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Palaeogeography, Palaeoclimatology, Palaeoecology 209 (2004) 219–226
PALAEO
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# Equilibrium-line altitudes on reconstructed LGM glaciers of the northwest Barguzinsky Ridge, Northern Baikal, Russia

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Received 1 January 2003; accepted 5 February 2004

## Abstract

The spatial extent of the Last Glacial Maximum (LGM) glaciers (MIS 2) in the northwest of the Barguzinsky Ridge has previously been mapped. Geographical information system (GIS)-computing of the glaciers' quantitative parameters allowed us to use various methods to evaluate the former equilibrium-line altitudes (ELAs) for the 10 largest glaciers. ELAs on reconstructed glaciers were calculated using four common methods: (1) the median elevation of glaciers (MEG), (2) the toe-to-headwall altitude ratio (THAR), (3) the accumulation area ratio (AAR), and (4) Gefer's method. The results suggest that the mean macroclimatic LGM "background" ELA for the area studied was about 1200 ± 145 m above present sea level and the mean ELA depression relative to modern conditions was about 1100 m. Tentative estimates suggest that the reconstructed glaciers could have existed in a drier (about 1.5 times drier-than-present) environment if the mean summer air temperature was about 8–9 °C lower than present day.

*Keywords:* Baikal; Last glacial maximum; Equilibrium-line altitude; Geographic information systems; Climate change

## 1. Introduction

A glacier's equilibrium-line altitude (ELA) is an important climate descriptor for the glacial watershed's summer (ablation season) air temperature and winter (accumulation season) precipitation. Normally, accumulation increases and ablation decreases with increasing elevation. The equilibrium-line altitude is a line on the glacier where accumulation equals ablation and specific mass balance equals zero. The ELA divides a glacier into a zone with a net gain of mass (net accumulation zone) and a zone with a net loss of mass (net ablation zone). On a climate-adjusted glacier, the climate-sensitive parameter ELA depends on accumulation and ablation-related processes. Winter precipitation and summer air temperature are the most important factors for midlatitude glaciers (Nesje, 1989).

Modern ELA can be determined by direct mass balance measurements on the glacier. Palaeo-ELAs can be used for reconstructing paleoclimate. As it is not possible to define mass balance on palaeo-glaciers, different, indirect approaches have been developed for palaeo-ELA evaluations. The main purposes of this paper were to calculate palaeo-ELAs using theoretical methods for the previously reconstructed Last Glacial Maximum (LGM) glaciers in the northeast of Baikal and to evaluate mean ELA depression during the LGM for future regional paleoclimatic reconstructions.

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doi:10.1016/j.palaeo.2004.02.021

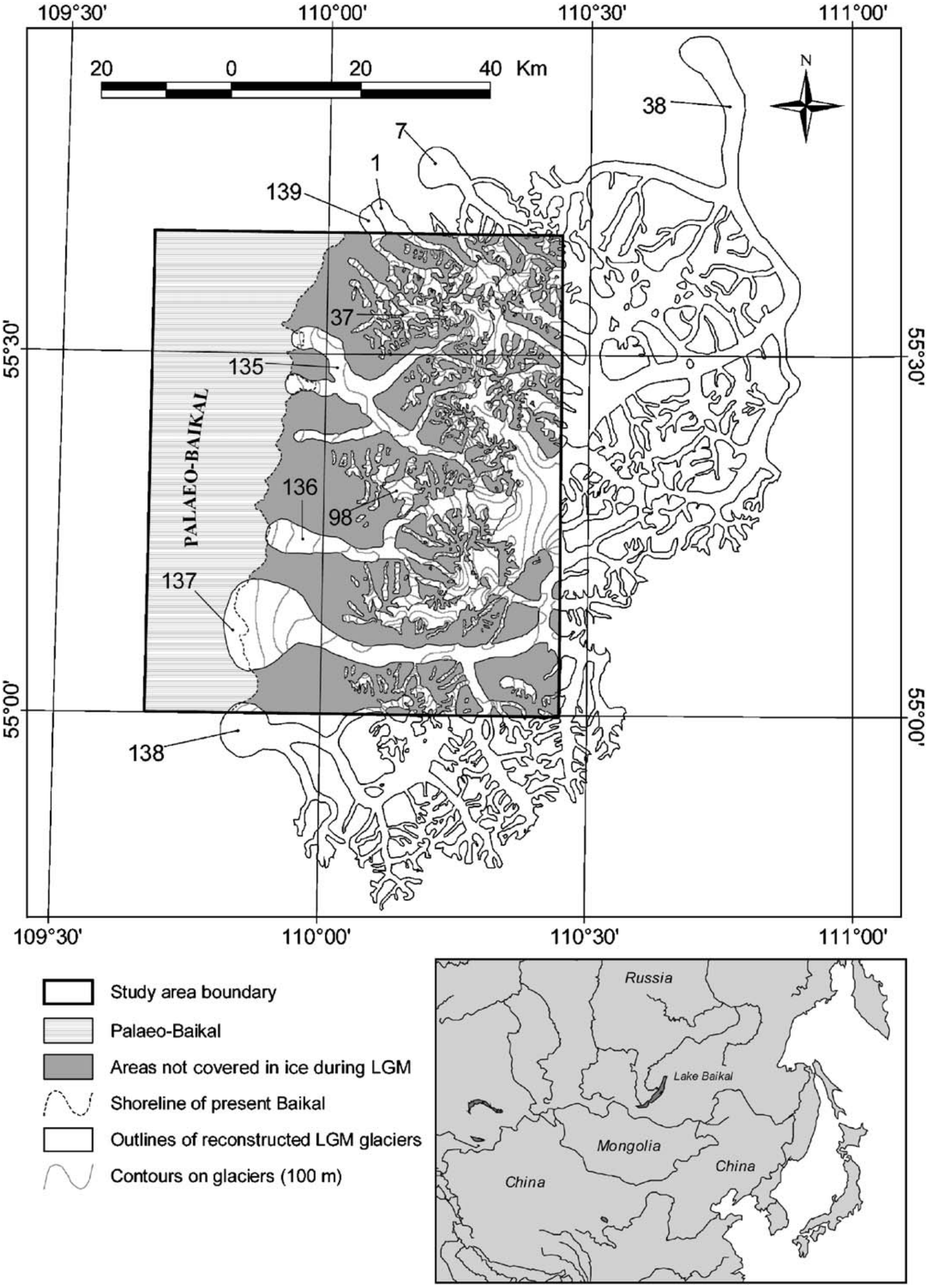

Fig. 1. Location and map view of reconstructed LGM glaciers in the study area (after Osipov et al., 2003). The numbers indicate the location of the specific glaciers sampled in this study (Tables 1 and 2).

## 2. The study area and reconstructed LGM glaciers

The study area is situated to the northeast of Lake Baikal and includes the northwest part of the Barguzinsky Ridge with summits more than 2200 m a.s.l. (the highest summit is 2436 m) and includes about 100 km of shoreline along the Baikal coast. Well-preserved glacial landforms located here were identified on stereo aerial photographs and investigated in the field. Terminal and lateral moraines, cirques, areas of glacial scour, palaeo-stream channels, and trimlines have enabled accurate three-dimensional geographical information system (GIS)-reconstruction of former glacier outlines during the LGM (Osipov et al., 2003; Fig. 1).

Correlation of the paleoglaciological reconstruction with the LGM (i.e. within the marine isotope stage 2—MIS 2) is mainly based on a tentative age correlation of terminal moraines occurring near the Baikal shoreline. Very "fresh" moraine morphology and similar relationships with two embedded lower lake terraces (about 3 and 8 m above present lake level, Mats, 1974) suggest a relative synchronism of the moraine deposition during a Late Pleistocene glacial maximum. The upper age limit of the maximal moraine deposition, as determined by singular $^{14}$C-dates of interglacial (MIS 3) organic matter mixed into in the moraine bodies (not in situ), is believed to be about 34–39 ka BP (Mats, 1993; Back and Strecker, 1998). The lower age limit, assigned by $^{14}$C-dates of organic matter from Aeolian sands covering an abrasion platform of the 8 m Baikalian terrace, is likely to be about 10–13 cal. ka BP (Popova et al., 1989; Back and Strecker, 1998). Formation of the terrace abrasion platform should correlate with a rise in lake level due to intensive glacier melting during the Bølling/Allerød warming (about 13–15 cal. ka BP). Hence, we can postulate that the coastal maximal moraines with "fresh" morphology seem to correlate with the global LGM, which occurred approximately 18–22 ka BP (Lowe and Walker, 1997). Detailed geomorphologic evidence and age interpretations of the glaciers' reconstruction are presented in Osipov et al. (2003).

As a result, 149 LGM glaciers with different morphologies were reconstructed within the region. The largest glacier tongues were tens of kilometers long and extended beyond the palaeo-Baikal shoreline, producing icebergs. In total, 46% (1528 km$^2$) of the territory studied was covered by ice, and its volume within the study area was about 174 km$^3$. For palaeo-ELA calculations the 10 largest LGM glaciers were used in this study (Table 1). All of these test glaciers have a valley morphology, six glaciers are "dendrite-like" and four glaciers are "complex."

Table 1
Parameters of the sampled paleoglaciers

| Glacier no. | Area (km$^2$) | Main tongue length (km) | Morphology | Aspect | MIN | MAX |
|---|---|---|---|---|---|---|
| 38 | 1067.1 | 97 | dendrite-like | SE | 480 | 2395 |
| 137 | 993.8 | 66 | dendrite-like | NW | 380 | 2310 |
| 138 | 397.6 | 51 | dendrite-like | NW | 430 | 2130 |
| 135 | 276.9 | 40 | dendrite-like | NW | 390 | 2040 |
| 136 | 159.8 | 31 | dendrite-like | W | 410 | 2040 |
| 7 | 116.3 | 27 | dendrite-like | NW | 560 | 2095 |
| 1 | 57.4 | 19 | complex | W | 540 | 2040 |
| 139 | 42.5 | 16 | complex | NW | 520 | 1860 |
| 37 | 20.9 | 7 | complex | SW | 965 | 1840 |
| 98 | 15.7 | 4 | complex | SW | 1110 | 1675 |

MIN—altitude of the lowest point of glacier, MAX—altitude of the highest point of glacier (meters above present sea level).

## 3. Methods of determining palaeo-ELAs

The palaeo-ELAs of the LGM glaciers were estimated from (1) the median elevation of glaciers (MEG), (2) the toe-to-headwall altitude ratio (THAR), (3) the accumulation area ratio (AAR), and (4) Gefer's method. Quantitative parameters of the reconstructed glaciers based on these estimates were analyzed with ArcView GIS.

### 3.1. Median elevation of glaciers

The median elevation of a glacier is often used for quick ELA estimates (Meierding, 1982) but empirical evidence from modern glaciers suggests that this method overestimates the ELAs (Meier and Post, 1962). In addition, the method fails to take into account variations in valley morphology (Meier and Post, 1962; Nesje, 1992; Aa, 1996). The best results are obtained for small, geometrically regular glaciers (Porter, 1981; Nesje, 1992).

### 3.2. Toe-to-headwall altitude ratio

A ratio between the maximum and minimum altitude of a glacier is also applied for quick estimates of ELA (ELA = lowest elevation of glacier + vertical range × ratio). The THAR method gives the best results on small, geometrically regular glaciers with a normal distribution of areas and altitudes (Porter, 1981). Meierding (1982) and Murray and Locke (1989) found that ratios of 0.35–0.40 gave the best results. Nesje and Dahl (1991); Torsnes et al. (1993) and Aa (1996) used THAR of 0.4. As a rule, values of the ratio vary from 0.35 to 0.42 depending on the degree of continentality of conditions. In this study a ratio of 0.42 was used.

### 3.3. Accumulation area ratio

This method is supported by a large amount of observational evidence and involves the calculation of the "accumulation–area ratio" (Meier and Post, 1962). The AAR is defined as the ratio of accumulation area (area above ELA) to the total glacier area. The AAR of a glacier varies mainly as a function of its mass balance; ratios below 0.50 indicate negative mass balance, 0.50–0.80 corresponds to steady-state conditions, and values above 0.80 reflect positive mass balance regimes (Andrews, 1975). The ratio 0.60 ± 0.05 is generally considered as characteristic for steady-state conditions of valley midlatitude glaciers (Porter, 1970, 1975; Andrews, 1975; Andrews and Miller, 1972). Values for ice caps and piedmont glaciers may differ significantly (Meier and Post, 1962; Pierce, 1979). In this study, ELAs were determined from an AAR value of 0.60 using reconstructed glacier outlines, 3D models of glacier surfaces and cumulative curves of glaciers (Fig. 2).

### 3.4. Gefer's method

According to this method, which is well known in the Russian language literature, the ELA can be determined as the arithmetic mean between the elevation of the lowest point of a glacier and the mean elevation of mountain summits surrounding its firn field (Kalesnik, 1963). This method gives satisfactory results if the cross section of a glacier changes insignificantly throughout its longitudinal profile. This method always overestimates the ELA in comparison with the MEG or THAR methods.

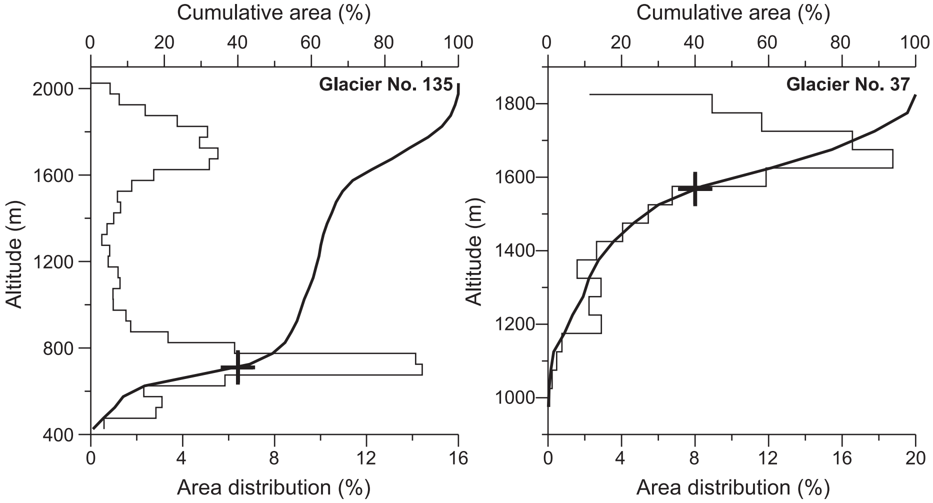

Fig. 2. Plots of area distribution (lower axis) and cumulative area distribution (upper axis) as a function of altitude for two reconstructed paleoglaciers. Cross marks indicate the ELA locations calculated with the AAR technique and a ration of 0.60. The locations of these glaciers are shown in Fig. 1.

## 4. Results and discussion

### 4.1. The ELAs of reconstructed LGM glaciers

ELAs for the LGM glaciers were calculated using various approaches and the results are presented in Table 2 and Fig. 3. The ELA values range from 690 m (glacier no. 135, AAR) to 1580 m above present sea level (glacier no. 37, AAR). The arithmetic mean for the ELA calculated by four different methods (AAR, THAR, MEG and Gefer's method) is 1270 m with a standard deviation of 165 m. The range of ELA estimates for the same glacier based on these different methods can be hundreds of meters (maximum 550 m for glacier no. 135). At the same time, spatial differences between the various glacier ELA estimates when using a single method vary from 230 m (Gefer's method) to 890 m (AAR). The AAR method is the most variable (the standard deviation is 280 m), and the MEG and Gefer's methods the least variable (the standard deviations are from 80 to 85 m). However, the latter two methods give the highest ELA values (arithmetic mean is 1310–1340 m). The THAR method yielded the lowest mean ELA (1190 ± 100 m). Despite some differences in the methods applied, the mean results for each individual glacier are similar. For example, the correlation ratios for pairs of methods vary from 0.78 (MEG-AAR) to 0.98 (Gefer's-MEG).

Table 2
Calculated ELAs of the sampled glaciers

| Glacier no. | Methods | | | |
|---|---|---|---|---|
| | MEG | Gefer's | THAR = 0.42 | AAR = 0.60 |
| 38 | 1440 | 1470 | 1280 | 1510 |
| 137 | 1350 | 1360 | 1190 | 1390 |
| 138 | 1280 | 1300 | 1140 | 1250 |
| 135 | 1220 | 1240 | 1080 | 690 |
| 136 | 1230 | 1260 | 1090 | 950 |
| 7 | 1330 | 1380 | 1200 | 1090 |
| 1 | 1290 | 1330 | 1170 | 1140 |
| 139 | 1190 | 1260 | 1080 | 1240 |
| 37 | 1400 | 1440 | 1330 | 1580 |
| 98 | 1390 | 1400 | 1350 | 1500 |
| Arithmetic mean | 1310 | 1340 | 1190 | 1230 |
| St. deviation | 85 | 80 | 100 | 280 |

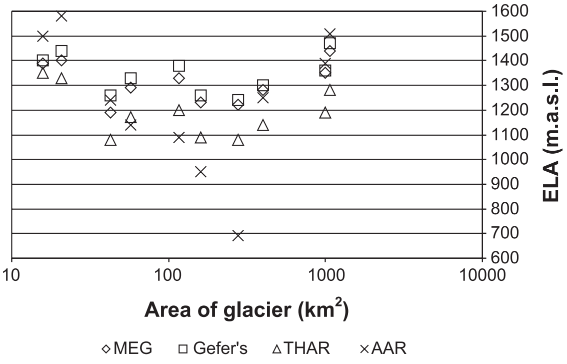

Fig. 3. Estimated ELAs for 10 reconstructed glaciers as a function of glacier areas.

The differences in the calculated ELAs cannot be explained by climatic variations within this relatively small region. Rather, these differences can be explained by the choice of the method applied, its accuracy, number of glaciers sampled and local glacial conditions. Multiple studies have paid special attention to methodological factors (Meierding, 1982; Nesje, 1992; Torsnes et al., 1993, etc.). In general, the results obtained in the area studied do not contradict previous inferences. The MEG and Gefer's methods take the least account of local glacier conditions (unlike the AAR method) and give very similar but overestimated ELAs. The AAR method has a more satisfactory physical basis because it integrates surface areas and absolute elevations. However, it is known (Nesje, 1992) that the method strongly distorts ELAs on glaciers with unusual AAR or elevation. This method is likely to underestimate ELAs on glaciers with relatively large ablation areas (nos. 135, 136, Fig. 2) and to overestimate ELAs on glaciers with relatively large accumulation areas (nos. 37, 38, 98, 137, Fig. 2). The THAR method seems to give results that are more reliable for all glaciers, although possibly slightly underestimated. The examination of calculated ELAs on the paleoglaciers shows a strong dependence on local glacier environments (aspect, morphology and topography). For example, ELAs on large windward (W and NW) facing glaciers with complex architecture (nos. 1, 7, 135–139) are lower and more variable (Tables 1 and 2). Earlier, it was established that in glaciated mountain regions the ELA variation range decreases with an increase in the glacier's area (Seversky, 1978). The mean level of this range can be regarded as specific macroclimatic or "background" ELA ("reduced" ELA after Seversky, 1978) for the region. Calculations in many regions showed that for glaciers with an area exceeding 14 km$^2$, further increases in area do not change the ELA (Seversky, 1978). This suggests that ELAs calculated for glaciers with an area of more than 14 km$^2$ can be regarded as ELAs adjusted to the macroclimate of the given region. In this study, only glaciers with an area exceeding 14 km$^2$ and with NW or W aspects (windward macroslope of Barguzinsky Ridge) were used to estimate the mean "background" ELA. The ELAs calculated for seven sampled glaciers (Table 1, glacier nos. 1, 7 and 135–139) vary from 690 (glacier no. 135, AAR method) to 1390 (glacier no. 137, AAR method) m. The arithmetic mean was calculated, to account for underestimation and overestimation of ELAs calculated using different methods, and this value equals 1200 ± 45 m. Thus, the mean "background" (macroclimatic) LGM ELA for the northwest of Barguzinsky Ridge may be estimated as about 1200 m above present sea level.

### *4.2. The ELA depression during the LGM*

The ELA depression of a glacier due to climate change is significant for paleogeographical reconstructions. The term "LGM ELA depression" in this study means the lowering of ELA due to climate changes favorable for the glaciers' mass balance during the LGM (Kotlyakov et al., 1984). Since glacier mass balance is a function of accumulation and ablation, changing ELA must reflect the combined effect of air temperature and precipitation. The value of the ELA depression can be calculated as the difference between former and modern ELAs.

There are no glaciers within this region at present. Therefore modern ELAs can be determined only by indirect methods. It must be pointed out that there is some evidence for the possible existence of small cirque glaciers in the highest mountains of Barguzinsky Ridge (personal communication from tourists and L. Plastinin, Koshelev, 2000). Moreover, this possibility was predicted by a map of the modern ELA distribution field (Krenke, 1982). Nevertheless, these data have not yet been verified. In this study, a "virtual" modern ELA is considered and it may be evaluated using indirect approaches. The closest glaciated mountain region to the area studied is the Kodar Ridge (57°N and 117.5°E) situated about 500 km to the northeast where there are about 30 small valley and cirque glaciers at present (Preobragensky, 1960; Dolgushin and Osipova, 1989). North facing Kodar glaciers (windward glaciers) have a modern ELA level of 2050 to 2550 m a.s.l. (the mean is 2300 m). Due to the geographical proximity of the modern Kodar glaciers to the area studied, the environments of these regions are very similar. The presence of glaciers at the Kodar Ridge and their absence at the northwest of Barguzinsky Ridge can be explained by the higher summit level on the Kodar Ridge. Accordingly, if there were glaciers in the area studied, the ELA would be situated at about 2300 m a.s.l. Snowfields, whose levels can be directly determined in the region, can be indirect descriptors of ELA elevation. According to Tronov (1966), differences between ELAs and snowfield levels are about 300–500 m (mean 400 m). On the basis of topographic map analyses (scale 1:25 000) and field investigations, the mean altitude of the snowfield level is about 1900 m a.s.l. Hence, the modern ELA estimated in this way is also about 2300 m. Therefore, if the "modern" ELA altitude is about 2300 m and the former LGM ELA altitude was about 1200 m, the mean ELA depression in the area studied at the LGM was about 1100 m. No correction factor for glacio-isostatic depression (during the LGM) or tectonic uplifting (after the LGM) was added to the ELA depression because they seem to be minimal (within the standard error of applied ELA calculation methods). This inference is supported by the depth of postglacial erosion incisions into trough bottoms in areas of maximal ice thickness (usually not more than the first tens of meters, Jacenko, 1950) and by an estimate of the mean glacial erosion rate (Osipov et al., 2003). On the whole, this estimate of LGM ELA depression is similar to those that have been calculated for other regions (Brigham-Grette et al., 1997; Heine, 1997; Bacon et al., 2000; Porter, 2001).

### *4.3. Some palaeo-climatic inferences*

The LGM is regarded as a time of cold and dry climate conditions in this area. Many pollen records from Lake Baikal sediment cores (Horiuchi et al., 2000) clearly show that glacial-type grasses were the dominant vegetation types in the lake watershed during the LGM, which also suggests a cold and dry environment. However, conditions were unlikely to have been extremely dry because palaeo-Baikal, which was free of ice during at least 5 months of the year (Shimaraev et al., 1995), and may have been an additional source of moisture. A plausible scenario assumes a 1.5–2 times decrease in total precipitation compared to present-day conditions. Given such aridity, the estimated ELA depression (1100 m) implies a substantial lowering of air temperature (especially during the summer season) during the LGM. Based on the assumption that the mass balance for steady-state glaciers was controlled solely by summer (ablation season) temperature, and assuming a full-glacial temperature lapse rate of 6.3 °C/km (Preobragensky, 1960), the depression of mean annual temperature in glaciated mountain areas was about 6.9 °C. A tentative calculation based on an ELA depression/temperature/precipitation model (Glazyrin, 1991) suggests that an ELA depression of 1100 m accompanied by a 33% reduction in annual precipitation (1.5 times less than in modern conditions) requires a decrease in summer air temperature of 8.5 °C. These estimates are in good agreement with multiple regional and global palaeo-climate reconstructions (Dong and Valdes, 1998; Volkova and Mikhajlova, 2001).

## 5. Conclusion

Four independent methods provide similar estimates of the LGM (MIS 2) ELAs on 10 test paleoglaciers previously reconstructed in the northwest of Barguzinsky Ridge. The arithmetic mean of values calculated by AAR (with ratio 0.60), THAR (with ratio 0.42), MEG and Gefer's methods is 1270 m a.s.l. with a standard deviation of 165 m. However, the ELAs adjusted to macroclimatic conditions during the LGM can be calculated only on glaciers with areas that exceed 14 km$^2$ and with west or northwest (i.e. windward) exposure for the area studied. The calculations for these seven representative glaciers gave a mean arithmetic ELA value of about 1200 m a.s.l. (1200 ± 145 m) and ELA depression during the LGM about 1100 m. Tentative estimates suggest that the reconstructed glaciers could have existed in drier environments (1.5 times drier than in present conditions) if the mean summer air temperatures was lower by about 8–9 °C.

## Acknowledgements

The author thanks Prof. M. Grachev (Limnological Institute, Irkutsk) for his general support of this study, Dr. O. Savoskul (Institute of Geography, Moscow) for useful recommendations in the calculation of palaeo-ELAs and two anonymous reviewers for their constructive suggestions and remarks.

## References

Aa, A.R., 1996. Topographic control of equilibrium-line altitude depression on reconstructed 'Little Ice Age' glaciers, Grovabreen, western Norway. Holocene 6 (1), 82–89.

Andrews, J.T., 1975. Glacial Systems. An Approach to Glaciers and their Environments. Duxbury Press, North Scituate.

Andrews, J.T., Miller, G.H., 1972. Quaternary history of northern Cumberland Peninsula, Baffin Island, N.W.T., Canada: Part IV. Maps of the present glaciation limits and lowest equilibrium-line altitude for south Baffin Island. Arctic and Alpine Research 4, 45–59.

Back, S., Strecker, M.R., 1998. Asymmetric late Pleistocene glaciations in the North basin of the Baikal Rift, Russia. Journal of the Geological Society (London) 155 (Part 1), 61–69.

Bacon, S.N., Van Dissen, R.J., Goldstein, H.L., et al., 2000. Late Pleistocene equilibrium line altitude estimates from glacial features in the inland Kaikoura Range, New Zealand. Abstracts with Programs—Geological Society of America 32 (7), 18.

Brigham-Grette, J., Mostoller, D., Gualtieri, L., et al., 1997. Limited glacial ice extent across N.E. Russia during LGM, evidence from the Tanyurer River valley, Chukotka. Abstracts with Programs—Geological Society of America 29 (6), 110.

Dolgushin, L.D., Osipova, G.B., 1989. Ledniki Mysl, Moscow. In Russian.

Dong, B., Valdes, P.J., 1998. Simulations of the Last Glacial Maximum climates using a general circulation model: prescribed versus computed sea surface temperature. Climate Dynamics 14, 571–591.

Glazyrin, G.E., 1991. Gornye Lednikovye Sistemy, Ih Struktura i Jevoljucija Gidrometeoizdat, Leningrad. In Russian.

Heine, J.T., 1997. Glacial stratigraphy of the Goat Rocks, Cascade Range, Washington. Abstracts with Programs—Geological Society of America 29 (6), 39.

Horiuchi, K., Minoura, K., Hoshino, K., et al., 2000. Palaeoenvironmental history of Lake Baikal during the last 23 000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 157, 95–108.

Jacenko, A.A., 1950. Ob oledenenii Bajkal'skoj gornoj oblastiVoprosy Geographii, vol. 21. Geographgiz, Moscow, pp. 179–188. In Russian.

Kalesnik, S.V., 1963. Ocherki glaciologii Geografgiz, Moscow. In Russian.

Koshelev, A.A., 2000. Ledniki u Baikala: istoriya obnarujenia. Geografia i Prirodnye Resursy 4, 155–157 (in Russian).

Kotlyakov, V.M., Alekseev, V.R., Volkov, N.V., et al., 1984. In: Kotlyakov, V.M. (Ed.), Glaciologichesky Slovar. Gidrometeoizdat, Leningrad. 528 pp (in Russian).

Krenke, A.N., 1982. Massoobmen v lednikovykh sistemakh na territorii SSSR Gidrometeoizdat, Leningrad. In Russian.

Lowe, J.J., Walker, M.J.C., 1997. Reconstructing Quaternary Environments. Longman, Harlow, Essex.

Mats, V.D., 1974. Bajkal'skie Terrasy Nizkogo Kompleksa. Priroda Bajkala, Leningrad, pp. 31–58. In Russian.

Mats, V.D., 1993. The structure and development of the Baikal rift depression. Earth-Science Reviews 34, 81–118.

Meier, M.F., Post, A.S., 1962. Recent variations in mass net budgets of glaciers in western North America. Publication-De l'Association Internationale d'Obergurgl 58, 63–77.

Meierding, T.S., 1982. Late Pleistocene glacial equilibrium-line in the Colorado Front Range: a comparison of methods. Quaternary Research 18, 289–310.

Murray, D.R., Locke, W.W., 1989. Dynamics of the late Pleistocene Big Timber Glacier, Crazy Mountains, Montana, USA. Journal of Glaciology 35 (120), 183–190.

Nesje, A., 1989. Glacier-front variations of outlet glaciers from Jostedalsbreen and climate in the Jostedalsbreen region of western Norway in the period 1901–1980. Norsk Geografisk Tidsskrift 43, 3–17.

Nesje, A., 1992. Topographical effects on the equilibrium-line altitude on glaciers. GeoJournal 27 (4), 383–391.

Nesje, A., Dahl, S.O., 1991. Late Holocene glacier fluctuation in Bevringsdalen, Jostedalsbreen region, western Norway (ca. 3200–1400 BP). The Holocene 1, 1–7.

Osipov, E.Yu., Grachev, M.A., Mats, V.D., Khlystov, O.M., Breitenbach, S., 2003. Mountain glaciers of the Pleistocene Last Glacial Maximum in the northwestern Barguzin Range (Northern Lake Baikal): paleoglacial reconstruction. Geology and Geophysics 44, 652–663.

Pierce, K.L., 1979. History and dynamics of glaciation in the northern Yellowstone National Park area. Professional Paper-U.S. Geological Survey 729-F. 89 pp.

Popova, S.M., Mats, V.D., Chernjaeva, G.P., et al., 1989. In: Logachev, N.A. (Ed.), Paleolimnologicheskie rekonstrukcii (Bajkal'skaja riftovaja zona). Nauka, Novosibirsk. In Russian.

Porter, S.C., 1970. Quaternary glacial record in Kohistan, West Pakistan. Geological Society America Bulletin 81, 1421–1446.

Porter, S.C., 1975. Equilibrium-line altitudes of late Quaternary glaciers in Southern Alps, New Zealand. Quaternary Research 5, 27–47.

Porter, S.C., 1981. Glaciological evidence of Holocene climatic change. In: Wigley, T.M.L., Ingram, M.J., Farmer, G. (Eds.), Climate and History Studies of Past Climates and their Impact on Man. Cambridge Univ. Press, Cambridge, pp. 82–110.

Porter, S.C., 2001. Snowline depression in the tropics during the last glaciation. Quaternary Science Reviews 20 (10), 1067–1091.

Preobragensky, V.S., 1960. Kodarsky lednikovy raion (Zabaikalie). In: Avsyuk, G.A. (Ed.), IX Razdel Programmy MGG (Glaciologia). Izdat, vol. 74. AN SSSR, Moscow. In Russian.

Seversky, I.V., 1978. K metodike rascheta srednikh godovyh summ tverdyh osadkov na granize pitaniya lednikov. Vestnik Akademii Nauk Kazahskoj SSR 11, 43–50 (in Russian).

Shimaraev, M.N., Granin, N.G., Kuimova, L.N., 1995. Opyt rekonstrukcii gidrofizicheskih uslovij v Bajkale v pozdnem plejstocene i golocene. Geologija i Geofizika 36, 97–102 (in Russian).

Torsnes, I., Rye, N., Nesje, A., 1993. Modern and Little Ace Age equilibrium-line altitudes on outlet valley glaciers from Jostedalsbreen, Western Norway: an evaluation of different approaches to their calculation. Arctic and Alpine Research 25 (2), 106–116.

Tronov, M.V., 1966. Ledniki i Klimat Gidrometeoizdat, Leningrad. In Russian.

Volkova, V.S., Mikhajlova, I.V., 2001. Prirodnaja obstanovka i klimat v jepohu poslednego (sartanskogo) oledenenija Zapadnoj Sibiri (po palinologicheskim dannym). Geologija i Geofizika 42 (4), 678–689 (in Russian).