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QUATERNARY GLACIATION IN NORTHERN CENTRAL ASIA

In Central Asia, Pleistocene glaciations occurred in two climatic regimes: arid regions where annual precipitation was <150 mm, and more humid regions where it was greater. In the former, the precipitation controlled the ELA and size of the glaciers; in the latter it was temperature. Temperatures are less variable spatially than precipitation, and therefore the glaciers of the arid regimes have a wide range of ELAs. This leads to highly local, idiosyncratic glacial chronologies because of local rain-shadow effects as well as nuances in the pattern of moisture distribution by storms affected by topography and the jet stream. However, southern Siberia appears to have followed the global pattern of glacial advances, while the complexities are largely farther south.

Mountain glaciers in arid Central Asia are important in and of themselves because their meltwater is necessary to sustain some communities through dry seasons when rainfall is slight. Furthermore, glaciers are commonly associated with ice-dammed lakes that can rupture to release dangerous outburst floods downstream. However, because of their widespread distribution in Central Asia, the most significant role for glaciers may be as a warning system for climate change and a signal for the degradation of permafrost and consequent release of greenhouse CH_4 into the atmosphere.

Key words: *quaternary glaciation; paleoclimate; paleo-precipitation; climate-change.*

Introduction

Glaciers develop in response to many climatic forcing functions, especially winter precipitation and summer temperatures. However, summer cloudiness, wind speed and humidity all play important if commonly secondary roles in modifying the loss of ice (ablation) from the glacier's surface. Topographic factors such as shadowing by ridges also may be important.

Glaciers (fig. 1) grow when the accumulation of ice exceeds the ablation. Because for many glaciers summer temperatures are the dominant factor in ablation, and because temperatures decrease with elevation about 6.5°C km^{-1} (environmental lapse rate), except in polar regions glaciers are preferentially found in mountains today. At high elevations, accumulation exceeds ablation and the glacier grows. As the ice thickens, it also flows downslope to lower elevations and higher temperatures. There, ablation exceeds accumulation and the glacier melts. Thus the glacier exists in a dynamic state, balancing accumulation and loss. If accumulation increases, the glacier will advance downslope; if it is reduced, the glacier will melt back and appear to retreat upslope. The elevation or altitude at which accumulation balances ablation is known as the equilibrium line altitude, or ELA. This is an important parameter characterizing glaciers (fig. 2).

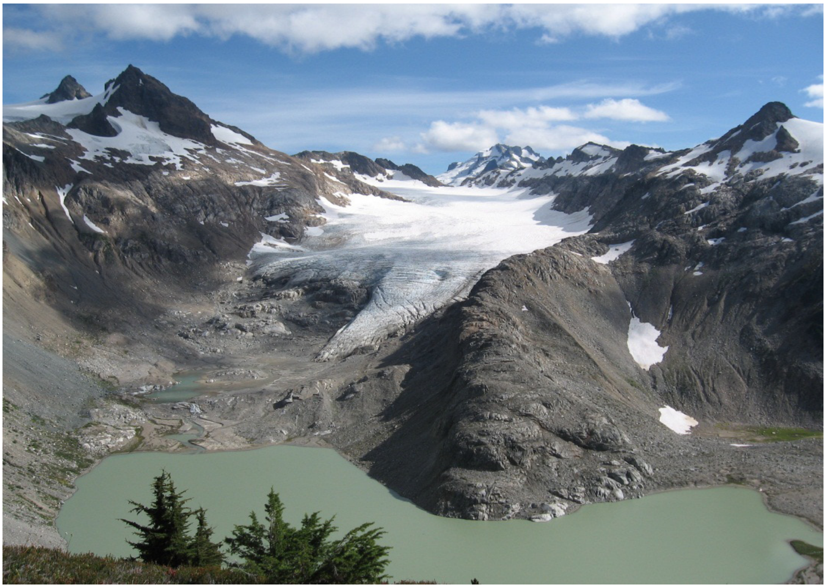


Fig. 1. Photograph of the South Cascade Glacier in retreat, Cascade Mountains. The landscape has been modified by repeated glaciation. The steep cliffs above the lateral margins of the glacier were produced by glacial erosion and mark the height of the glacier during the Ice Age. Ablation zone is the darker part of the glacier near its terminus, where light-toned snow has melted. View to SE. Photograph: Kurt Parker, 2007

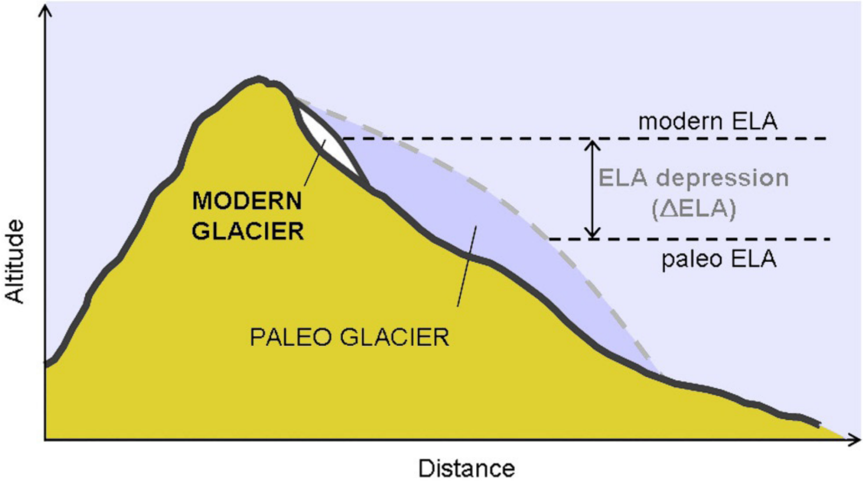


Fig. 2. Schematic cross section of glaciated mountain showing the ELA for glaciers of two sizes

The ELA represents a loosely characterized long-term average of the actual elevation of equilibrium, which fluctuates daily and seasonally and on longer time scales as well. In late summer this line is easy to see on a glacier, because above it the snow is preserved and appears white, but below it darker bare ice is exposed.

In Central Asia the fundamental observation that must be explained is the high variability in the ELA from place to place, on length scales of 500 km or less. This is quite unlike, for example, the Sierra Nevada in California (USA) in which the ELA rises systematically with latitude for hundreds of km [1]. This lack of systematic behavior in some places, and with it the lack of asynchronism of the local LGM, was noted by [2], but it has taken years of careful dating of glacial deposits by many different researchers to confirm.

In this paper, the response of glacial ELAs to climate is discussed first. Then, examples of dated glacier systems from northern Mongolia, southern Siberia, and the Kyrgyz Tien Shan are summarized. Finally, some implications for modern climate-change studies are discussed.

Climate and glacier dynamics

Climate is long-term weather and, on long time scales, the common short-term annual or decadal oscillations in weather tend to average out. It is this average that is indicated by the ELA. Climate has fluctuated throughout the Quaternary Period, and on a wide range of time scales. Some climatic changes have led to expanded high-latitude ice sheets, and in these times the eustatic sea level is lowered accordingly. Along with lowered sea levels, the ratio of ^{18}O and ^{16}O in the remaining seawater is changed because the lighter ^{16}O is preferentially evaporated. The isotopic ratio from fossils in marine sediment cores reflects the changing sea-water values, and the oscillations in the fossil oxygen are interpreted as climatic changes (fig. 3).

Along with growth and decay of the high-latitude ice sheets, mountain glaciers advance and retreat – but not necessarily all in synchrony with the polar ice, or with each other [2]. This is probably because of local or regional changes in weather systems and the jet stream: climate cannot be well-characterized by simple global averages. The southern border regions of Siberia, and Central Asia to the south, are locations in which the variability of paleo-precipitation especially was pronounced, with strong effects on the glacial landscape.

Given this complexity, how can we use the glacial record to infer anything of value concerning paleoclimate? We first must understand how glaciers form and behave under the influence of climate, and how to ‘read’ geologic deposits and landforms to learn the distributions of vanished glaciers that occupied the landscape in more favorable times.

Glaciers commonly, but not always, erode the landscape on which they are found. The erosion is strongest near their heads, where the ever-increasing mass drives the ice downward onto the bed and sides of the glacier, grinding away the rock. Below the ELA, the load – lightened by ablation from the top of the glacier – is lessened, and the flow lines are up and out from the base of the glacier. This upward and outward flow of ice carries with it the rocky rubble that was eroded from its sides and base by the glacier, and this material is deposited as till along the sides of the glacier, forming lateral moraines, and at the snout, forming end or terminal moraines (fig. 4).

Lateral moraines are found only below the ELA. Therefore, the ELA of long-vanished glaciers can be estimated from the highest elevation of the moraines it left behind when it melted away. The highest lateral moraines can be seen just inside the mountain front in Figure 4, and from this observation it is possible to infer a local paleo-ELA of ~2400 m asl.

In the Hoyt Agaya Uul (Fig. 4), the Pleistocene moraines have not been eroded and their highest occurrence can be identified in the field to within a few meters or tens of meters, but commonly lateral moraines often occur within steep mountain valleys where preservation is poor. Here the highest lateral approach cannot be used to find the paleo-ELA, and other techniques must be employed. The ELA can be also estimated by from the toe and headwall altitudes, or from the areas of the accumulation and ablation zones. In both these approaches, the elevations (or areas) are ratioed.

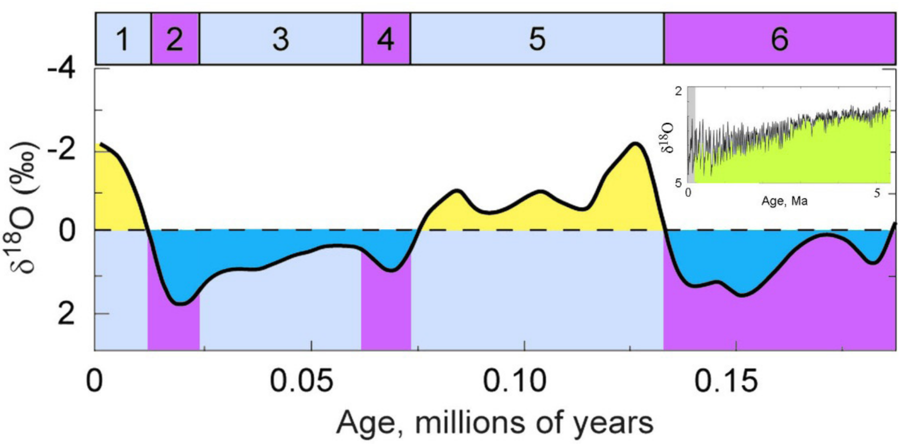


Fig. 3. Climatic record of the past 200,000 years, from oxygen isotopic data for planktonic foraminifera. Marine oxygen isotope stages (MIS) 1–6, defined by these data, are shown in the horizontal bar above the curve and by color bands below the curve itself. Even-numbered stages are considered to be glaciations; odd-numbered stages are interglaciations. $\delta^{18}O$ is a measure of the ratio of oxygen isotopes ^{18}O and ^{16}O (relative to modern seawater) and increases in sea water when evaporation lowers sea level, and thus when continental ice caps are large. Warm intervals of low ice-sheet volume are indicated by $\delta^{18}O<0$ (yellow); cold seas and high glacial volume are indicated by positive values (dark blue). Inset shows $\delta^{18}O$ data for deep-water foraminifera [3] for the past 5 Ma. Sea level began dropping gradually towards the end of the Tertiary Period (2.6 Ma) and began oscillating more strongly as the Ice Age intensified during the Pleistocene. The expanded curve fits into the gray bar at the left-hand side of the inset

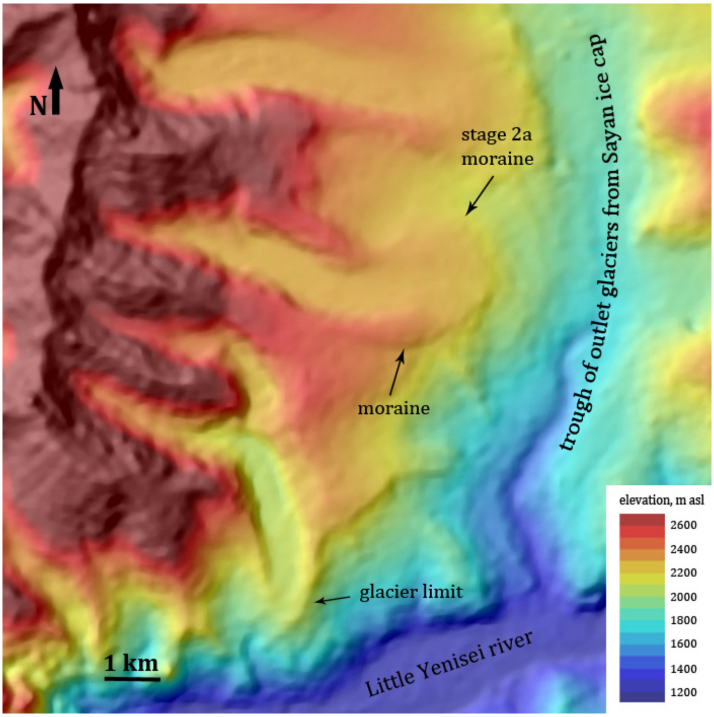


Fig. 4. NASA-ASTER Digital Elevation Model 30-m shaded-relief image showing moraines in the Hoyt Aguy Uul, a range in the Mongolian headwaters of the Little Yenisei River (Shishhid Gol) that is presently unglaciated. Lateral and end (terminal) moraines are indicated. End moraines mark the downhill limit of a glacier. “Stage 2a” refers to the relative age of a moraine, and does not refer to an MIS. End moraines for this valley, and for the valley to its north, were never deposited because the glacier flowed into a larger south-flowing outlet glacier draining the Sayan ice field during the Pleistocene. In contrast, the probably coeval end moraine marked “glacier limit” is well-developed because the glacier was isolated (not flowing into another glacier) and stable for some time. Courtesy of J. Batbaatar

The ELA typically occurs about halfway between the toe and the headwall, or where about ⅔ of the area of the former glacier is at higher elevations. The values are empirically found and differ from climate to climate [4], but where the behavior of the ELA is well understood, the Toe-Headwall Altitude Ratio (THAR) [5] or the Accumulation-Ablation Area ratio (AAR) [4–6] can “predict” the ELA within about 100 m for individual glaciers [1]. Where the lateral moraines are well-preserved, the agreement among all three techniques is within this limit.

The ELA has received some much attention because, if it can be recovered for past glaciers, something about the paleoclimate can be inferred. This is because pairs of summer temperatures and winter precipitation values at ELAs for existing glaciers have been compiled for different regions. Figure 5 shows the curve for China. Before exploring this curve, it is good to note that it steepens under arid conditions. In addition, since the curve can vary from region to region (at a given time), it may also vary from time to time (at a given place) as conditions there change. Consequently, modern curves may not be perfectly applicable to bygone ages.

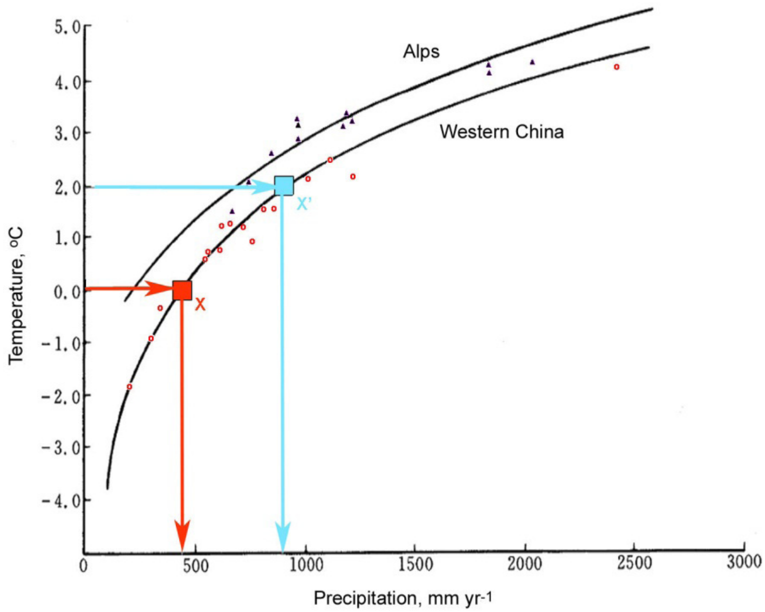


Fig. 5. Average annual temperature T and precipitation P at ELAs in western China (red circles) and Europe (solid black triangles) [7]. The boxes and colored arrows show that for a glacier in western China an increase in P ($\Delta \approx 450$ mm yr^{-1}, ~450 to ~900 mm yr^{-1}) that would be required to counteract a 2°C increase in T, if the ELA was unchanging. In general, it is summer temperatures and winter precipitation that control ELA, but in western China the precipitation peaks in the autumn and winters are commonly dry, clear and cold. The curve given for the Alps is poorly defined for glaciers with P<750 mm yr^{-1} precipitation. Furthermore, there is considerable scatter about the trend lines such that even if T is well-known, recovered P values are only accurate to about ±150 mm yr^{-1} (1 σ, at P~1000 mm yr^{-1})

Figure 5 shows that the temperature and precipitation co-vary at the ELA such that ELAs for different glaciers can be achieved by different pairs of temperature and precipitation, but not by all possible pairs – that would fill the plane of fig. 5, and instead the data are distributed along a curved line. If one value can be estimated independently, the other can then be inferred. Because temperatures are less spatially variable than precipitation, and therefore the y axis can be expressed in terms of elevation, calculated from temperature using an assumed lapse rate. More usefully, the change in ELA between two glaciations can be related to the change in precipitation, once allowance has been made for regional differences in temperature between the two times. Differences for precipitation at a given elevation have been estimated a number of different ways – for example, palynology can be used to estimate paleo-precipitation – and thus paleo-temperatures and not just paleo-precipitation can be estimated from paleo-ELAs.

We can describe the relationship between the change in temperature and ELA at two times, *i* and *j*, as a function of precipitation:

$$T_j - T_i = \frac{\partial T}{\partial z}\left(ELA_i - ELA_i\right) - f\frac{\partial P}{\partial z}\left(ELA_i - ELA_i\right) - f\left(P_i - P_i\right) \quad (1)$$

where z is elevation (km), ELA is in km, f is a factor describing the mutual dependence of temperature and accumulation at the ELA. Some values given for f are ~0.003°C mm^{-1} [8], and ~0.008°C mm^{-1} for arid ranges [7]. $\partial T/\partial z$ is the adiabatic lapse rate (e.g., ~6.5–8.5°C km^{-1}) and $\partial P/\partial z$ is the change in P with elevation at the ELA (mm km^{-1}).

If $\partial T/\partial z$ is known, the y axis in fig. 5 can be converted from T to elevation of the ELA. In this case, the change in precipitation over time can be inferred from the rise or fall of the ELA between two sets of moraines in a chronosequence. Temperature decreases for the northern Tibetan Plateau during the LGM have been estimated at 7–9°C [7]; depending on the modern value of P, these temperature decreases at the ELA correspond to an unrealistically large precipitation reduction if the ELA is to remain fixed. Therefore, the ELA drops in elevation, with the effect that the change in T there is reduced, as is the required change in P.

This raises an important point. In humid conditions (e.g., P > 500 mm yr^{-1}), $\partial T/\partial P$ has a low value. In very arid conditions (P < 150 mm yr^{-1}), however, $\partial T/\partial P$ is much greater. This means that, for arid conditions, ELA is insensitive to temperature, but very sensitive to even small changes in precipitation. In contrast, temperature is a much bigger factor controlling ELA in more humid regions.

Why is this? The answer involves sublimation of ice to water vapor due to direct heating by the sun instead of by the air. This can occur even at sub-freezing temperatures such as characterize high-altitude mountains. It requires 740 cal g^{-1} deg^{-1} to sublime winter accumulation at 0°C, compared to only 80 cal g^{-1} deg^{-1} to melt it, a factor of ~9 less. Therefore, for P = 125 mm yr^{-1}, 9250 cal cm^{-2} is required for sublimation if the ice already at 0°C. The amount of energy available from sunlight depends on latitude, time of year, cloudiness and, to a lesser degree, elevation (because thinner air at high elevations absorbs less radiation), but in the Altai Republic about 90 kcal cm^{-2} are available at the ground surface, of which 80% is reflected by snow. Assuming 50% cloud cover during summer months, about 9000 cal cm^{-2} is available for ablation – a close match.

If precipitation falls much below 150 mm yr^{-1}, for accumulation to balance sublimation the temperature must fall greatly, because it requires only 1 cal g^{-1} deg^{-1} to warm the ice to 0°C. This explains the steepness of the curve in Figure 5 for hyperarid regions. Because of the adiabatic lapse rate, this means that in general the ELA must rise precipitously. If the temperature changes, on the other hand, only a small adjustment in ELA is necessary to restore equilibrium. In other words, ELA is highly sensitive to precipitation, but not temperature for arid conditions. If precipitation increases, insolation is no longer capable of ablating the whole mass of ice, and ELA will drop until adiabatically rising air temperatures impart enough heat to melt the 'excess' ice. The air acts as an 'infinite' source of heat, but the transport to the ice is linearly proportional to the temperature contrast between the ice and air, and it also depends strongly on wind speed and the aerodynamic roughness of the ice. Thus, in less arid conditions the ELA is mostly sensitive to air temperature, not precipitation.

Modern annual precipitation in Central Asia ranges from <75 mm (e.g., western Tibet, Gobi Desert) to 200 mm (Gobi-Altai range, Mongolia) to 400 mm (Sayan Range, Siberia) to more (Kyrgyz Front Range, near Bishkek). It appears that glaciation is strongly preconditioned by aridity and therefore, in continental cores glaciation is highly sensitive to rain-shadow effects and changes in storm tracks. The theory presented above suggests that glacial advances should have different histories from place to place in Central Asia today, and also in the past.

Discussion in the next section focuses on differences in glacial chronologies where there are dated moraine sequences. It is not intended to be an exhaustive review, but to illuminate different history from place to place.

Glacial conditions in southern Siberia

Advection of moisture. Moisture is delivered to Central Asia in two main ways: low-pressure cyclonic distances carried along the jet stream, and southern moisture brought north by the Monsoon (fig. 6). The jet stream varies seasonally, and so do the tracks of surface westerlies bearing moisture. Displacement of the jet stream during the Pleistocene was likely associated with changes in precipitation patterns.

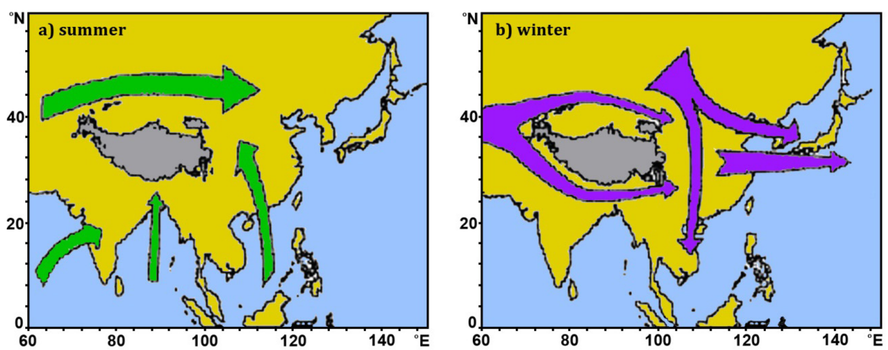


Fig. 6. Moisture advection in Asia [9]. a) Summer, the jet stream (West–East arrow) is to the north over southern Siberia and moisture is transported north by the Monsoon (North-directed arrows). Much is blocked by the Himalaya. b) In winter, the jet stream is shifted southwards and spilt by the Pamir. Cold air moves south from the thermal high-pressure cells over Siberia. Tibetan plateau is shown in gray

The summer jet stream passes over southern Siberia, but low-pressure disturbances bring little regional precipitation because the path from distant oceans is so long. Yet, orographic precipitation is common. Moisture transported north by the Monsoon is blocked by the Himalaya and the region of the Altai Republic is little affected. Orographic precipitation occurs from both sources, however, aided by recycling, including recycling of water made available by melting permafrost.

In winter, the jet stream is shifted southwards and spilt around the Pamir. Cold air moves south from the thermal high-pressure cells over Siberia, and precipitation reaching northern Central Asia is limited. During the Pleistocene, the jet stream was typically farther south than today, split more often, and the Monsoon was weaker, resulting in greater aridity.

The decreased precipitation resulted in some Pleistocene glaciers being in the precipitation-dominated regime discussed above, and others being in the temperature-dominated regime. The regime changed not only between modern and Pleistocene climate, but also within the Pleistocene.

Glaciers in southern Siberia

The Altai and Sayan mountains of southern Siberia and northern Mongolia were extensively glaciated during the Pleistocene (fig. 7). In particular, the northern parts of both ranges were covered in the Pleistocene by large ice sheets. The purpose here is not to supply a full review of the literature on glaciers in this area, but to refer to studies for which chronologies have been developed.

In the Sayan, the oldest well-preserved moraines date from the global LGM or a little after, around 16–20 ka (^{10}Be) [12]. Glaciers from the Sayan crossed and blocked the Little Yenisei River (Shishhid Gol), impounding a lake that drained repeatedly [13]. ^{14}C and Optically Stimulated Luminescence (OSL) dates from the lake sediments [9], including new and unpublished dates, support the ^{10}Be ages but also suggest the presence of an earlier lake at ~40 ka. The highest shorelines associated with the ~20 ka glaciers are at 1710 m, but there are higher ones up to ~1825 m that are heavily eroded and must date from an earlier glaciation with larger glaciers and a deeper dam [13]. Thus, the global LGM was only the most recent of multiple glaciations with large glaciers – and the local LGM was actually earlier than the global one.

This is an example of asynchronous behavior of mountain glaciers in Central Asia compared to the advances and retreats of the high-latitude ice sheets [2]. It is possible that the earlier piedmont glaciers of Jarai Gol terminated and floated in the lake (‘Ledoyoms’), leading to a disorganized and distributed end moraine that was covered by silt during the ~20 ka advance.

Twenty recent and unpublished ^{10}Be dates from the Sayan in southern Siberia, just across the border from Darhad Basin, support the ~20 ka age of the last large Sayan ice cap and its outlet glaciers.

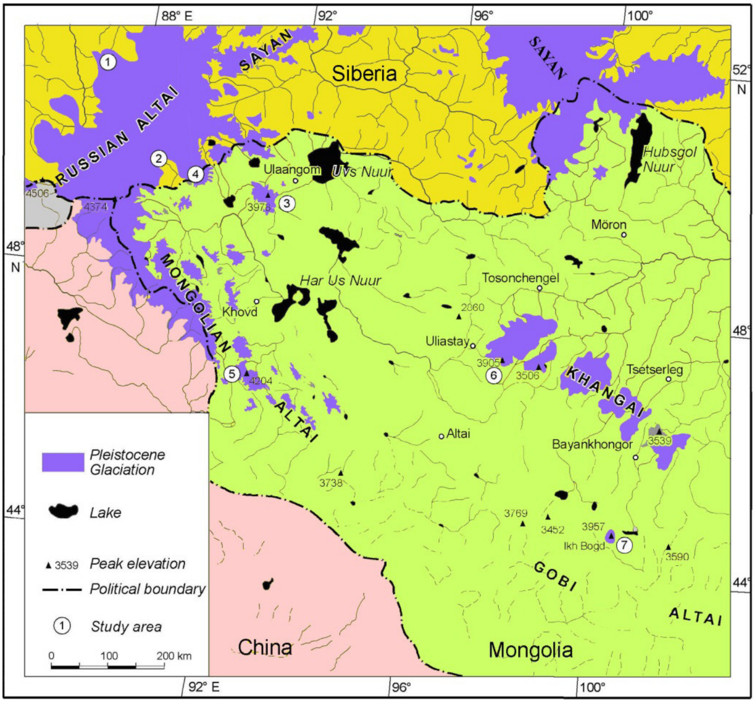


Fig. 7. Distribution of Pleistocene (blue) and modern (black) glaciers in southern Siberia [10, 11]. The Russian Altai is in the upper left

Fig. 8. View of the piedmont moraines (16–20 ka, ^{10}Be: [12]) from the terminal moraine of the Jarai River, draining into Darhad Basin Mongolia. Photograph was taken looking east. The location is shown by the red box in the inset index map

In the Kyrgyz Republic, parts of the Tien Shan are more arid than the Sayan, while the northern part of the Front Range near Bishkek receives more precipitation, probably because the moisture-bearing storms are diverted to the north by the wedge of high mountains, leaving the interior ranges in a rain shadow. In the Ala Bash area, south of the large inland lake Issyk Kul, the Pleistocene glaciers reached the piedmont, but not recently (fig. 9) [14]. The local LGM glaciers at ~18 ka (^{10}Be) were little more extensive than the modern ones.

Fig. 9. Ala Bash, Tien Shan, Kyrgyz Republic. Dates shown are ^{10}Be exposure ages. The MIS 5 dates on the right are for the local LGM left-lateral moraine; the younger dates to the left are for LIA and global LGM moraines, respectively, both found in the cirque and not on the piedmont like the local LGM moraines to the right. The ELA for the global LGM advance here was only ~50 m lower than for the LIA advance. The location is indicated by the red square in index map [14]. Photography: S. Thompson

The ELA trends from north to south across the Kyrgyz Tien Shan (fig. 10) show the effects of the rain shadow, both today and during the Pleistocene [14]. Essentially, the Kyrgyz front ranges on the northern flank of the Tien Shan block many moisture-bearing storms from crossing southwards to the central Tien Shan and the Tarim Basin beyond. The pronounced discordance in the trends can be attributed to relative changes in precipitation. Especially, the local LGM saw a dramatic rise in ELA into the rain shadow, consistent increased aridity then, and consistent with the model presented in this paper. The observations can be explained if LGM precipitation in the core of the Kyrgyz Tien Shan crossed the 150 mm yr^{-1} threshold, while in other areas precipitation exceeded that value.

The ^{10}Be dates were compiled in [12] and are compared in Figure 11. In the Sayan (Darhad Basin), there are two sets of moraines that date from ~20 ka and ~40 ka, and both of the glaciers that left them impounded lakes that left silt sediments yielding similar OSL ages. The Sayan, even in the Pleistocene, probably received more precipitation [12] than the 150 mm yr^{-1} regime threshold. In contrast, the Ala Bash is closer to the threshold today and possibly dipped below it during the global LGM [14].

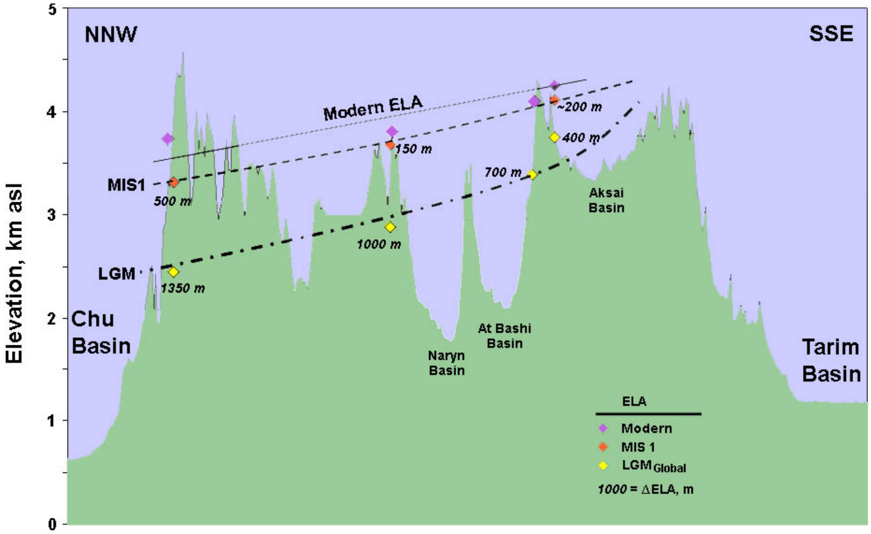


Fig. 10. ELA trends for modern, Holocene and local LGM glaciers in the Kyrgyz Tien Shan [14]. The LGM trend is strikingly discordant with the modern trend. Italicized numbers show the depression of the paleo-ELA relative to interpolated modern values

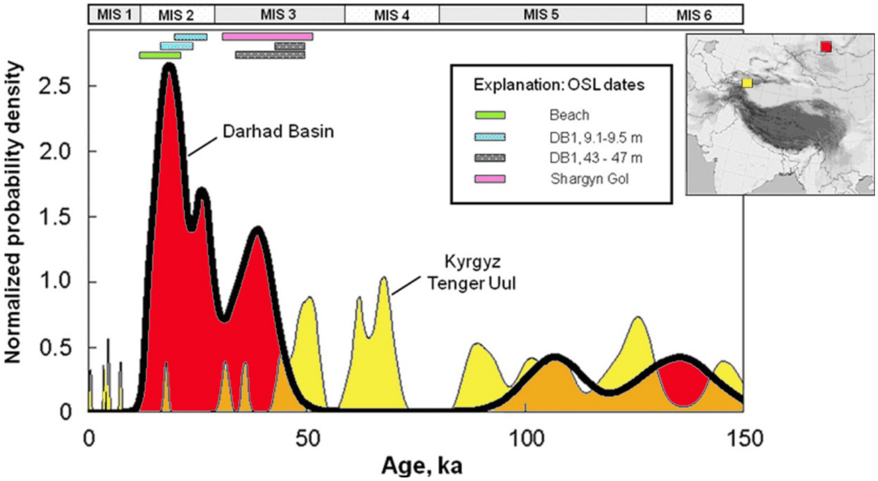
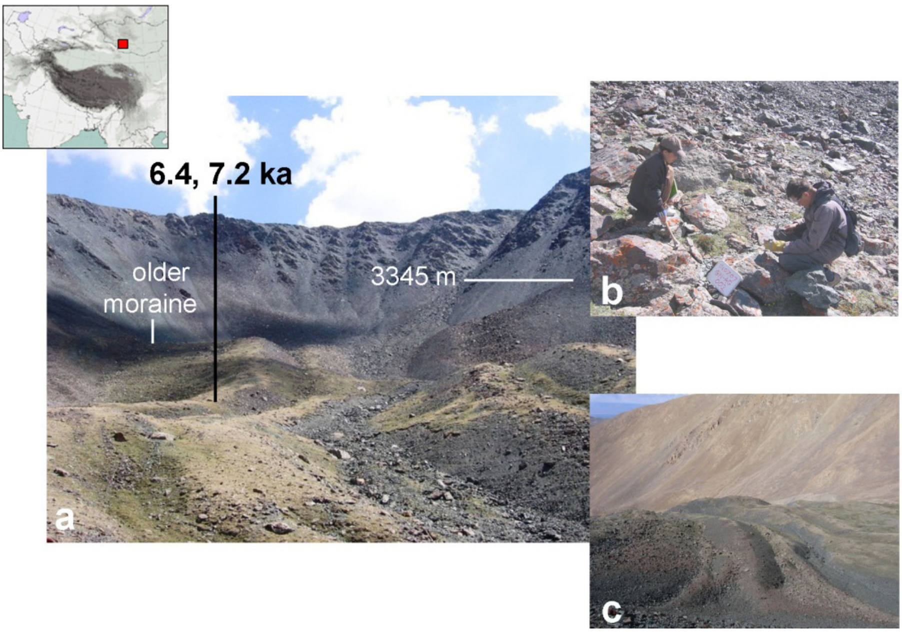


Fig. 11. Glacial chronology from Darhad Basin, southern Sayan range in Mongolia [12], and the Kyrgyz Tien Shan (Tenger Uul: 'Uul' = mountain range) [14]. The curves are for the ^{10}Be dates. Above the curves are rectangles giving the OSL dates for the glacial paleolake that filled Darhad Basin. In the explanation, 'DB1' refers to the Darhad Basin core extracted near the town of Renchinlkhűmbe in 2004; Shargyn Gol refers to a prominent cut bank through the lake sediments north of the drill site. Bars at the top show the marine oxygen isotope stages (MIS) defined by changes in $\delta^{18}O$ in marine fossils. The chronology in Darhad Basin is essentially synchronous with the sea-level curve (fig. 3). The red square in the right center of the index map shows the location of Darhad Basin; yellow box in left center shows the Kyrgyz Tien Shan

In any case, the global LGM glaciers are little larger than the modern ones, in contrast to those from earlier in the last 100,000-yr glacial cycle, which extended beyond the range front (figs. 9, 10) [14]. Figure 11 shows, for the moraines dated in [14], the global LGM moraines are under-represented in the Kyrgyz Tien Shan compared to in the Sayan, and even the ~40 ka moraines are less prominent in Tien Shan than in the Sayan.

Recently, we have discovered moraines in the Gobi-Altai ranges of the Gobi Desert, in Mongolia (fig. 12).



Fig/ 12. Moraines in the Gichigniy Nuruu, Gobi Desert, Mongolia. Index map with red square shows the location of the Gichigniy Nuruu in the Gobi-Altai range. a) Preliminary ^{10}Be ages (~7 ka) suggest that the largest moraines date from the mid-Holocene Altithermal and over-ride a more weathered, older moraine. Preliminary ages for the younger, higher moraines are ~1.6 and 2.0 ka, probably dating from the Little Ice Age (LIA). The highest deposits of the LIA moraine (and hence the ELA) are at 3345 m asl. The cirque is eroded into a mesa covered by a Pleistocene ice cap. View is to the south. b) Sampling for ^{10}Be on the "Altithermal" moraine. c) View NE from the LIA moraine at the older moraine sequence. A total of five advances are represented. Photographs by. J. Batbaatar

Dating them confirmed their unweathered appearance, which suggested a low age: the largest moraine dates from ~6–7 ka, a time when Mongolia is thought based on lake high stands to have received more moisture than today. This, too, is in accordance with the theory presented above. Today, the annual precipitation in the Gobi Altai is about 200 mm, close to the 150 mm yr^{-1} threshold. It appears that it may have been greater during the Altithermal, leading to advancing glaciers. In contrast, during the global LGM it is likely that the Gobi was colder and drier than today, dropping under the 150 mm yr^{-1} precipitation threshold, and causing the LGM ELA to rise above the Altithermal ELA, to near the 3600-m top of the Gichigniy Nuruu ('Nuruu' = massif or range), instead of lowering as it seems to have done in southern Siberia. The young "Gichigniy Nuruu" moraines burying an older undated one whose weathered appearance is similar to global LGM moraines from nearby in the Central massif (Otgon Tenger, Khangay Nuruu). Thus, as at Ala Bash, the arid global LGM appears to have been too dry to support low-elevation glaciers compared to the climates that preceded and followed, it. Climate-change studies.

The growth and decay of glaciers is in response to climatic changes, primarily in temperature and precipitation, but also to cloudiness, wind, and airborne dust. Despite this complicated picture, alpine glaciers are important in climate studies in Central Asia because they are widespread – there are ~6000 modern glaciers in Kyrgyzstan alone. Therefore, even though inferences from single glaciers may be uncertain, together they present a spatial record of climate parameters that is different from and complementary to records from point sources, such as ice or lake-sediment cores. In addition, mass balance can be inferred from glacier extent, making regional measurements of hundreds or thousands of glaciers feasible. Thus, they form an important repository not only of paleoclimatic information, but also information regarding modern climate change.

Implications of aridity for climate-change studies… Although it is certainly true that glaciers respond to changes in temperature by advancing or retreating, in very arid regions such as are found today in much of Central Asia, their sensitivity to precipitation changes is much greater. Therefore, it is necessary to consider the amount of precipitation before using the advance or retreat of a glacier as evidence for global warming or cooling. Because warm air holds more moisture than cold air, glaciers in arid regions may well advance in the face of increasing temperature, if warmer storms bring more moisture to the accumulation area. Thus, glacier advance or retreat alone is insufficient to determine the sense of climate change, yet anecdotal accounts of singular advancing glaciers is commonly used in popular discussions of climate change as evidence that the climate as a whole must be cooling.

Importance of meltwater to populations… In arid regions glacial meltwater has been acknowledged to be critical is sustaining populations through the dry seasons. Thus the advance or retreat of glaciers in and of itself is important to consider. However, in the long run it is long-term aquifer recharge, and hence precipitation itself, that is most critical, since arid communities commonly mine water with wells and karez. Because glaciers are dynamic repositories of water, their loss is primarily of short-term importance.

Outburst floods and retreating permafrost... Glaciers often are associated with marginal lakes that are dammed by the glaciers themselves. When such glaciers retreat, ice-dammed lakes are likely to generate outburst floods that can be damaging to populations downstream. In both the above cases, the glaciers themselves are of fundamental interest; however, glaciers are also of interest because they can be used, where P>150 mm yr^{-1}, to help study temperature changes in remote areas far from gauges, or between gauges. In Arctic Canada, Alaska, and Siberia, this is of great importance, because warming conditions will be associated with retreat of permafrost northward. Among the numerous environmental impacts this may have, one stands out: permafrost is thought to trap (‘sequester’) large amounts of CH_4, a potent ‘greenhouse’ gas. Liberation into the atmosphere is a kind of forward feedback mechanism, potential increasing further global warming and degradation of permafrost, followed by the liberation of still more CH_4, in a vicious circle. Monitoring alpine glaciers is thus not only of scientific interest, but also of practical importance.

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ЧЕТВЕРТИЧНОЕ ОЛЕДЕНЕНИЕ В СЕВЕРНОЙ ЧАСТИ ЦЕНТРАЛЬНОЙ АЗИИ

Одним из важнейших направлений четвертичной геологии является изучение следов, оставленных древними оледенениями. Хотя, на взгляд автора, хронология оледенений на юге Сибири изучена в значительно меньшей степени, чем в других районах нашей планеты, сегодня она постепенно проясняется и начинает становиться более понимаемой исследователями. На Алтае развитие четвертичных оледенений и их хронология подобны тому, что имеет место в Саянах, но отличны от того, что происходило в более южных и засушливых областях Центральной Азии. Отличия обусловлены особенностями палеоклиматических условий во внутренних районах данной территории, особенно в гипераридных областях, где в течение плейстоцена среднегодовое количество атмосферных осадков составляло всего около 150 мм.

В плане экологического прогноза важно, что на основе изучения следов древних оледенений и восстановления палеогляциологических показателей можно проводить определенные экстраполяции с данными по климату. Прежде всего посредством анализа положения оставленных в краевой части древних ледников конечных морен и ледниковых цирков в области их питания возможно реконструировать положение границы питания этих ледников. А отсюда – выйти на показатели, обусловливающие положение этой границы: количество атмосферных осадков и температурный режим. В свете современных изменений климата получение таких показателей крайне важно для снятия имеющихся разногласий в плане соотношения данных об общих, усредненных и конкретных, местных, условиях развития оледенения, а также разночтений в сопоставлении показателей динамики ледников (в процессе их продвижения и отступания) и хода температур. В гипераридных условиях они могут быть инверсионными: повышение температуры может привести к увеличению осадков и продвижению ледников, как это случилось в пустыне Гоби в голоцене в так называемый высоко-термальный период. Выяснение всех особенностей такого рода поможет исследователям более детально вникнуть в процесс оледенения, лучше понять его закономерности и построить более надежную основу экологического прогноза.

Ключевые слова: *четвертичное оледенение; палеоклиматические условия; палеогляциологические показатели; экологический прогноз.*

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