dominantly driven by temperature, although precipitation also plays a role. Our findings are consistent with and support the Rupper/Roe model, which calls for glaciation in arid conditions only at high altitudes of sub-freezing temperatures, where the melt fraction in ablation is low. We expect a heterogeneous pattern of glacial responses to a changing modern climate in cold arid regions; an individual glacier advance should not be necessarily interpreted as evidence of cooling climate.

1. Introduction

Glaciers respond to a number of forcing functions that are active over a wide range of scales from local (e.g., topographic shadowing) to regional or even global. Of these, annual snowfall and summer air temperature are commonly considered to be the most important. If one of these parameters is independently known, glacial records may be useful in reconstructing the other parameter in continental settings where paleoclimate proxy records are scarce. Specifically, the timing and magnitude of local maximum glacial advances have been used to improve the understanding of changes in climate during the past cycle of glaciation (e.g., Gillespie and Molnar, 1995; Porter, 2001; Clark et al., 2009).

The global "Last Glacial Maximum" (LGM) is defined as the period during the latest ~10^5 yr glacial cycle when the global ice volume achieved its maximum. Climate reconstructions based on oxygen-isotope records of marine foraminifera (Hays et al., 1976) placed the timing of the global LGM at ~23–19 ka (Mix et al., 2001). Integrating the high-latitude ice-sheet and mountain-glacier records appeared to strengthen the concept of a synchronous global LGM and also extended its period to ~26–19 ka (Clark et al., 2009).

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However, recent evidence from mid-latitude southern hemisphere glacial records (Augustin et al., 2004; Putnam et al., 2013; Rother et al., 2015; Darvill et al., 2016) and continental Asian valley glacier systems (Gillespie et al., 2008; Koppes et al., 2008; Heyman et al., 2011a; Batbaatar and Gillespie, 2016; Gribenski et al., 2016) suggests a more complex behavior than that of synchronized 'global' glaciations, highlighting the often-overlooked importance of regional factors. Such spatial variations in the magnitude of glaciations during a given period were suspected before (Gillespie and Molnar, 1995; Hughes et al., 2013), but with the widespread introduction of *in-situ* cosmogenic surface exposure dating, new quantitative glacial chronologies (e.g., Hughes et al., 2013; Heyman, 2014) have allowed a reliable temporal comparison of maximum mountain glaciations that might not coincide with the timing of the global LGM.

Glacial records from the arid to humid continental environments (Zomer et al., 2008) of Central Asia (Fig. 1) have revealed that the spatial patterns of glacier advances and retreats as well as the timing of the maxima differ from place to place on a scale of a few hundred kilometers. We postulate that the concept of synchronous glaciations may break down in arid environments where glacier mass balance is controlled by different suites of factors than in more humid settings (e.g., Cuffey and Paterson, 2010, pp. 169–173). For example, in arid–dry subhumid parts of the Kyrgyz Tien Shan (locations are shown in Fig. 1) the largest glaciers date from Marine Oxygen-Isotope Stage (MIS) 3 or earlier, and MIS 2 glaciers were restricted to cirques (Koppes et al., 2008; Blomdin et al., 2016). On the other hand, in humid southern Siberia, the largest glaciers dated from MIS 3, and the MIS 2 glaciers were only slightly smaller (Gillespie et al., 2008; Batbaatar and Gillespie, 2016). In parts of the northeastern Tibetan plateau, the largest mountain glaciers occurred earlier than ~100 ka (i.e. prior to MIS 4) and no evidence of MIS 2 glaciation has been found (Heyman et al., 2011a). Numerical glacial modeling (Rupper and Roe, 2008; Rupper et al., 2009), albeit of low spatial resolution (1.875°), suggests that this heterogeneous pattern of glacial response is due to the different sensitivity of glaciers to climate forcing in cold, arid regions, where sublimation accounts for more than 50% of the total ice loss. However, this model (Rupper and Roe, 2008; Rupper et al., 2009) has yet to be validated with field observations.

In this article, we examined the glacial history in five sites in central Mongolia (Fig. 2), with modern environments grading northward from arid to dry subhumid. The sites are distributed across a cluster of five cells of the Rupper and Roe model (2008) (Fig. 3). We selected the sites to be in cold continental climates where melt versus sublimation was predicted to be a significant factor controlling glacier mass balance, and therefore where glaciers and paleoglaciers could be used to test the Rupper/Roe numerical model. According to the Rupper/Roe model, almost all of glacier ice in arid Gichginii is lost via sublimation and in the semiarid Sutai and Ih Bogd ~10–30% of ice is lost via sublimation. In contrast, in dry subhumid Hangai region melting is responsible for more than 40–60% of total ablation (Fig. 3).

In low-precipitation, sub-freezing sublimation regimes, glaciers are restricted to altitudes close to or above the zero isotherm. As snowfall increases above the amount that can be ablated by sublimation, the glacier will advance below the zero isotherm, but not far because melting is much more efficient at ablation than sublimation. Only when the incoming glacier ice plus the local snowfall in the melt zone exceeds ablation will glaciers flow to lower altitudes. This is a mechanism for desynchronizing glacier advances because of their non-linear response to precipitation differences from place to place: in arid regions glaciers may be restricted to cirques, whereas in more humid regions they may advance or retreat. Likewise, glacier advances in a given valley may respond differently in the face of climate change, for the same reasons.

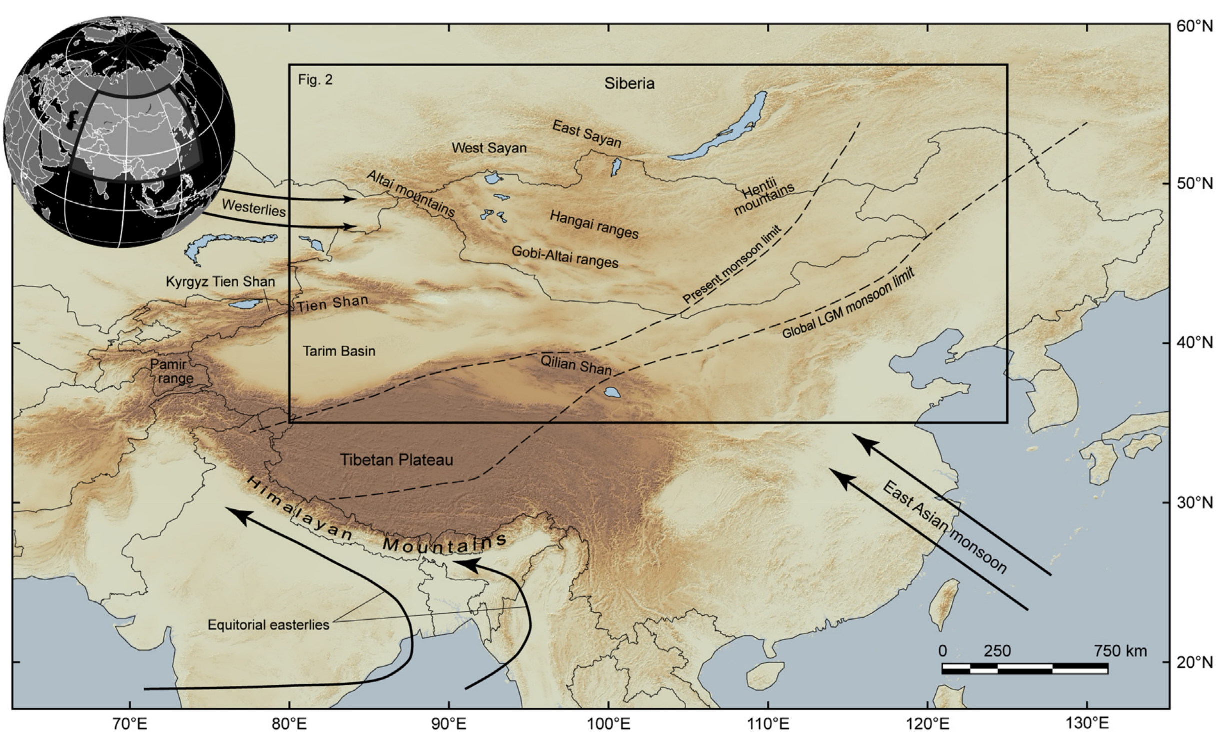

Fig. 1. Geographic location of the Hangai and Gobi-Altai ranges in East and Central Asia. Dashed lines indicate the modern and global LGM limits of East Asian monsoon (Shi, 2002). Solid lines indicate the general direction of major air flows (Benn and Owen, 1998). The black rectangle inset refers to the extent of region shown in Fig. 2.