# A Glacier Inventory for the Buordakh Massif, Cherskiy Range, Northeast Siberia, and Evidence for Recent Glacier Recession

Authors: Gurney, S. D., Popovnin, V. V., Shahgedanova, M., and Stokes, C. R.

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# A Glacier Inventory for the Buordakh Massif, Cherskiy Range, Northeast Siberia, and Evidence for Recent Glacier Recession

*S. D. Gurney*‡
*V. V. Popovnin*†
*M. Shahgedanova** and
*C. R. Stokes**

*Department of Geography, University of Reading, PO Box 227, Whiteknights, Reading, RG6 6AB, U.K.
†Department of Cryolithology and Glaciology, Geographical Faculty, Moscow State University, Leninskie Gory, Moscow 19899, Russia
‡Corresponding author: s.d.gurney@reading.ac.uk

## Abstract

The Buordakh Massif, in the Cherskiy Range of northeast Siberia, contains mountains over 3000 m and, despite its arid climate, numerous glaciers. This paper presents a glacier inventory for the region and documents some 80 glaciers, which range in size from 0.1 to 10.4 $km^2$ (total glacierized area is ca. 70 $km^2$). The inventory is based on mapping derived from Landsat 7 ETM+ satellite imagery from August 2001, augmented with data from field investigations obtained at that time. The glaciers in this region are of the 'firn-less,' cold, continental type, and their mass balance relies heavily on the formation of superimposed ice. The most recent glacier maximum extents have also been delineated, and these are believed to date from the Little Ice Age (ca. A.D. 1550–1850). Glacier areal extent has reduced by some 14.8 $km^2$ (ca. 17%) since this most recent maximum. Of the 80 glaciers catalogued, 49 have undergone a measurable retreat from their most recent maximum extent.

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## Introduction

Retreat of mountain glaciers affects regional freshwater resources and will contribute to sea-level rise over the next 50 to 150 years (e.g. Arendt et al., 2002; Raper and Braithwaite, 2006). Glacier retreat is widespread (e.g. Oerlemans, 1994, 2005) but the magnitude and spatial pattern of this retreat is uncertain (Braithwaite, 2002; Kargel et al., 2005). There are some regions where glacier attributes are unknown and for which glacier inventories have not yet been compiled.

The Buordakh Massif, in the Cherskiy Range of northeast Siberia is one of those regions which has been lacking a glacier inventory. This mountain range was first documented following an expedition led by Obruchev in 1926, but Nekrasov and Sheinkman (1981) were the first to publish a report about the glaciers in this region, although the maps accompanying this work were generalized and without a scale. Their work was based upon aerial photographs obtained in 1970 and supplemented with field investigations conducted between 1971 and 1976 by the Institute for Permafrost Research of the Russian Academy of Science. The data from these field investigations include glacier geometries, geomorphological context, measurements of the vertical distribution of ice temperature and accumulation, and ablation rates (limited to 1971 and 1972). Ice flow velocities were also measured on Obruchev and Sumgin glaciers in 1972 (Nekrasov et al., 1973). These investigations represented all the scientific work conducted in the region until 2001 when fieldwork was conducted by two of the present authors within the framework of a joint Russian/British expedition.

The aims of this paper are (1) to describe the glaciers of the Buordakh Massif based on remotely sensed imagery and field surveys, and (2) to produce a satellite-based glacier inventory for the region.

## Study Area

Multiple glaciations have affected the Cherskiy Range during the Quaternary. Alpine glaciers descended to between 1500 and 1300 m a.s.l. during the Middle Pleistocene (Arkhipov et al., 1986). In the Late Pleistocene the glaciation was possibly more extensive, occupying some 40% of northeast Siberia, and it has been presumed that all interior mountains over 2000 m had ice cover (Arkhipov et al., 1986). During the Last Glacial Maximum the main center of ice was located west of the Cherskiy Range in the Verkhoyansk Range, and ice extended out into the lowlands in the form of a piedmont glacier. In the Cherskiy Range ice was generally restricted to the higher areas where cirque and valley glaciers formed (Chanysheva and Bredikhin, 1981). By the time of the post-glacial climatic optimum (7 to 5 ka BP) it is thought likely that all glaciers had disappeared (Bespalyy, 1984) and, therefore, the contemporary glaciers postdate this period. Presently, the main concentration of glaciers in the Buordakh Massif, Cherskiy Range, are centered around 65°12′N, 145°56′E.

East of the central Yakutian Plain, the geology of Siberia is complex and arises from continental collision and accretion in the Mesozoic (Molnar and Tapponier, 1975). This vast area consists of the Verkhoyansk and Cherskiy mountain ranges, which are separated by the Lena, Yana, Indigirka, Kolyma, and Anadyr Rivers and their tributaries (Huh et al., 1998). The Cherskiy Range trends NW–SE and contains 3000 m peaks, the highest of which is Mount Pobeda (3147 m).

The climate of the Cherskiy Range is continental and characterized by large seasonal variations in air temperature, atmospheric pressure, and precipitation (Lydolph, 1977; Shahgedanova et al., 2002). Temperatures in winter reach −71 °C and in summer exceed 30 °C. Annual precipitation is 208 mm at the closest meteorological site of Oimyakon. The dominant climatic control in the region is the 'Siberian high,' an extensive semi-permanent anticyclone which develops between October and March in response to continuous and strong radiative cooling over the snow-covered surface of northern Asia (Lydolph, 1977; Panagiotopoulos et al., 2005). Being mainly thermally induced, the Siberian high is a shallow cold-core system confined to the lower troposphere. It is replaced by a trough of low pressure above the 700 hPa pressure surface. As a result, the October–March period is characterized by (1) low precipitation below 2000 m a.s.l., which accounts for about 15% of the annual total; and (2) an increase in air temperatures up to 1000 m a.s.l.. Both observations and modeled data suggest that a substantial warming has been observed in eastern Siberia since 1979, both in winter and summer; the former coincides with a pronounced weakening of the Siberian high which has been unprecedented since 1871 (Panagiotopoulos et al., 2005). Furthermore, the recently observed warming and associated changes in atmospheric pressure in northern and eastern Siberia have been extensive (Johannessen et al., 2004; Panagiotopoulos et al., 2005), and a wintertime decline in sea-level pressure in this region has been the highest in the northern hemisphere (Gillet et al., 2003). Climate projections indicate that these trends will likely continue (IPCC, 2001).

Contemporary glaciers in the Buordakh Massif of the Cherskiy Range are of the cold, continental type and belong to the class of 'superimposed ice' of Müller (1962) or the 'infiltration-congelation' class of Shumskii (1964). The lack of firn and the creation of superimposed ice through the refreezing of percolating meltwater in summer are characteristic (Nekrasov and Sheinkman, 1981). The thin snow cover and very low air temperatures in winter result in low ice temperatures similar to those observed in the neighboring Suntar-Khayata Range, where mean annual temperatures for the near-surface ice have been reported at $-10$ °C and below (Koreisha, 1963).

## Methods

### *SATELLITE REMOTE SENSING*

Mapping for the area which could be obtained prior to the fieldwork was extremely limited. The available 1:300,000 maps do not show all of the glaciers, and the sketch maps of Nekrasov and Sheinkman (1981) illustrate most of the glaciers but are without a scale and hence were of limited use. In order to conduct the mapping, therefore, two Landsat 7 ETM+ scenes (from 7 August 2000 and 25 July 2001) were obtained. These were purchased in a geocoded format, since the necessary data for geocoding and orthorectification was not available to the authors; specifically, there is no sufficiently detailed Digital Elevation Model available for the area.

Image processing of the August 2000 scene was conducted in order to produce the best possible images for use during the fieldwork. A 'resolution merge' image of the study area was created which combined the multi-spectral information from three bands (Bands 7 [2.09–2.35 μm], 5 [1.55–1.75 μm], and 3 [0.63–0.69 μm]) with 30 m ground resolution with the 15 m ground resolution band (Band 8 [0.52–0.90 μm]). This process creates an excellent product for identifying geomorphological features, such as glacier margins. Further image processing enabled the removal of areas obscured by cloud on the image so that it would not be confused with snow. The thermal band (Band 6 [10.4–12.5 μm]) was utilized to differentiate cloud from snow cover (the tops of clouds being much colder than snow on the ground), and this technique proved highly effective. During the initial field period the accuracy of the imagery geocoding was assessed using Ground Control Points (GCPs), whereby specific locations which could be clearly resolved on the imagery were visited on the ground to obtain a reference (in degrees, minutes, and decimal seconds) through the use of a Garmin GPS (Global Positioning System) receiver. These references were then compared to the location report provided by the 'Inquire Cursor' function in the Erdas Imagine image-processing software. This process revealed that, in the area under direct investigation at least, the geocoding was accurate to within 1 or 2 pixels of Band 8 ($\pm$20 m).

Following the fieldwork, the glacier mapping was conducted from the 25 July 2001 scene (the satellite overpass took place during the fieldwork). Once again image processing enabled a 'resolution merge' image to be created and clouds to be accurately identified, although it should be noted that the 2001 imagery had very little cloud cover and that present did not hinder the mapping process. Field data obtained at the GCPs (mentioned above) was also used to validate the image interpretation and ground-based photographs from known locations were also employed. The contemporary glaciers and their most recent limits were delimited (mapped) manually through the creation of vector file overlays on top of the ETM+ imagery using Erdas Imagine software. Attempts to use a classification scheme for the mapping (supervised or unsupervised) proved unsatisfactory. The authors' experience of using Landsat ETM+ scenes for glacier mapping elsewhere (Gurney and White, 2005; Stokes et al., 2006) as well as that of others (e.g. Paul et al., 2002; Heiskanen et al., 2002) informed the whole procedure. The discrimination between areas occupied by ice at the most recent glacier maxima and those outside this limit is greatest in Band 5 of the Landsat ETM+ imagery as is evidenced in Figure 1. Figure 2 further illustrates this point by presenting the difference in pixel Digital Numbers (DNs) for equal-sized populations inside and outside the most recent glacier maximum (cf. Eckardt and Milton, 1999). It was precisely this degree of discrimination which permitted the recently glaciated areas to be readily determined and mapped for the inventory.

### *FIELD OBSERVATIONS AND MEASUREMENTS*

While in the field eight glaciers were visited and more detailed studies were made of five of these, namely: Tsaregradskiy, Obruchev, Sumgin, Melnikov, and a glacier without a name which is numbered '48' in the inventory. Ground data was collected at over 50 sites in order to verify interpretations of the satellite imagery as previously mentioned. At each site an accurate location ($\pm$7 m in the $x$ and $y$) was obtained using a hand-held Garmin GPS receiver. Ground data collection sites included moraine junctions, inactive moraines, glacial trim-lines and glacier margins associated with the five glaciers mentioned above, and other features that could be used to provide geomorphological context.

## Results

### *A GLACIER INVENTORY FOR THE BUORDAKH MASSIF*

The glacier inventory given in Table 1 contains information on 80 glaciers in the core area of the Buordakh Massif (some 1550 km$^2$). The inventory does not, however, include those ice aprons, glacierets, and very steep cliff or niche glaciers which occur in the higher parts of the mountain basins above 2000 m. Glacier length ranges from a few hundred meters to over 7 km. Areal extents vary from 0.1 to 10.4 km$^2$, while total glacierized area is believed to be approximately 70 km$^2$. The glaciers which have been mapped are predominantly cirque and small valley glaciers and occur in most valleys above 1650 m. The larger glaciers terminate at elevations of around 1550 m. Maps of the glaciers in the inventory are given in Figures 3 and 4, and Table 1 provides data on the individual glaciers. It should be noted that many of these glaciers have no name and thus the current study has used the numbers previously assigned by Nekrasov and Sheinkman (1981). Since this earlier work covered a larger area,

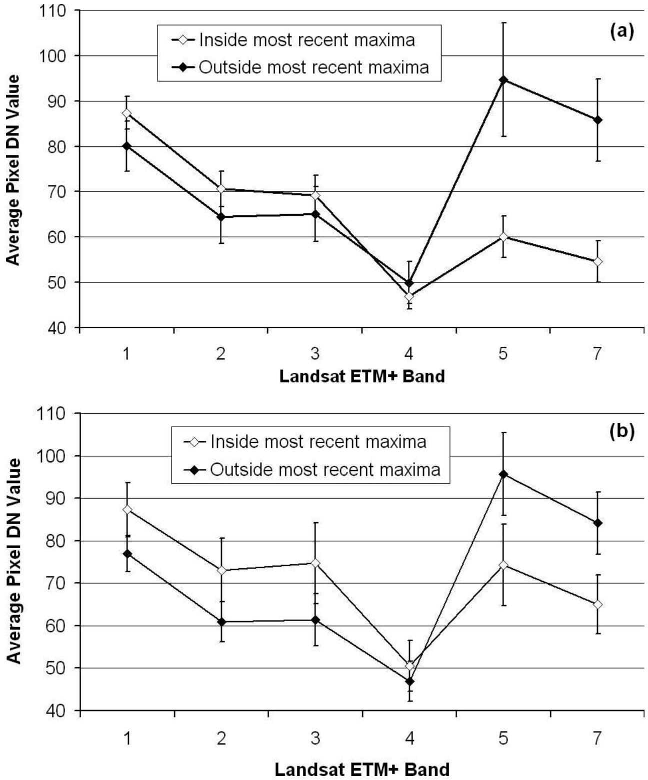


**FIGURE 1. Average pixel spectra for areas inside and outside the most recent glacier maximum for Tsaregradskiy (a) and Obruchev/Sumgin (b), indicating the power of discrimination in Landsat ETM+ Bands 5 and 7.**

the glacier numbers of the present inventory are not entirely sequential.

The four largest glaciers in the region are Tsaregradskiy (41), Obruchev (47), Sumgin (46), and Melnikov (45). These have multiple-cirque origins, and the cirque backwalls are covered with hanging ice nearly up to the ridge-crests. These glaciers have much supraglacial debris which supply moraines on the glacier snouts and which, in turn, have led to the deposition of moraines in the proglacial area. In addition to the largest glaciers there are numerous cirque glaciers and very steep niche or cliff glaciers. Due to the paucity of precipitation, no mountain ice cap has developed (Serebryanny and Solomina, 1996; Solomina, 1999).

In general, the five glaciers that were studied in detail were characterized by debris-covered snouts, large medial moraines, well developed supraglacial streams (some flowing in deeply incised channels), narrow crevasses (at least in summer), extensive 'dead ice' in the immediate glacier foreland, and well defined trim-lines above the current glacier surface in their lowermost parts. The surface of Sumgin glacier displayed numerous slush pools (also referred to as 'snow swamps', e.g. Hambrey and Alean, 2004) which, in turn, generated slush flows.

## Discussion

### *GLACIER RETREAT SINCE THE MOST RECENT MAXIMUM*

It is believed that most glaciers in the study area achieved their maximum Holocene extents during the Little Ice Age (LIA, ca. A.D. 1550–1850; see Matthews and Briffa, 2005; Solomina, 2000). The moraines are unvegetated and only small lichens have

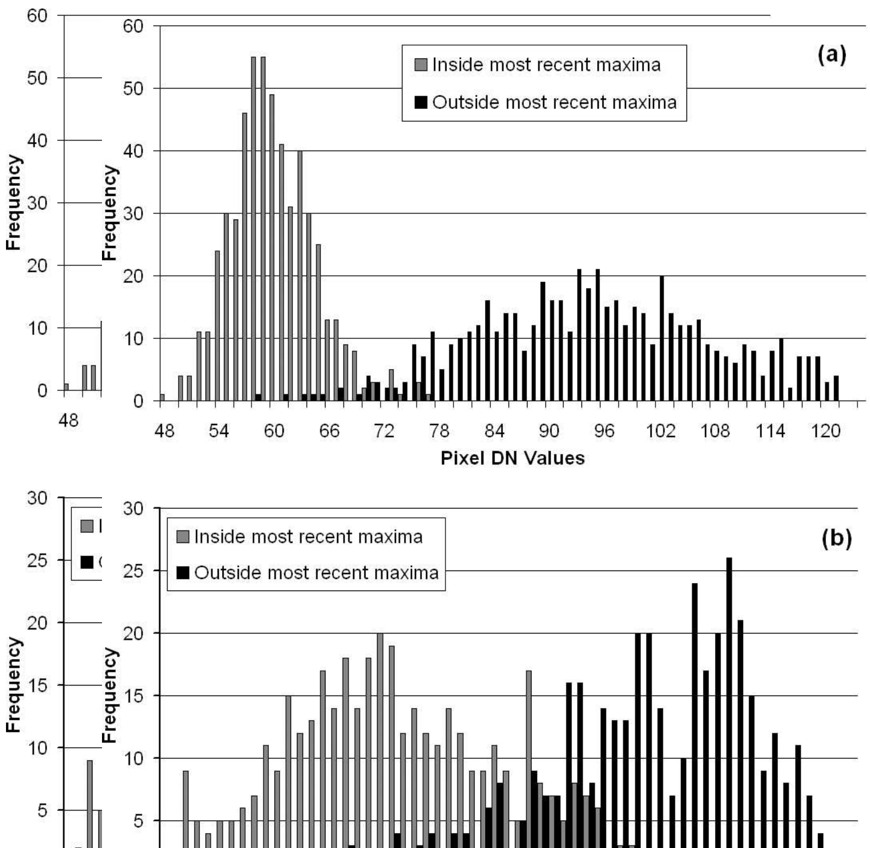


**FIGURE 2. Frequency distributions for pixel DN values (Landsat ETM+ Band 5) from inside and outside the most recent glacier maximum for Tsaregradskiy (a) and Obruchev/Sumgin (b).**

**TABLE 1**

**Glacier inventory for the Buordakh Massif, Cherskiy Range, Siberia. Glacier locations (by number) as can be seen in Figure 4.**

| Glacier Number | Recent maximum extent ($km^2$) | 2001 extent ($km^2$) | Areal difference ($km^2$) | Length (km) | Retreat (km) |
|---|---|---|---|---|---|
| 9 | 0.274 | 0.274 | 0.000 | 1.01 | 0.00 |
| 10 | 0.242 | 0.242 | 0.000 | 1.02 | 0.00 |
| 11 | 0.975 | 0.975 | 0.000 | 2.29 | 0.00 |
| 12 | 1.771 | 1.771 | 0.000 | 2.22 | 0.00 |
| 13 | 0.711 | 0.484 | −0.227 | 1.64 | 0.58 |
| 14 | 0.288 | 0.288 | 0.000 | 1.02 | 0.00 |
| 16 | 0.213 | 0.213 | 0.000 | 0.86 | 0.00 |
| 17 | 1.015 | 1.015 | 0.000 | 2.22 | 0.00 |
| 18 | 2.939 | 2.533 | −0.406 | 3.72 | 0.60 |
| 19 | 1.202 | 0.723 | −0.479 | 2.35 | 0.95 |
| 20 | 0.283 | 0.283 | 0.000 | 0.74 | 0.00 |
| 22 | 0.213 | 0.213 | 0.000 | 0.71 | 0.00 |
| 24 | 0.208 | 0.208 | 0.000 | 1.13 | 0.00 |
| 25 | 1.784 | 1.784 | 0.000 | 3.41 | 0.00 |
| 26 | 0.844 | 0.548 | −0.296 | 1.50 | 0.71 |
| 27 | 0.864 | 0.538 | −0.327 | 1.59 | 0.52 |
| 29 | 2.663 | 2.256 | −0.408 | 3.53 | 0.89 |
| 30 | 0.161 | 0.161 | 0.000 | 0.62 | 0.00 |
| 31 and 32 | 4.652 | 4.065 | −0.586 | 3.94 | 1.05 |
| 33 | 0.834 | 0.597 | −0.237 | 1.14 | 0.46 |
| 34 | 1.846 | 1.550 | −0.296 | 2.75 | 0.53 |
| 35 | 0.529 | 0.529 | 0.000 | 1.25 | 0.00 |
| 36 | 0.493 | 0.354 | −0.139 | 1.26 | 0.32 |
| 37 | 0.796 | 0.623 | −0.173 | 1.84 | 0.45 |
| 38 | 2.730 | 2.372 | −0.358 | 3.64 | 0.35 |
| 39 | 0.224 | 0.110 | −0.114 | 0.56 | 0.29 |
| 40 | 0.652 | 0.652 | 0.000 | 1.33 | 0.00 |
| 41 and 41A | 12.445 | | −1.502 | | |
| 41 | | 10.378 | | 7.80 | 1.48 |
| 41A | | 0.564 | | 1.60 | 0.31 |
| 42 | 0.945 | 0.753 | −0.192 | 1.92 | 0.30 |
| 43 | 0.507 | 0.306 | −0.201 | 1.28 | 0.20 |
| 44 | 0.545 | 0.347 | −0.198 | 0.95 | 0.43 |
| 45 | 4.039 | 3.199 | −0.840 | 4.63 | 1.41 |
| 46 and 47 | 12.241 | | −1.815 | | |
| 46 | | 3.686 | | 5.00 | 0.31 |
| 47 | | 6.740 | | 8.42 | 1.20 |
| 48 and 48A | 1.444 | | −0.507 | | |
| 48 | | 0.658 | | 1.24 | 0.32 |
| 48A | | 0.279 | | 0.68 | 0.32 |
| 49 | 1.082 | 0.654 | −0.427 | 1.66 | 0.92 |
| 51 | 0.688 | 0.404 | −0.284 | 1.33 | 0.42 |
| 52 and 52A | 1.774 | | −0.481 | | |
| 52 | | 1.015 | | 2.31 | 0.80 |
| 52A | | 0.277 | | 0.90 | 0.68 |
| 53 | 0.344 | 0.150 | −0.193 | 0.65 | 0.32 |
| 54 | 1.332 | 1.129 | −0.202 | 2.18 | 0.37 |
| 55 | 0.241 | 0.241 | 0.000 | 0.72 | 0.00 |
| 56 | 0.290 | 0.290 | 0.000 | 0.79 | 0.00 |
| 57 | 0.202 | 0.202 | 0.000 | 0.60 | 0.00 |
| 58 | 1.218 | 0.933 | −0.285 | 2.14 | 0.45 |
| 59 | 1.481 | 1.293 | −0.189 | 2.04 | 0.16 |
| 60 | 0.624 | 0.624 | 0.000 | 1.49 | 0.00 |
| 61 | 1.263 | 1.038 | −0.225 | 2.57 | 0.22 |
| 62 | 0.376 | 0.376 | 0.000 | 1.18 | 0.00 |
| 63 | 0.867 | 0.867 | 0.000 | 1.78 | 0.00 |
| 64 | 1.679 | 1.280 | −0.400 | 1.67 | 0.71 |
| 65 | 0.305 | 0.305 | 0.000 | 0.97 | 0.00 |
| 66 | 0.121 | 0.121 | 0.000 | 0.43 | 0.00 |
| 67 | 0.840 | 0.840 | 0.000 | 1.66 | 0.00 |
| 68 | 0.133 | 0.133 | 0.000 | 0.57 | 0.00 |
| 69 | 0.097 | 0.097 | 0.000 | 0.43 | 0.00 |
| 70 | 0.176 | 0.176 | 0.000 | 0.51 | 0.00 |
| 71 | 0.290 | 0.290 | 0.000 | 0.79 | 0.00 |
| 73 | 0.608 | 0.606 | −0.002 | 1.19 | 0.04 |

**TABLE 1**

**(Continued)**

| Glacier Number | Recent maximum extent (km$^2$) | 2001 extent (km$^2$) | Areal difference (km$^2$) | Length (km) | Retreat (km) |
|---|---|---|---|---|---|
| 74 | 0.628 | 0.128 | −0.501 | 0.43 | 0.48 |
| 75 | 0.243 | 0.090 | −0.154 | 0.48 | 0.13 |
| 76 | 0.448 | 0.293 | −0.155 | 0.94 | 0.20 |
| 77 | 0.288 | 0.079 | −0.209 | 0.35 | 0.28 |
| 78 | 0.573 | 0.113 | −0.460 | 0.60 | 0.26 |
| 79 | 0.569 | 0.239 | −0.330 | 0.63 | 0.48 |
| 82 | 0.301 | 0.123 | −0.178 | 0.44 | 0.25 |
| 82X | 0.101 | 0.000 | −0.101 | 0.00 | Total |
| 83 | 0.169 | 0.135 | −0.034 | 0.49 | 0.05 |
| 84 | 0.481 | 0.424 | −0.058 | 1.08 | 0.15 |
| 85 | 0.500 | 0.366 | −0.133 | 0.87 | 0.18 |
| 86 | 0.647 | 0.426 | −0.221 | 0.91 | 0.22 |
| 87 | 0.224 | 0.191 | −0.033 | 0.92 | 0.06 |
| 87A and 87B | 0.300 | | −0.198 | | |
| 87A | | 0.051 | | 0.40 | 0.27 |
| 87B | | 0.051 | | 0.32 | 0.28 |
| 88 | 0.827 | 0.795 | −0.032 | 1.77 | 0.02 |
| 89 | 0.390 | 0.390 | 0.000 | 1.18 | 0.00 |
| 90 | 0.183 | 0.183 | 0.000 | 0.57 | 0.00 |
| 91 | 0.455 | 0.455 | 0.000 | 1.28 | 0.00 |

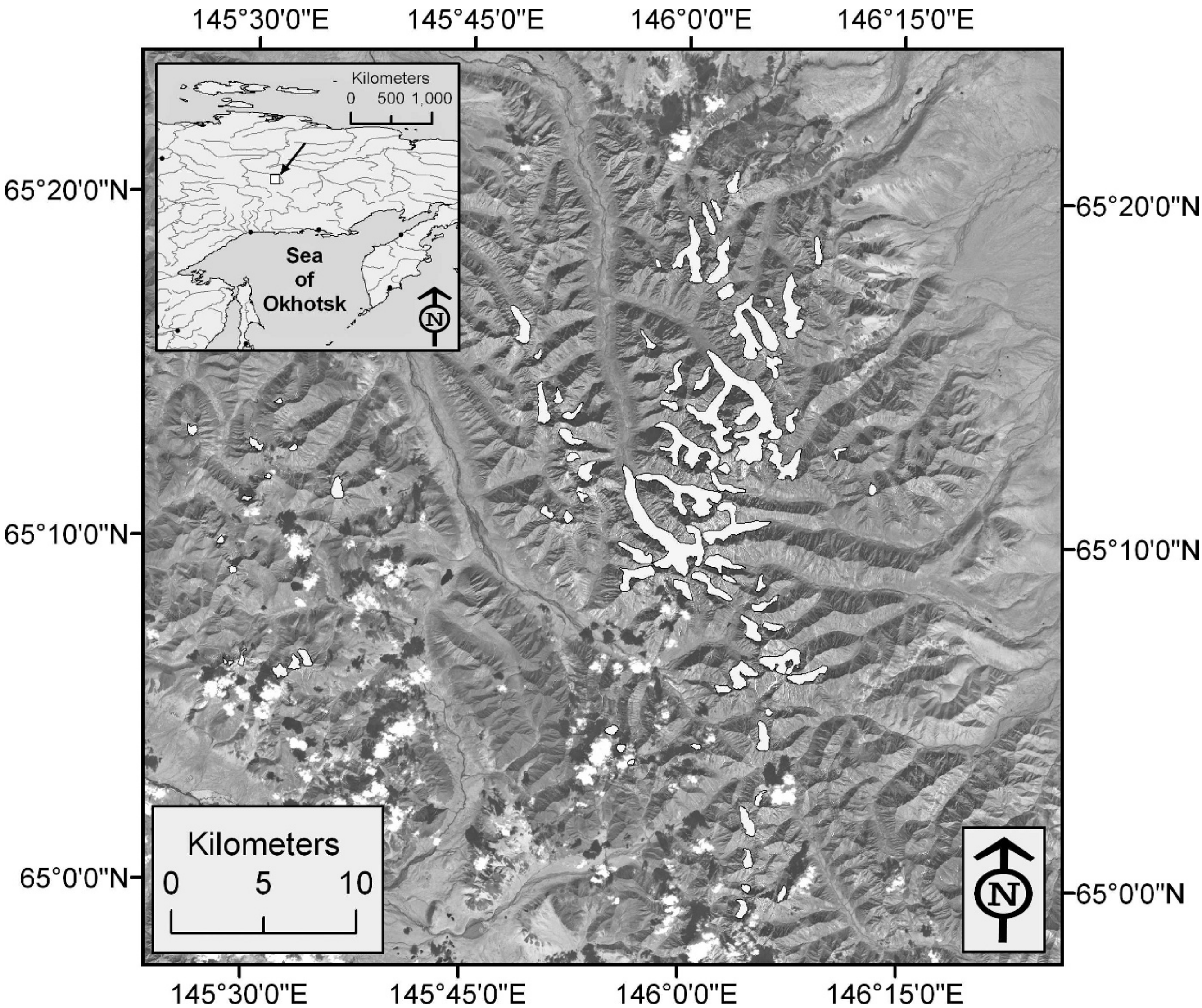


**FIGURE 3. The study area (inset) and the contemporary glaciers mapped within it. The Landsat ETM+ imagery for July 2001 used for the mapping provides topographic context.**

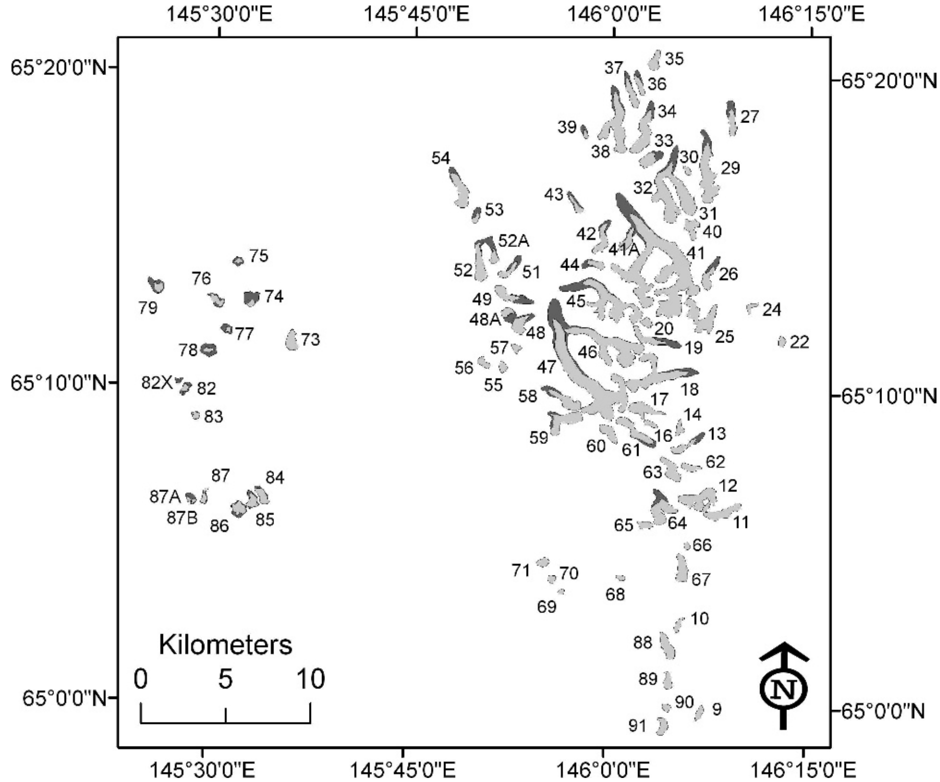


FIGURE 4. The glaciers mapped with their number as used in the inventory (see Table 1). The areas in red show the most recent glacier maximum believed to date to the Little Ice Age (see text for discussion).

colonized boulders in the glacier forelands. Lichen thalli diameters obtained from the foreland of Melnikov Glacier by the present authors yielded an average size of 15.5 mm inside the most recent glacial limit compared with 86.1 mm just outside the glacial limit. The lack of absolute dating or a locally derived lichen growth curve, however, prevents more precise age estimates of the moraines of this study. Nevertheless, we suggest that the most recent glacier maximum discussed in this paper relates to the LIA.

The glaciers lost about 14.8 $km^2$ between the end of the LIA and 2001, which represents a reduction in glaciated area of 17%, corresponding to a mean annual rate of just 0.11%. The magnitude of loss is not uniform throughout the Buordakh Massif; with 62% of the glaciers displaying a measurable retreat from their most recent maximum extent and 38% appearing to be stable, although a proportion of these may, of course, have lost mass through thinning. The pattern and extent of the retreat is illustrated in Figure 5.

Recession rates in the Buordakh Massif appear to be lower than those reported for other mountainous areas of northeastern Siberia. For example, in the Suntar-Khayata glacier termini have retreated by 0–19% and 5–28% between the end of the LIA and 1973 in the northern and southern sectors of the mountains, respectively (Ananicheva et al., 2005). Most of the retreat (70–80%) occurred between the LIA and 1945 while the period between 1945 and 1973, characterized by low summer temperatures (Johannessen et al., 2004), accounts for the remaining loss of ice.

## Conclusions

Using Landsat ETM+ imagery, we have compiled the first georeferenced glacier inventory for the Buordakh Massif, Cherskiy Range, northeast Siberia. Eighty glaciers were mapped and combined account for ca. 70 $km^2$. The glaciers are predominantly

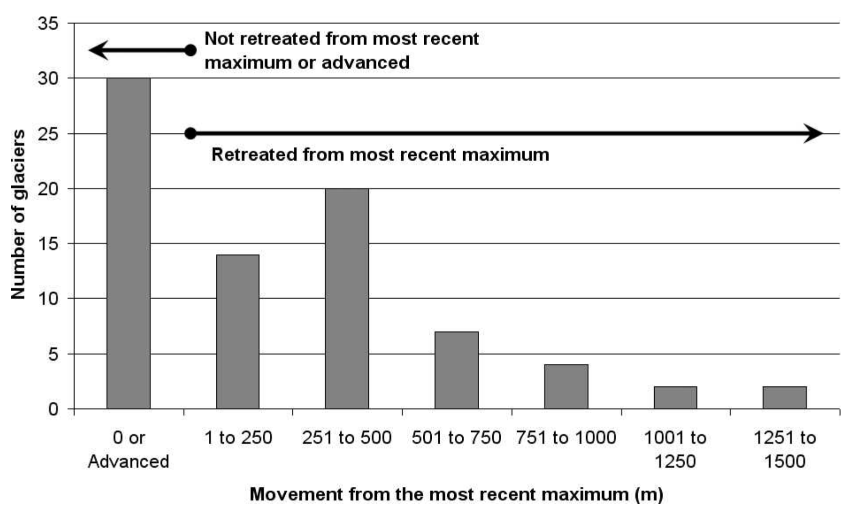


FIGURE 5. Data on the amount of retreat since the most recent maximum.

cirque and small valley glaciers of the alpine type and occur in most valleys above 1650 m. The extreme continental climate of the Cherskiy Range, with very low winter temperatures and precipitation and relatively high summer temperatures, results in cold glaciers without firn where superimposed ice formation is important.

Although the date of the most recent glacial maximum is poorly constrained, it is likely that it relates to the Little Ice Age maximum (cf. Solomina, 2000). Our analysis suggests that the areal extent of the glaciers in the Buordakh Massif has reduced by around 17% since this time. This reduction is somewhat lower than that reported for other mountainous areas in NE Siberia (e.g. Ananicheva et al., 2005).

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