Climate change impact on high-altitude geomorphological systems

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Abstract. Some of the most important consequences of global climate change are the rising mean annual or seasonal temperature and the rising or diminishing precipitation at the regional level. An analysis of midterm meteorodata shows that the average annual air temperature in Western Mongolia has increased by 2.08 °C from 1940 to 2017. The impact of these changes is observed in the high-mountain basins of Mongolian Altai. Thus, the sum area of deglaciated areas of Sutai and Tsambagarav glaciers has increased by 37.5 sq. km since the time of the Little Ice Age maximum. Field data and geothermal observations during the last 25 yr indicate an increase in permafrost temperatures, and the average active-layer thickness has increased by 24% in comparison to the early 1990s.

1. Introduction
The geographic shell of the Earth is developing under the influence of exogenic and endogenic factors. Solar energy is the main energy source for the exogenic processes occurring in the hypergenesis zone. The climatic conditions create a characteristic relief, form the elements and regime of the hydrographic network, and set the boundaries of glaciation for thousands of years. The heat and moisture balance determines the type and structure of any landscape. In the middle of the last century, A. A. Grigoryev and M. I. Budyko [1] explored the relationship between the ratio of heat and moisture and the type of landscapes, which resulted in a law of geographic zonality. The law of geographic zonality shows that the spatial distribution of geographic zones is determined by the distribution of the solar energy balance and the ratio of the radiation balance to the amount of heat required to evaporate the annual precipitation. I. A. Volkov [2] studied the similarities of latitudinal geographic zones on the plains and vertical landscape zones in the mountains and came to the conclusion that the thickness of the Earth's atmosphere has a distinct stratification which is divided into several hydrothermal layers, each of which is characterized by a corresponding dominant balance of heat and moisture.

In the Quaternary glaciation, deep transformation of climatic conditions caused a change in the high-altitude position of each hydrothermal layer [3, 4] which, in turn, led to displacement of the boundaries of latitude geographic zones on the plains and vertical landscape zones in the mountains. The surface areas that were previously included in any natural zone or belt shifted to other zones due to the new conditions of heat and moisture, creating a completely new landscape-forming environment.

The glaciation of Mongolian Altai reached its maximum during the period of planetary cooling and a decrease in regional summer temperatures by 4.5-5 °C in the late Neo Pleistocene. The snow line lowered by 800-850 m and shifted the borders of the hydrothermal zones accordingly [5, 6 7]. The glaciation areas have been steadily declining since the last glacial maximum. Periglacial landscapes, which are important structural elements of high-mountain geosystems, formed after the upward displacement of hydrothermal boundaries and landscape zones, which causes a radical restructuring from the ice of the terrain.
Periglacial landscapes of Mongolian Altai are characterized by youth and dynamism caused by active nival, cryogenic, and gravity processes. Climate is the main factor in the formation of periglacial landscapes, since it determines the dynamics of glaciation, the surface runoff, and the nature of exogenous processes.

2. Geographical setting of the study area

Mongolian Altai is a mountain range consisting of several parallel ridges stretching for 1000 km from North to South-East and separated by longitudinal tectonic valleys. The main ridges of Mongolian Altai are 3200-3500 m high, the peaks are mainly plateau-shaped, and the highest mountains are characterized by Alpine relief. The rocks consist of granite, porphyry, porphyrite, and shale. Mongolian Altai connects to the lower ridges of the Gobian Altai, which do not form a single massif. The north-eastern part of the system is bordered by the Great Lakes Depression. Mongolian Altai is adjacent from the north to Russian Altai. The Tavan Bogd massif is the main orographic knot of Mongolian Altai, the highest point (Nairamdal mont) is 4356 m.

The atmospheric circulation of the region is characterized by the predominance of westerlies air mass transfer and the development of cyclonic activity on the arctic and polar fronts. Annual precipitation is typical for areas with a continental climate. More than half of the winter precipitation falls from November to December, a period that is characterized by unstable cyclonic weather. Winter passes against a background of high pressure during the main period (from January to March). The precipitation amount during this period is small. The cyclonic activity is enhanced in spring and, as a result, the amount of precipitation increases slightly and reaches a maximum by July.

Features of the relief have the main influence on the thermal regime of the region, these are the absolute height values and the characteristics of the snow cover. Minimum air temperatures are observed in January and maximum ones, in July. Accurate calculation of the air temperatures is possible for the slopes of the ranges Sutay and Tsambagarav according to the data from the nearest weather stations taking into account the established gradient (0.58-0.59 °C per 100 meters of climb) in summer.

The Tsambagarav Mountain (Figure 1) node is located in the central part of Mongolian Altai, bordering the Great Lakes Depression. The mountain knot is separated from the main ridges by a straight tectonogenic gully/hollow. The ridge stretches in the north-western direction for 30-35 km and in the meridional one for 25 km, and has a trapezoidal shape in the scheme. The ridge refers to the Hungin-Nuruu system according to the morphostructural elements, and is a strongly dissected highland. The mountain knot Tsambagarav consists of 3 massifs: Tsast-Uul, Huh-Nuruu-Uul, and Yamat-Uul. The absolute height within the mountain knot Tsambagarav changes from 2840 m to 4193 m. There are 40 glaciers concentrated in the nival-glacial belt of the Tsambagarav mountain knot. The regional climatic conditions and features of the ridge structure determined the spatial distribution (up to 40% of the rock glaciers are confined to the slopes of the Northern and Northern-Eastern expositions) and the morphology of the glacial formations (valley, corrie-valley, corrie, hanging and flat-top glaciers) [8].

The Sutay ridge is located in the southern part of Mongolian Altai (Figure 1) and belongs to the area of epiplatformic orogenesis. This area is composed of strongly dislocated sedimentary-volcanic rocks from the lower and middle Paleozoic, and is distinguished by a complex tectonic structure. The ridge has a typical Alpine appearance with characteristic attributes - a dense network of corries, aretes, and deeply embedded troughs. The Sutay ridge was subject to repeated glaciation in the Quaternary period, as shown by a number of classical forms (glacial-exarational, glacial-accumulative, and fluvioglacial) preserved in the relief of the glacial valleys and intervalley spaces.

The Sutay ridge is the most southern center of the glaciation of Mongolian Altai. The lower limit of the nival-glacial belt of the ridge is 150-200 m higher than in the other glacial regions of Western Mongolia. The modern glaciation of the Sutay ridge consists of 14 glaciers of four morphological types: flat-top, hanging, corrie, and corrie-valley. The glaciers are concentrated at an altitude between 3600-4150 m and have a northward exposure. The most important features of the relief which
determine the morphological features of the Sutay glaciers are: a flat, plateau-like apical part of the watershed, which makes a basin for the accumulation of snowdrift, corrie, and hanging glaciers; stepped slopes near the tops which contribute to the concentrated accumulation of snow-firm masses; the inherited orientation of the main snow accumulation basin related to the dominant Western moisture transfer.

The Alpine zone of the Sutai and Tsambagarav ranges is characterized by a significant variation in the daily temperatures. Frequent zero-mark crossings in spring and autumn create favorable conditions for the development of mechanical weathering, leading to the formation of numerous rock-falls, placers and scree on the watersheds and slopes of the valleys. The modern relief-forming processes cause high values of the altitude and relative height, differences in the composition and structure of rocks, and changes in the temperature conditions and the precipitation regime.

The ranges of Mongolian Altai have many elevations that define a highly dissected terrain and extensive development of vertical zonation. The mountain system has a high position above ocean level, and even with relatively small fluctuations in the heights (200 - 300 m) it is possible to observe a natural change of vegetation. North-Western Mongolia region, with its extended continental climate, is widely represented by arid altitudinal zonation [9]. This type of altitudinal zonation is characterized by a large number of belt shifts: from deserts or desert steppes in the foothills to high-mountainous wolds on the summit surfaces. Some belts on the ranges of Sutai and Tsambagarav are reduced or completely absent, especially the forest belt where there is direct contact of the Alpine belt with the dry and desert steppe. The exposure of the slopes is of particular importance in the distribution of the plant communities of Mongolian Altai.

3. Methodological basis of research
The climatic changes of the previous decades include significant and irreversible changes to the spatial structure of the nival-glacial geosystems of the highlands of Mongolian Altai, which are expressed in the formation of the latest morphosculpture. A geoinformation and analytical system (GIAS) called «EuCLiD» (Evolution and Climatogenic Landscape Dynamics) developed, tested, and implemented quantitative assessment of the landscape transformation. The system is created in the open package software environment Microdem/TerraBase V.16.0, Petmar Trilobite Breeding Ranch® - a simple and efficient tool for storing, visualizing, and analyzing spatial data [10, 11].

The databank is the information basis of the GIAS «EuCLiD» organized in the form of catalogs including sheets of topographic base scale 1:25000, thematic databases in DBASE format, and
materials of polychronous remote sensing. The spatial data of the GIAS «EuCLIId» are given in a unified datum (WGS 84) and transformed into a UTM projection, the vector maps are presented in the format of Shape-files. Aster Global DEMs (second generation) and NASA SRTM matrices with a resolution of 1 arcsec were used as a digital elevation model. The databank of the GIAS «EuCLIId» was formed from open network portals and file archives of the USGS Geological Survey, the NASA EOSDIS, and the Geoportal of Roscosmos. The catalog of polychronous remote sensing data includes high-resolution multispectral digital images from Landsat 8, Landsat 7 ETM+, Landsat 5, ERTS, WorldView -2, and monochrome images KH-4B. Geocorrection and abstracting of imagery from the KH-4B satellite were performed according to the characteristic points, which were taken to be the intersections of landscape contours, headlands of rock, the mouths of tributaries, the characteristic curves of channels, and other objects displayed on aerial photographs. The number of hard reference points was at least twenty in all cases.

Digitization of the open water surfaces was made by interpreting signs from a space survey. The main interpreted features of surface waters included a smooth photo tone and specific monotone or expressive structure of a water image, and the shape of lakes and water bodies attached to the depressed relief elements [12]. The lakes were interpreted when their shape became apparent. Even small lakes could be identified among a large cluster of lakes. In the images small lakes are depicted in the form of small points.

Images were synthesized using channels 7-5-3 in the program Microdem/Terra Base V. 16.0, for a clearer and contrasted display of the glacier outlines in the processing of multispectral images from Landsat. The panchromatic band (channel 8) was used to increase the spatial resolution of Landsat 7.8 scenes. Vectorization of the landscape elements was carried out in the manual mode. The SRTM NASA Matrix and ASTER GDEM V.2 was used in the calculation of the three-dimensional surface of glaciers as a digital elevation model. Verification of the digitized polygon reference points conducted in the field revealed a measurement error not exceeding 8-10%. The boundaries of the Little Ice Age glaciers were reconstructed and well-expressed in the relief of the marginal moraine complexes [13].

The studies of changes in the hydrothermal regime in the territory of Western Mongolia are carried out by analyzing indicators from the international weather database, NOAA's National Centers for Environmental Information (NCEI), during the period from 1958 to 2017, for 14 weather stations that have varying observation times. The weather stations Altai, Uliastai, Hovd, Ulaangom, and Ulgi have the greatest periods of temperature regime observations for 60 years (1958-2017). The weather stations Omno-Gobi, Tolbo, and Baitag have observations for 30 years (1984-2001). The remaining six stations have a period of observation for only the last 18 years (2000-2017). The precipitation data are most complete for the last 18 years, and for some individual stations only for 10 years. The mathematical processing of the NCEL meteorological data was performed by converting the information into an Excel application, where the indicators from the traditional U.S. Customary System were transferred to the international system of units (SI). The reliability of the data is confirmed by the results of statistical analysis and comparison with similar studies [14].

4. Results and discussion

An analysis of the average annual temperature shows a steady increase at all weather stations. For the period from 1958 to 2017 (Table 1) it was 2.3 °C, with the highest increase of 3.1°C observed at Hovd located at a medium-high level in the central part of the study area. The average annual temperature is negative, and is -1.06°C for four weather stations in Western Mongolia. The average annual temperature is positive only at Ulgi. The standard deviation by year is about 1 °C for all stations listed. The highest values of the average annual temperatures are between 1990-2000, in which there is a fluctuation in the amplitudes of the average annual temperatures from the mean annual value of 2 °C to 5 °C. The average annual temperature may drop to minus 5 °C in some years (e.g. Altai) and rise to plus 3 °C in some years (e.g. Hovd).

Data for 1960-1970 are incomplete for some weather stations, which are, therefore, discrete. Analysis of the data for the 30-year observation period also showed a positive trend with angular
coefficients from 0.030 to 0.059; for this period the temperature increase is less than that of the 60-year period where the average warming is 1.6 °C.

Table 1. Change of average annual temperature for 1958 - 2017 at Western Mongolia meteostations.

| Stations  | habs, m |  \( \bar{t} \), °C | \( \Delta t \), °C | k     | \( \sigma \), °C |
|-----------|---------|-----------------|----------------|-------|----------------|
| Altai     | 2181    | -1.01           | +2.07          | +0.037| 0.96           |
| Uliastai  | 1759    | -1.85           | +1.53          | +0.026| 1.01           |
| Ulgi      | 1715    | +0.74           | +2.22          | +0.039| 1.24           |
| Hovd      | 1405    | -0.96           | +3.07          | +0.053| 1.37           |
| Ulaangom  | 939     | -2.53           | +2.03          | +0.037| 1.19           |

\( h_{abs} \) is the absolute height above sea level, \( \bar{t} \) are the annual average temperatures, \( \Delta t \) is the change of the average annual temperature, \( k \) is the coefficient of trend, \( \sigma \) is the standard deviation.

Weather data for a larger network of weather stations are presented for the period from 2000 to 2017, which fairly evenly covers the territory of Western Mongolia. A number of data analyzed by the thermal regime showed a further steady increase in the average annual temperatures, with the exception of the weather station Barunurtuuruu located in the north-east of the study area (Table 2).

Table 2. Change of average annual temperature and precipitation for 2000 - 2017 at Western Mongolia meteostations.

| Stations     | habs, m | \( k \)     | \( \Delta t \), °C | \( \bar{R} \), mm | \( \sigma \), mm | C, % |
|--------------|---------|------------|-----------------|----------------|----------------|------|
| Altai        | 2181    | +0.017     | +0.27           | 182.37         | 54.90          | 30   |
| Uliastai     | 1759    | +0.019     | +0.30           | 210.49         | 62.66          | 30   |
| Ulgi         | 1715    | +0.019     | +0.30           | 112.85         | 25.19          | 22   |
| Hovd         | 1405    | +0.017     | +0.27           | 124.00         | 46.43          | 37   |
| Ulaangom     | 939     | +0.013     | +0.21           | 133.34         | 42.70          | 32   |
| Omno-Gobi    | 1590    | +0.021     | +0.36           | 133.34         | 42.70          | 32   |
| Barunurtuuruu| 1232    | -0.013     | -0.21           | 220.52         | 55.43          | 25   |
| Baitag       | 1186    | +0.077     | +1.23           | 90.29          | 41.35          | 46   |
| Erdeni       | 2417    | +0.163     | +1.90           | 60.01          | 25.70          | 43   |
| Tolbo        | 2101    | +0.043     | +0.67           | 187.78         | 112.43         | 60   |
| Tonhil       | 2095    | +0.053     | +0.74           | 97.97          | 30.34          | 31   |
| Nogoonnur    | 1480    | +0.126     | +0.04           | 98.58          | 33.17          | 34   |
| Urgamal      | 1263    | +0.135     | +1.89           | 99.18          | 37.25          | 38   |
| Hunhataaortoo| 1051    | +0.083     | +1.20           | 127.06         | 80.37          | 63   |

\( h_{abs} \) is the absolute height above sea level, \( k \) is the coefficient of trend, \( \Delta t \) is the change of the average annual temperature, \( \bar{R} \) is the average annual precipitation, \( \sigma \) is the standard deviation, C is the coefficient of variation.

The increase in the average annual temperatures is observed at all stations - about 0.6 °C, with the largest increase (1.9 °C) at Erdeni, which has the highest absolute altitude (2417 m). The dynamics of the average temperature of the ablation period (the average temperature from June to September) (Figure 2a) and the dynamics of the amount of winter precipitation (the amount of precipitation from November to April) (Figure 2b) were additionally analyzed.

The average annual air temperature growth was 2.6 °C for Hovd during the 60-year period, 1.29 °C for Omno-Gobi during the 30-year period, and 0.67 °C for Tolbo during the final 18 years. The value of total winter precipitation is highly variable in the years of observations, both in the area of the investigated ridge and throughout Western Mongolia. Permafrost occupies about 35% of the mountain structures of Mongolian Altai. Permafrost is widespread largely due to the extreme continental climate of the region. The average annual air temperatures fall in some regions to -10 °C, and a small amount
of precipitation is unequally distributed over the territory. Mosaic climatic characteristics affect the properties of frozen ground - from seasonally to permanently frozen ground, having a continuous, discontinuous, and island bedding.

The geothermal conditions of Mongolian Altai have spatial heterogeneity, which has caused a wide variety of cryo-morphogenesis processes whose development is facilitated by low soil temperatures and the difference in the depth of the active layer. Geothermal field observations in 2017 have revealed that the minimum depth of spring-summer thawing is fixed in peaty rocks, and is 0.8 m on the test site of Ehen-Nuur (Figure 1). The maximum depth of the active layer (up to 5 m) was observed in coarse-grain, boulder-pebbles, lake-proluvial, and fluvo-glacial deposits. The depth of the active layer is in the range of 1-1.7 m in deluvial-proluvial sediments (rubble with loamy filler), 1.5-2.5 m in the morainic boulder-loams, and about 1 m in clay.

The 2016 observation at the geo-cryologic Ehen-Nuur test site showed that active near-surface freezing of the active layer began in October and reached maximum depths by late February. A stable thawing of the seasonally frozen layer was observed in April. The top layer, about 20 cm deep, warmed up to 15 °C by the middle of summer, but only in August this temperature penetrated to a depth of 80-85 cm. Maximum ground warming recorded at the end of September reached a depth of 3 m. The rocks at this depth warmed up to 0.5 °C.

A pronounced high-altitude differentiation is observed in the distribution of cryogenic landscapes within the studied ranges of Sutay and Tsambagarav. The forms of frost weathering: blockfields, blockstripes, and altiplanation terraces are typical for relatively well-moist areas of slopes within the subnival zone, where the temperature of the near surface layer of air and the upper horizons of soils

Figure 2. Dynamics of average temperature of ablation period (a), and dynamics of total winter precipitation (b).

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often passes through 0 °C. Frosty sorting of the stone material occurs at similar hypsometric levels within the aligned or inclined (up to 4°) surfaces, with the formation of stone polygons and rings up to 2 m in diameter forming frost scars. Stone polygons are observed on the watersheds of the south-eastern slope of the Sutai ridge, and folded from the surface with loose rubble sediments with inclusions of coarse-grained material.

Throughout the year, sharp fluctuations in the surface-air layer temperature lead to the appearance of discontinuous deformations in the surface layer of soil and frost crack formation, which most actively occurs on the surface of river terraces, flat areas of slopes, and bottoms of local depressions. The cracks that appear in this case have a depth of 2 meters, with a width in the upper part of up to 15 cm. The processes of cryogenic heaving similarly occur with cracking geomorphological levels. Precipitation, mostly by the end of summer, supports the development of cryogenic heaving; such moisture contributes to a significant moisture saturation of the surface layer soil by the beginning of the freezing season. Seasonal (up to 1 m high) and perennial (up to 2-3 m high) mounds are distinguishable among the various forms of cryogenic heaving.

Ground ice thawing plays an important role in transforming the mountainous areas of Mongolian Altai. With this in mind, special emphasis was placed on research involving thermokarst development in the modern conditions.

The dynamics of the thermokarst processes is studied using polychronous space survey and ground observations. The analysis of remote sensing data performed in the environment of the GIAS «EuCLiD» for 1962 - 2016 showed a widespread and steady increase in the number and area of the thermokarst genesis lakes within the moraine complexes of the Tsambagarav massif Little Ice Age. A shallowing tendency and a reduction of water in the "mature" thermokarst water bodies is at lower hypsometric levels in the zone of discontinuous permafrost, with simultaneous appearance of new water bodies due to the intensive subsurface thawing of ice-bearing loose sediments (Figure 3).

The traces of glacier activation in the Little Ice Age (17th-19th centuries) are expressed in the form of marginal moraine complexes clearly preserved in the relief of the Sutai and Tsambagarav valleys. The main morphological feature of the complexes is the existence of a frontal moraine ridge, reliably recognized by space survey and used as a reference point for the reconstruction of the nival-glacial zone spatial characteristics for the Little Ice Age. The glacial landscapes occupied the 16.02 sq. km ridge Stay and were distributed on 99,104 square kilometers within the Tsambagarav range at the maximum transgressive stage of the Little Ice Age based on 3D topography.

The decrease in the regional temperatures by 0.6-0.8 °C caused a 200 meter lower boundary inversion of the ice belt. The thickness of the valley glaciers in the basin of the Tsagangol River is two times superior to the modern one in a number of mountain-glacial basins. The thickness of the glaciers was reconstructed by the hypsometry of lateral moraines.

The climate change in the post-maximum phase of the Little Ice Age [15] resulted in a spatial transformation of the nival-glacial belt of the ridges, expressed in a progressive reduction in the size of the glaciation and the uplifting of its lower vertical limits. By August 2015, the total area of the Sutai ridge glaciation decreased to 11.21 sq km, and that of the Tsambagarav ridge decreased to 66.57 sq km. The subglacial deposits moved to the subaerial category, in the deglaciation zone, under the influence of the changed climatic background. Embryonic periglacial landscapes began to form on a young lithogenic basis.

The space-time dynamics was strictly subject to the change in the external hydrothermal conditions, which is the main property of landscapes developing within the periglacial zone of the Sutai and Tsambagarav ridges. Temperature weathering, solifluction, cryogenic slumping and thermokarst are among the most important processes involved in their formation.

Solifluction forms are widely spread in the study area and confined to the lower parts of the slopes of the valleys in the altitude interval from 2400 to 3000 m. Their genesis and dynamics are associated with widespread permafrost loose rocks, the hydrothermal regime of the region, and the development of vegetation. As a rule, solifluction forms occur in groups and occupy convex parts of the sides of valleys with angles from 10° to 30°. They have the form of festoons; larger forms are represented by
terraces. The size of the terraces varies widely: the length from 4 to 30 m, the width from 0.5 to 6 m, and the height of the scarp from 0.5 to 1.5-2 m.

Open not covered forms of the solifluction formations are confined to higher hypsometric levels of the slopes, often with a pronounced scarp of rough debris. At the base of the slopes, more widespread are solifluction grass-covered terraces and main blades with postgenetic development of microforms of frost heaving and frost sorting.

Figure 3. Comparative GIS analysis of Tumurt mountain-glacial basin (Tsambagarav massive):

a) blue line (sensor KH-4B, 1968-08-11) showing position of Tumurt glacier terminus in 2015
b) red lines (sensor WorldView – 110, 2015-08-19) indicate the contours of lakes formed within LIA moraine from 1968 to 2015.

The internal structure of the solifluction forms revealed the cycles of their development. It is established that each cycle of the soil flow was completed by the stage of soil formation. Compared with the two older stages, the soil horizon thickness of the present stage indicates a longer period of its formation.

Open forms of cryogenic landslides are formed through processes of freezing-out of large debris on the surface during the day from sediments with a dominant loamy fraction, followed by a downward displacement. The open forms have a low scarp (20-40 cm) and a limiting border; they have the form of a tongue in the scheme.
When moving up the slopes, their natural rejuvenation is noted, expressed in the recency of the morphological elements and the absence of lichen coating on the debris. The modern formations are numerous, but much smaller in size than the older ones. The specificity of the structure of permafrost forms indicates the existence in the recent past of conditions conducive to more intensive development of the cryogenic processes. A distinct feature of the Sutai ridge periglacial zone is the absence of lakes. This is explained by the morphology of glaciation caused by the ridge’s topographical features. Primarily, there is a predominance of hanging glaciers, which do not produce frontal-moraine complexes required for favorable lake-forming conditions. In the belt of modern deglaciation of the Tsambagarav ridge, the appearance and increase in the area of the waters of 8 glacial lakes (Figure 4) was noted, in contrast to the Sutay massif.

Figure 4. Spatial distribution of glacial lakes in Tsambagarav: a) modern glaciers in 2017; b) deglaciation area from Little Ice Age; c) glacial lakes in 2017.

The vast majority of lakes which formed within fifty years refer to the foreground of modern glaciers (moraine-dammed lakes and lakes of intermoraine depressions) and glacial-accumulative complexes of the Little Ice Age (thermokarst lakes). The periods of increased activity of glacial and thermokarst limnogenesis (1992-98, 2012-2016) were revealed by means of GIS analysis of polychronous spatial data.

5. Conclusions
The planetary climate experienced significant changes during the 20th century. The global changes consisted of an increase in temperature - the main characteristic of the Earth's climate. Modern climatic changes are clearly observed in all regions of the Earth. The average air temperature has increased by 0.74 °C since the beginning of the 20th century, and about two-thirds of this growth has occurred since the 1980's. Each of the last three decades was warmer than the previous one. The air temperature is higher than in any previous decade since 1850 [16].

The warming was accompanied by climatic anomalies everywhere, as a result of which the regional climates underwent significant changes, which were most clearly expressed at the beginning of the 21st century. An analysis of the medium-period observations showed that the average annual air temperature in Western Mongolia increased by 2.07 °C.
The climatic changes have led to significant and irreversible changes in the spatial structure of the nival-glacial and cryogenic systems of the Mongolian Altai highlands. On the mountain glaciers of Sutai and Tsambagarav, the deglaciation area has increased by 37.5 sq. km since the time of the Little Ice Age maximum (about 18 sq.km in the last 50 years). The landscape belts have moved due to climatogenic uplifting to heights of 180-200 m in the mountain-glacial basins of Mongolian Altai. In the deglaciation zone of the ridges, the subglacial deposits became subaerial ones under the influence of the changed climatic background. New periglacial and limno-periglacial geosystems have begun to form on the young lithogenic basis.

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