Debris-covered glacial forms and dynamics of glaciers of the Mongun-Taiga mountain massif (Altai-Sayan mountain system).

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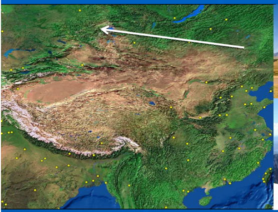
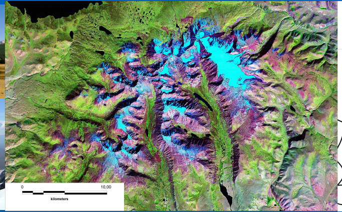
Mongun-Taiga mountain massif (3970 m, 50°16'N.L. 90°8 ' E.L.) is situated in the intersection of Russian Altai, Mongolian Altai and Sayan mountain ridges. The massif is located to the south of the watershed of the Arctic Ocean and the inland drainage basin, in particular, the Great Lakes basin. Modern glaciation of the massif is represented mostly by small forms, its total area is 20 km². The first general description of the glaciation was made by Yu.P. Seliverstov in 1965. Since 1988, the glaciation has been studied by the members of the Faculty of Geography, St. Petersburg State University. The study of the glaciers includes in situ monitoring of their current state in order to obtain information about the area, length, morphology, and the altitudinal glaciological levels, delineation and surveying of glaciers' edges, and meteorological and balance observations.

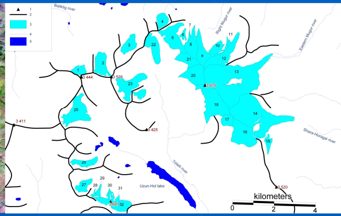
General location of the area of research.



Mongun-Taiga massif from space.



Modern glaciation of the massif. 1 - peaks, 2 - ridges, 3 - rivers, 4 - lakes, 5 - glaciers



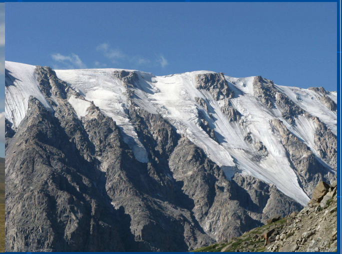
Average annual temperature at the foot of the massif is -2.6°C, annual precipitation is 145 mm (about 300 mm at the altitude over 3000 m with about 35-50% in the summer). In these arid and sharp continental climatic conditions glaciers exist due to low temperatures and high concentration of snow on the leeward north-eastern slopes. The coefficient of snowdrift and avalanche sediment concentration on glaciers is mainly between 2 and 3 with 6 to 8 at the cirque glaciers. The ELA average altitude is 3380 m. Ablation/accumulation on the firn line of the glaciers ranges from 7 to 213 g/cm² in dependance of snow concentration. Low energy of the glacierization (average activity index 2.6 mm/m) determines its considerable response to changes in the mass balance.

Over 80% of the glaciers have the area of less than 1 km², but the larger glaciers (including the four valley) comprise approximately 50% of the total glacier area of the massif. The largest glaciers of the massif, *East Mugur* and *Seliverstov*, are the multilevel glaciers formed by several streams of ice from the two tiers of circuses and kars (3,250-3,350 m and 3,600-3,700 m) that merge and form the glaciers' tongues. The northeastern aspect prevails (about 40% of the glaciation). In the central part of the massif the glaciers form a complex around the main peak; the other smaller complex is located in the southwest of the massif with the highest point of 3,681 m. Both complexes have ice fields on the dome-shaped or flat mountain tops in their central parts that make united accumulation zones for the glaciers that radiate from them. Other glaciers are not connected with each other.

East Mugur glacier.

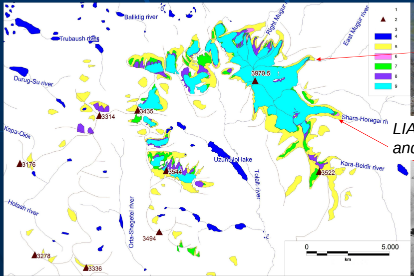
The glacial complex of the main peak of the massif.

Western glacial complex.

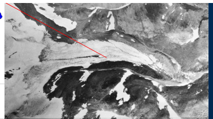


The last glacial advance took place in the LIA with maximum about 1845-1855 (according to our dendrological reconstruction). Since the maximum of the LIA the glaciers retreat, short stabilizations took place in early 1920-s, mid-1960-s and mid-1980-s. According to our reconstruction based on geomorphologic methods in the LIA the total area of the glaciers was about 2.4 times larger than now, the ELA altitude about 120 lower than now. The most rapid decrease of the glacial area (19% loss) happened in 1995-2008. Climatic data from the nearest meteostation Mugur-Aksy show that at least from the 1960-s the glacial retreat was caused both by warming and decrease of precipitation. Our observations showed extremely dry conditions in 2006-2008 when the firn line elevated 200-300 meters and most glaciers lost their accumulation areas. After 2009 the snow accumulation increased and the firn line returned to the levels of the mid-1990-s. High rates of the recent degradation of the glaciers are caused by 2 processes. The first one is decrease of the area of high elevated firn-fields and uncovering of rocks in the highest parts of the glaciers due to rapid reduce of solid precipitation. The second process is separation and armoring of the lower parts of the glaciers.

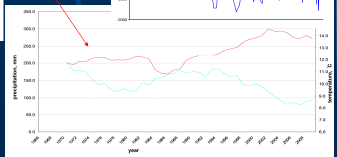
Evolution of glaciation of Mongun-Taiga massif. 1- mountain tops, 2- mountain ridges, 3- rivers, 4- lakes; area lost by glaciers: 5- from the maximum of the LIA till 1925, 6- in 1925-1966, 7- in 1966-1995, 8- in 1995-2008; 9- modern glaciers (2008-2012)



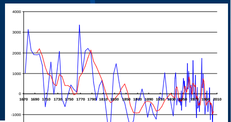
LIA moraines on the photo (above) and on the aerial photo of 1965 (below)



Average annual sums of precipitation, mm, (blue) and average summer temperatures, °C, (red) (smoothened) according to data from Mugur-Aksi in the period 1966-2009.



Changes of mass balance index of glaciers of the massif at the level of 3200 m



Decrease of the area of glaciation after the LIA maximum is not only the result of retreat and melting of glacial terminus, but mostly of formation of the massifs of buried ice which soon become debris-covered.

The first group of debris covered ice forms is connected with moraines of LIA (altitude 2650-3000 m). They consist of ice core and debris cover of different thickness. The mechanism of their formation is the following: stabilization of the edges of the glaciers causes accumulation of the debris, they armor the ice, preventing it from melting. When warming starts the exposed part of the glacier grows thinner, the ice under the moraine looses contact with the main body of the glacier. Increased flow of glacial melt water in the last 10 years led to exposure of moraine ice. Some glaciers which supported LIA moraines on the internal side, retreated abruptly in the period of 1995-2008. Moraines lost their stability, they collapse intensely and ice core melts out. This is observed at Seliverstova glacier (2.8 km²). Modern thermokarst processes on LIA moraines expose numerous parts and trunks of wood with radiocarbon age 58-43 t.e. BP, probably buried by earlier glacial advances.

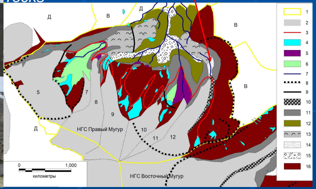
Thermokarst on moraines of LIA near Seliverstova glacier

Wood melting out of LIA moraine at altitude about 3000 m a.s.l.

The second group (altitude 2850-2950 m) is situated between LIA moraines and modern glaciers. It is represented by layers of ice, triangle in ground plan, covered by thin (several hundred cm) moraine. The edges of the layers are sometimes marked by streams that join together at the lowest point of the formation. These streams now expose ice to the depth of 1-3 meters, it is caused by increase of glacial runoff. Most of streams infiltrate into moraines further down the slope. Analysis of aerial photos of 1965 show that the location of the edges coincide with the edges of the glaciers in 1965, during the last stabilization. These parts of glacial tongues turned into dead ice, partly melted but mostly were armored in the next period.

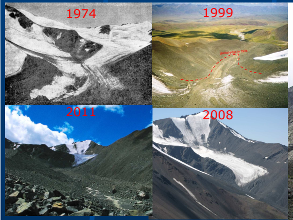
Aerial photo of the north-east slope of the massif in 1965 and modern photos of the same place. 1- area that was debris-covered after 1995; areas, that became debris-covered in 1965-1995; 2- former terminal parts of the glacier, former central moraine

The same area on the scheme. Some of the points of the legend: 2- LIA moraines, 3- edges of glaciers in 1965, 4- snow patches, 5- areas debris-covered in 1965-1995, 6- areas, debris covered after 1995, 16- rocks



Objects of the third group are situated several dozens meters higher or are adjacent to the objects of the previous group. These are former parts of glaciers that abruptly lost their connection with the main glacial masses and turned into dead ice in the period of 1995-2008 and several small cirgue glaciers that lost their accumulation area and activity. The process of armoring of these ice masses is now very active, showing the mechanism of formation of debris-covered ice.

Stages of armoring of the terminus of Left Mugur glacier



A small partly debris covered cirque glacier in Tolaiti valley.

A small glacier in Tolaiti valley completely debris covered in 1995-2007

The beginning of the process (a tributary of Left Mugur glacier)

Medial moraines of valley glaciers are likely to join this group of objects in the nearest future. Central moraine of East Mugur glacier in 1995 was at the same level with the open part of the terminus, at 2011 it was 5-10 m over it. In future lower part of medial moraine can become separate objects.

Rock glaciers of the massif have glacial genesis. Periodic cutoff of new masses of buried ice from the glaciers provides continuous alimentation of rock glaciers. We mapped 17 rock glaciers with total area of 5.5 km². 2 active rock glaciers under valley glaciers Left Mugur and Right Mugur have the shape of tongues cutting through moraines of LIA and extending 350-500 m further down the slope. We estimate the average rate of their advance from the beginning of LIA 0.5-0.7 m/year .

The main cause of active formation of debris covered glaciers and rock glaciers in the massif is sharp continental climate that leads to intensive physical weathering that creates large masses of debris. In periods of dryer climatic conditions accumulation of debris on glacial surface increases. Low energy of water erosion processes preserves debris cover. At the same time low precipitation and generally cold conditions prevent debris covered ice from melting for dozens and even hundreds of years. Stepped relief of the massif leads to periodic cut off of debris covered glacial and formation of "dead ice".

Medial moraine of East Mugur glacier.

Rock glaciers cutting through the LIA moraines