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RECENT AND FORECASTED CHANGE OF GLACIERS OF THE NORTHEASTERN ASIA

ABSTRACT

Paper presents the results of comparative analysis of the satellite images data about the glacier state in glacier systems of Byrranga, Suntar-Khayata, and Chersky ranges (2003) with the data given in the Glacier Inventory of the USSR (1945, 1967 and 1970). We studied change of glacier area since the Glacier inventory compilation, which was based mainly on areal-photo and visual services with the satellite (*LANDSAT)* images data. The retreated glaciers have been analyzed by groups, sorted by the same aspect and morphological type of a glacier in terms of the rate of reduction. In total glacierization of Chersky Range reduced by about 30% (1970–2003), Suntar-Khayata by 20% (1945–2003), Byrranga – by 17% (1967–2003).

The method for projection of glacier systems development in 2049–60 is applied for NE Asia Mountains using the ECHAM 4.5 and some other climatic scenarios. We have considered continental glacier systems (Suntar-Khayata, Chersky, Orulgan) and temperate-marine ones (Kamchatka). The method involves construction of vertical balance profiles for baseline and projected period, hypsographic schemes of ice distribution via altitude in a glacier system. The results of the method application to the glacier systems of the NE Asia are discussed in the paper.

KEY WORDS: Glacier system, ELA, glacier area, glacier termini, balance, model, climate change, climatic scenario, Northeastern Siberia, projection

INTRODUCTION

Northern Siberia (subarctic zone of Eurasia) is a very poorly studied region in terms of glacier state (change). They were under measurements only during the IGY in 1957–59, since then no regular observation has been conducted.

Temperature regime of this huge region in the 20th century is suggested to be the most essential factor of the large changes in glacier size, as by the data of RIHMI-WDC (Obninsk, Russia, www.meteo.ru) the maximal absolute values of the linear trend factor (number of days in the winter or summer when average daily temperature exceeded critical value) for the period from 1961 to 2000, are obtained for the south of Russia and Eastern Yakutia. Apparently, the NE Siberia region is anomalous enough regarding climate warming started in the end of 20th century that has had an effect on essential retreat of glaciers. Glaciological observations were started in the IGY period, just at the threshold of changing the cold phase onto warming, which proceeds till now [Ananicheva, et al, 2002] (Fig. 1).

This was a motivation for the study of the assessment of glacier change of this vast region by remote sensing method and a projection of glacier behavior for the future.

Comparison of the glacier areas obtained by *Landsat* imagery and the Glacier Inventory of USSR (1960–80s) allowed assessing the glacier retreat for the period of current

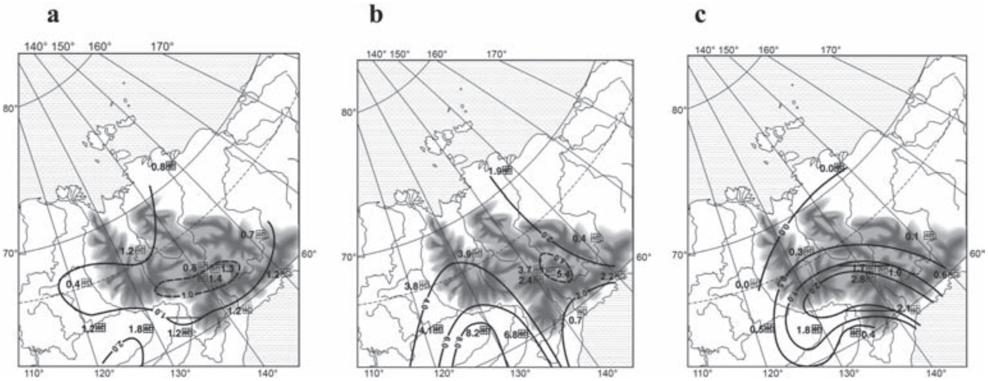

Fig. 1. Spatial distribution of positive temperature trends:

a — annual values for the warming up to 1995, T°C/50 years; b — summer trends for the same period, T°C/50 years; c — winter trends for the same period, T°C/50 years

warming. The estimate was done for the glacier groups with the same morphological type and aspect.

We also developed method of projection and reconstruction the areas, altitudinal distribution and mass balance of glacier systems as a whole according the climate scenarios using calculation of ELA changes and altitudinal distribution of ice in a changing system by linear and non-linear variants. Method is applied to 17 glacier systems in the North-East Siberia and Kamchatka for a period 2040–2069 using ECHAM4 and for 4 selected ones – also 2 other AOGCMs.

GLACIERS STUDIED

Glacier systems analysed in the paper represent a wide spectrum of morphology and regime types – from small cirque glaciers of the Orulgan range to large dendritic glaciers of the Chersky Range and specific volcano-glacier complexes of Kamchatka.

The Suntar-Khayata Range

The Suntar-Khayata Range is a watershed between the river basins of the Aldan and the Indigirka tributaries entering the Arctic Ocean. Its elevations reach almost 3000 m. It is one of the largest centers of present glacierization in NE Russia – about 195 glaciers cover 163 km^2 [Ananicheva et al., 2005]. The main source of snowfall for the glacier systems is moisture that has been brought from the Pacific and the Sea of Okhotsk, in particular in spring, summer and early autumn. For the northern glacier massif of the range, Arctic air invasions are also significant in winter. Glacier 31 in the Northern Massif was chosen as a key glacier for the study during the IGY (Fig. 2 *a*)

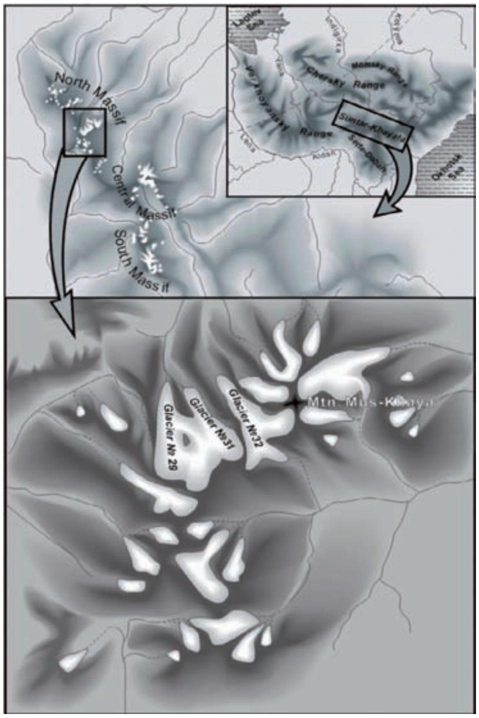

Fig. 2. Maps and schemes of the regions under study:

a) Suntar –Khayata Mountains

The Chersky Range mountain system

The Chersky Range mountain system (which contains a number of ridges) occupies the inner part of NE Siberia located to the north of the Suntar-Khayata Range and closer to the Aleutian Low, in the area of prevailing moisture supply from the Pacific Ocean. Therefore, the overall equilibrium line altitude (ELA) here is lower: 2150–2180 m against 2350–2400 m in Suntar-Khayata Range. According to the latest assessments, the Chersky Range contains about 300 glaciers which cover 113 km^2 [Ananicheva at al., 2005]. (Fig. 2 *b*)

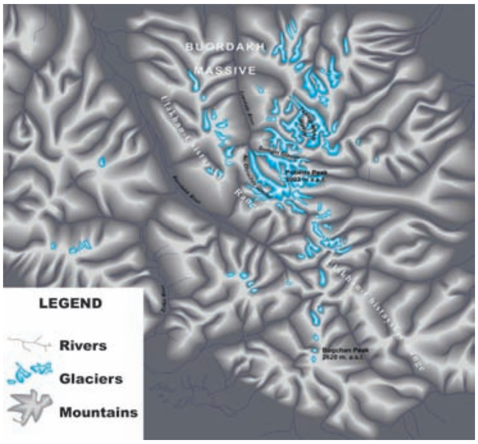

Fig. 2. Maps and schemes of the regions under study:

b) Chersky Range, Buordakh Massif (a center of glaciarization)

Orulgan Ridge

The glaciers of Orulgan Ridge (Verkoyansky Range) were first mapped in the 1940s. The present glacierization is located along the main watershed line, mainly on leeward (eastward-facing) slopes in concave relief forms – in two areas stretching 112 km and 25 km north to south. Glaciers of Orulgan (basically cirque and hanging glacier morphology; about 80 glaciers covering 20 km^2) exist on account of climate since the topography is relatively low. The modern glaciation is the only one in the continental-climate-influenced part of Russia where glacier termini descend to 1500 m; the ELA is lower than 2000 m, and the glaciers face incoming cyclones from the North Atlantic and western sector of the Arctic Ocean. (Fig. 2 *c*).

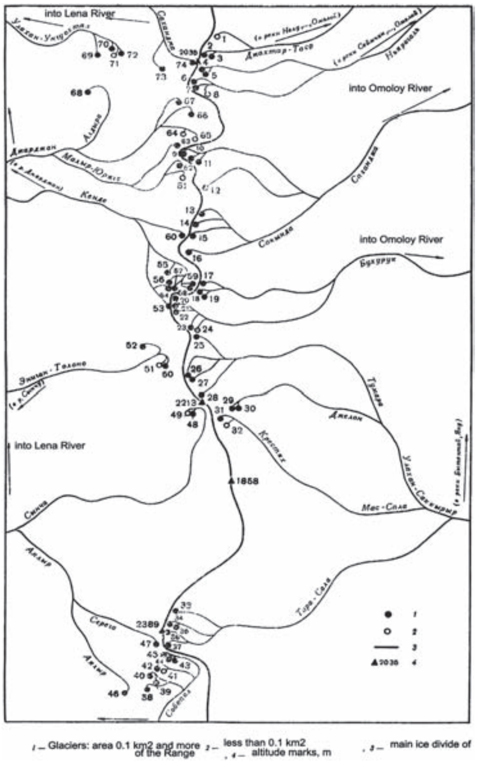

Fig. 2. Maps and schemes of the regions under study:

c) Orulgan Range

Kamchatka

The Kamchatka glacierization consists of 448 glaciers, with a combined area of about 906 km^2. Of these glaciers, 38% are located in the regions of active volcanism, 44% on ancient volcanic massifs (regions of Quaternary volcanism), and less than 19% in non-volcanic regions. Notably, out of all glaciated regions considered in this study, volcanism is the characteristic feature *only* for Kamchatka glaciers. The Kamchatka glaciers lies between 50 and 60° N, near the Pacific Ocean and the Sea of Ohkotsk, which feed the glaciers with moisture from cyclones related mainly to the Aleutian Low. Within the Kamchatka Peninsula, precipitation is higher than over any other region of Russia and shows seasonal variations being under the influence

Fig. 2. Maps and schemes of the regions under study:

d) Kamchatka

of the monsoon (Muraviev, 1999). Precipitation increases from north-west (400 mm yr^{-1}) to south-east (up to 2000 mm yr^{-1}) according to lowland weather stations (Russian Hydrometeorological Service, http://www.meteo.ru). The temperature and precipitation regimes, other climatic factors, relief and geological structures have led to the modern maritime-type of glaciation. Due to abundant precipitation on Kronotsky Peninsula, which faces the Pacific Ocean coast, the glaciers there descend to 250–500 m a.s.l. and the ELA is ~1000 m, whereas well inland on Kamchatka the ELA rises above 2200 m. (Fig. 2 *d*).

Byrranga Mountains

Byrranga Mountains are located in the northern part of the Taimyr Peninsular, NW Siberia. They are formed by the system of parallel or en echelon mountain chains and vast rolling plateaus. Valleys of Pyasina and Taimyra rivers divide the mountain system in three parts – western, middle, and eastern with the altitudes 250–320 m, 400–600 m и 600–1000 m correspondingly (maximal elevation is 1146 m). Mountains are composed with rocks of Precambrian and Palaeozoic age, among them gabbro-diabase plays an important role.

The fact of the glacier existence here became known later than other Russian mountain countries – only in 1950-s. Areal-photo surveys 1950-s и 1967-s defined a number, size of glaciers and their morphologic characteristics for these years. [Dolgushin, Osipova, 1989]

ASSESSMENT OF GLACIER AREA CHANGE FROM THE SECOND HALF OF THE 20TH CENTURY TILL PRESENT

Techniques applied to assess the glacier area change by satellite imagery for Northern Siberia glaciers

General and applied analysis techniques of multi-zonal imagery for mapping modern mountain glaciation were used for the start of glacier data base creation for the West (Taimyr Peninsular) and NE Siberia, which is a poorly explored region in terms of present time glacier state from the LGM to present. Up to now we identified lengths and areas of glaciers for the Suntar-Khayata Mountains, Chersky Range and Byrranga Mountains for 2002–2003 (data of *Landsat* surveys). Using the data about areas of the same glaciers from Glacier Inventory of the USSR, we can assess area loss for the time between the glacier area estimations, given in the Inventory and that of 2000s – ΔS.

Glacier areas of the Suntar-Khayata Mountains were defined in major cases by the data of aerial-photo survey (APS) conducted in 1945. In addition to this an evidence of Prof. M.M. Koreisha (an explorer of these glaciers during the IGY) was used for area determination dated by 1958–59 with addition of a few area measurements, made by expedition of the Institute of geography, RAS in 1970.

We analyzed ΔS for the groups of glaciers, sorted by the same morphological type of glaciers and their aspect. We calculated absolute area reduction, the mean for each

Table 1. Reduction of glacier area for Suntar-Khayata (by morphological type and aspect)

Aspect/Morthological type	S	SE	E	SE	S	SW	W	NW
1945–2003								
Compound-valley	0.41/1/13.7	0.43/2/16					0.7/2/27.5	0.22/2/8.2
Valley	0.12/5/9.5	0.21/7/20.2		0.1/1/6.3	0.16/1/0		0.48/1/26.7	0.25/9/17.9
Corrie-valley	0.2/6/27.5	0.16/10/17.5			0.87/1/87		0.33/1/33	0.12/10/15.4
Corrie	0.11/6/29.6	0.27/7/31.2					0.08/3/13.8	0.18/14/33.6
Hanging-corrie	0.18/13/27.5	0.24/3/69.1		0/1/0			0.16/1/20	0.17/5/36.7
Hanging	0.17/7/33.6	0.26/4/49.7	0.23/1/76.7			0/1/0		0.1/5/39
Shifting-valley			0.45/2/44.2					
1970–2003								
Compound-valley	0.41/1/13.7	0.43/2/16					0.7/2/27.5	0.22/2/8.2
Valley	0.12/5/9.5	0.21/7/20.2		0.1/1/6.3	0.16/1/0		0.48/1/26.7	0.25/9/17.9
Corrie -valley	0.2/6/27.5	0.16/10/17.5			0.87/1/87		0.33/1/33	0.12/10/15.4
Corrie	0.11/6/29.6	0.27/7/31.2					0.08/3/13.8	0.18/14/33.6
Hanging-corrie	0.18/13/27.5	0.24/3/69.1		0/1/0			0.16/1/20	0.17/5/36.7
Hanging	0.17/7/33.6	0.26/4/49.7	0.23/1/76.7			0/1/0		0.1/5/39
Shifting-valley			0.45/2/44.2					

Table 2. Reduction of glacier area for Chersky (by morphological type and aspect)

Aspect/Morthological type	S	SE	E	SE	S	SW	W
	1970–2003						
Dendritic	1.2/1/10						
Compound-valley	0.44/5/23.1	0.84/2/55.4	1.98/1/55				0.79/3/11.6
Valley	0.21/9/16.4	0.37/2/49.4	0.67/2/52	0.12/2/14.3		0.12/2/13.5	0.5/3/38.4
Corrie -valley	0.14/4/18.3	0.64/1/71.1	0.48/1/60				
Corrie	0.11/19/27.7	0.8/1/21.3	0.04/2/27.5	0.13/2/26.5	0.08/1/11.4		0.35/2/62.5
Hanging-corrie	0.08/3/25						0/1/0
Hanging	0.06/5/25	0.16/1/53.3					0.05/1/50.0

group ΔS (km^2), and relative decrease of area $\Delta S/S$, (%), where S – an area given in the Inventory. The results are presented in tables 1 and 2, the columns shows absolute retreat/number of glaciers in the group/relative retreat in %.

Method of Byrranga glaciers assessment by space imagery

The assessment of the Byrranga glacier state is made also by *Landsat* satellite images made by Thematic Mapper and Thematic Mapper + surveying devices.

Due to poor accessibility and resource-required transportation for the field research, remote sensing approach is a real chance to estimate glacier change in this insufficiently explored region and to map them. The location of the objects – glaciers behind the Arctic Circle and climate features ("polar night", cloudiness and gauze) has aggravated a selection of satellite images for Byrranga Mountains.

Additional difficulties consist in the fact that glaciers are open from snow for a short time – in the period of maximal ablation, approximately from 20.08 to 05.09 each year. In *Landsat* archives we managed to select a small number of images which fit these conditions. In this paper we present the results of analysis of three of satellite images, two of them are dated by August by 2001 and one – by 2003 when the survey was produced in the condition of broken corrector (SLC off).

We constructed contours for individual glaciers by interactive digitizing over raster baseplate. The comparison of the glacier contours for different dates (2001 and 2003) made possible to define the most real contours of glaciers for that time. Into the area of the glacier we included patches (lots), covered with ice both in 2001 and 2003. The absence of ice at least in one pattern indicates snow disappearing in summer. For more precise location of individual glaciers and corrections of glacier margins we applied DEM (ETOPO-30) with

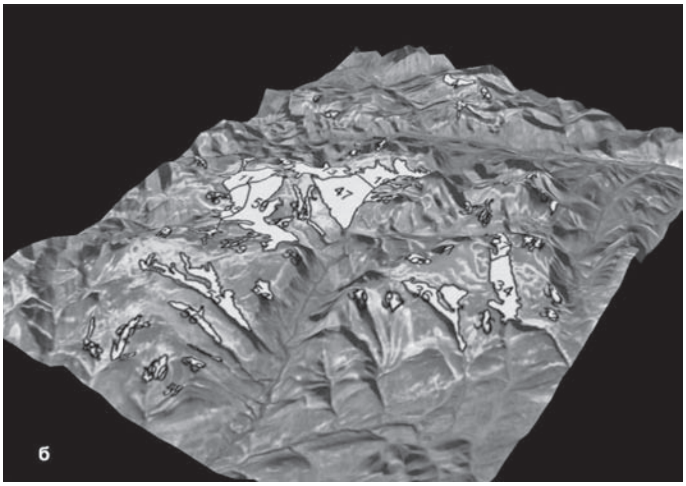

Fig. 2. Maps and schemes of the regions under study:

e) Byrranga Mountans, Taimyr, 3D model map

spatial resolution 1 km/pixel. Construction of pseudo 3D image by DEM facilitates specification of the margins between united transaction type glaciers (Fig. 2 *e*).

RESULTS OF THE ASSESSMENT OF NE SIBERIA GLACIER CHANGE

Reduction of the glacier area for the groups selected by morphological type and aspect

The overwhelming majority of the NE Siberia glaciers reduced their extent for the considered time period due to climate warming, which keeps up to now. There is this region that now is distinguished by maximal temperature trends especially in spring and fall [Gruza, Ranjkova, 2004, Ananicheva et al, 2003]. However about 5% of the entire glaciers of Suntar-Khayata and Chersky ranges have enhanced their extent. Besides really advanced glaciers due to the reasons, not related to general climate situation, we have obviously to include into these 5% the errors of our estimates both by the images (relatively low resolution, cloudiness, etc.) and those of possible wrong assessments of a glacier, given in the Inventory. However for individual glaciers these losses are significant, the reason may be rooted in the fact that warming over central part of Chersky Range (Buordakh Massive) is more intensive than in Suntar-Khayata Range [Ananicheva, Krenke, 2005].

The Chersky Range glaciarization is represented mainly by corrie, valley, and hanging glaciers, in general there are lesser glaciers of big size here than in Suntar-Khayata, however a number of relatively big glaciers of dendrite and complicated-valley types (the area $S > 10$ km^2) are developed. The scale of area loss is consistent with glacier size and intensity of warming lasting for recent 35 years. The prevailing aspect of glaciers is northern and north-western. In absolute value the valley and complicated-valley glaciers of these aspects lost maximum area – from 0.84 to almost 2 km^2. The largest difference (ΔS) is fixed among those corrie glaciers, of NW and NE aspect (0.7–0.8 km^2) that consistent with more intensive warming in this region. Relative portion ($S/\Delta S$, %) of the area lost is also large among NE, E, and NW aspects (higher warming) fir all morphological types, but especially for valley, corrie-valley and corrie.

Comparison of ΔS for the Suntar-Khayata and Chersky glaciers on the basis of tables 1 and 2 data (the same period of assessment – since 1970) is rather difficult, since the number of glaciers in the groups for both mountain systems is different. It is only possible to say that during 35 years large glaciers of the Chersky range reduced greater than those in Suntar-Khayata. The reason might root in the fact that there is central part of Chersky that distinguishes by maximum temperature anomalies for the recent warming in the NE Siberia. Warming in Suntar-Khayata for glaciers is smoothed out by increase of solid precipitation coming from Okhotsk sea region [Ananicheva, Krenke, 2005].

With account of [Ananicheva, Koreisha, Takahashi, 2005] we can say that the considered region demonstrates the following tendency: up to 1970-s (warming not intensive) glacier melting was greater in southern parts of the mountain systems, during the recent 30 years (warming strengthened) due to circulation process change the more intensive melting is characteristic for central and even northern parts of the ranges studied.

By our estimation in 2003 the entire glacier area of Suntar-Khayata mountains was 162.2 km^2. The area of the Suntar-Khayata glaciation in 2003 appeared to be less than the total area of glaciers according to the 1945 Inventory (199.4 km^2) by 37.2 km^2 or by 19.3%:

As for the Chersky range the space images cover about a half of the entire glacier of this system and their area is 84.2 km^2. In 2003 it decreased by 23.4 km^2 (28%) and was equal to 60.8 км^2. Under the assumption that the Chersky range glaciation retreat has the same rate, its area would decrease to 113 km^2 in 2003 compared to 156 km^2 in 1970.

Byrranga glaciers: change of the area

The major part of Byrranga glaciers has northern and northwestern aspect, the valley (19 glaciers) and near-slope (12) morphological types prevail, and there are relatively many transaction (twinned) glaciers (11). Since 1967 (the Inventory evidence) the biggest loss in absolute values is attributed to valley and transaction types, basically of the Northern aspect as the largest ones (2–4.5 km^2). On average these glaciers reduced in size from 0.1 to 0.7 km^2. Corrie, corrie-valley, corry-hanging, near-slope glaciers reduced their area as much as 0.01–0.1 km^2, the initial areas are 0.1 to 1.0 km^2 (data of 1967). In relative values (%) the biggest loss ΔS refers to corrie, valley and couloirs glaciers of middle and small size. As for the aspect that is to some extent a climate-related indicator, the glaciers, which face South and East, have suffered most.

This is in good correspondence with data of weather-stations, mentioned above. Specifically the positive annual trends T_{year} (summer T_{sum} – less) are recorded at the stations, located to the south from Byrranga Mts, herewith the trends are more pronounced eastward than westward. Byrranga Mts serves a barrier for western cyclones, so the glaciers retreated less on windward slopes than on leeward ones (Table 3).

In recent dozen years the almost entire cold period at least the south-western part of Taimyr has been under intensive cyclonic activity. In winter the most longstanding is now "elementary circulation mechanism" (ECM) 12s and 13w (s and w – summer and winter – correspondingly) by classification of Boris Dzerdzeevskii [1962, 1975], under which the south-western part of Taimyr undergoes cyclonic invasion; there are anti-cyclonic weather in the north-eastern part. In summer Taimyr is under many ECMs, and they basically bring anti-cyclonic weather.

However during the last decade a major part of the ECMs (49 types in total) are very rare – the frequency is 5 days and less on average. The largest role belongs to the ECMs – 13s (59 days per year, completely cyclonic weather) and 12w (24 days, western part in anticyclonic, eastern, bigger – in cyclonic pattern). That is why the T_{sum} trends are either close to zero, or slightly-positive. The T_{year} increase is due to the T of inter-seasons and winter that makes an ablation period longer. These processes lead up to different degree of glaciers reduction if noting their aspect.

Table 3. Relative retreat of Byrranga glaciers, grouped by morphological type and aspect, ΔS %

Parameter	Landsat data, km^2	1967 data, km^2	ΔS, %
Morpho-type			
Compound	0,00	0,0	00
Valley	0,05	0,3	13
Corrie-Valley	0,15	0,6	26
Corrie	0,04	0,2	20
Corrie-Hanging	0,02	0,1	16
Transection (twinned)	0,21	1,5	14
Couloir	–0,05	0,1	–45
Near-slope	0,02	0,2	14
Aspect			
N	0,5	0,5	21
NE	0,2	0,2	13
E	0,4	0,4	14
SE	0,2	0,2	21
S	0,1	0,1	00
SW	2,0	2,0	13
W	1,1	1,1	11
NW	0,3	0,3	17

Note: Minus indicates increase, on average by a group.

We estimated the glacier retreat by area up to 2003. The paper [Sarana, 2009], the author of which has been to the Byrranga Mts recently, presents new evidence about the glacier state, confirming our estimates: "nowadays Byrranga glaciers are retreating. For 40 years large glacier complexes have been broken out accompanied with adjunction of some glaciers from each other. Since 1967 the Yuzhniy Glacier tongue retreated by 100–120 m, Glacier 55 – by 200 m. Small glaciers shrink slower. They turned to be most resilient, and their size changed proportionally to large glaciers if any. Steep tongue, cut with channels for melt water discharge is attributed to the valley glaciers; terminal moraines are not available. The latter indicates slow movement rate and insignificant transporting ability of glaciers. There are no snow and firn on the valley glacier surfaces. They are not covered with moraine materials, the exclusions are sites of main channels of discharge. "Anthills" or rubble fields are forming along these channels".

In 2003 by our estimation the glaciation of the Byrranga Mountains, which was inventoried, has reduced as much as 17% as compared with the 1967 state (Table 4). Obviously, up to present the retreat of Byrranga glaciers has exceeded 20%, taking into account temperature trends and cited-above evidence of the V.A. Sarana expedition.

Reduction of the Suntar-Khayata glaciation since 1945 in 2003 appeared to be less than the total area of glaciers according to the Inventory (air-photo-surveys of various

Table 4. Total retreat of Byrranga glaciers

The number of glaciers, which area does not change	The number of glaciers with reduced area	Total glacier area, 1967, km^2	Total glacier area, 2003, km^2	Reduction of area for 36 years, %
15	46 (the rest disappeared)	29.2	24.39	16.5

Note: The table contains data about the glaciers from the USSR Glacier Inventory, the state of more than 30 glaciers lesser than 0.1 km^2 has not been considered.

dates) by 19.3%. As for the Chersky Range, up to 2003 the glaciers decreased by 28% that it is in good correspondence with the fact of maximal warming in the central part of this range within NE Siberia. The rate of retreat of Byrranga glaciers approximately the same as in Suntar-Khayata, where ablation loss is compensated by increased snowfall from the Sea of Okhotsk but is slower than the reduction of Chersky Range glaciarization.

ASSESSMENT OF "GLACIER SYSTEMS" CHANGE FOR NORTHEASTERN SIBERIA AND KAMCHATKA GLACIERS

The term "glacier system" refers to a set of glaciers united by their common links with the environment: the same mountain system or archipelago and similar atmospheric circulation patterns.

Projection and reconstruction of glacier systems as a whole according to climate change scenarios is very important task, which can not be solved by hydrodynamic methods up to now. We have developed method for non-tidal mountain glacier systems involving ELA response to climate change, equality of accumulation and ablation at the ELA level and the assumption of ELA to be between top and termini levels of the glacier systems in case of absence of direct measurements. The latter assumption is based on the Gefer/Kurowski method (e.g. Hess, 1904; Kalesnik, 1963), and used for situation when glaciers are in balance with climate. The period 1960–1980 (when the USSR Glacier Inventory was compiled) is a baseline that coincides to a major part with that of taken by WMO and in the most climate models. The construction of hypsographic schemes showing the distribution of glacierized area versus altitude in the glacier system is a basis for modeling vertical change of glacier system (shift of ice covered surfaces upward) under climate change (Fig. 3).

To estimate vertical distribution of present mass-balance components all available climatic data is used. Ablation is calculated from summer temperature by general empirical formula [Krenke, 1982]. Correction on glacier cooling was introduced. Accumulation is calculated from solid precipitation (weather stations records) with correction on coefficient of snow concentration on glacier surface depending on prevailing morphological type in the system.

We extrapolated precipitation in northeast Siberia according to the Suntar-Khayata meteorological station (2050 m a.s.l.) and in Kamchatka by precipitation gradients identified by observation at 1500 m, incorporating extrapolation based on accumulation values at the ELA, equal to ablation and parallel to accumulation profile for present time. We used the assumption

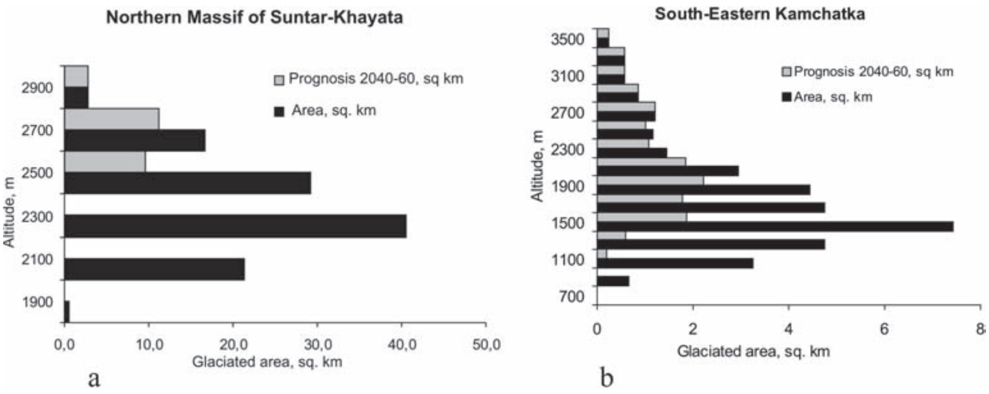

Fig. 3. Examples of hypsographic curves (distribution of ice area versus altitude) for northeast Siberia glaciers systems (*a*) and for Kamchatka (*b*).

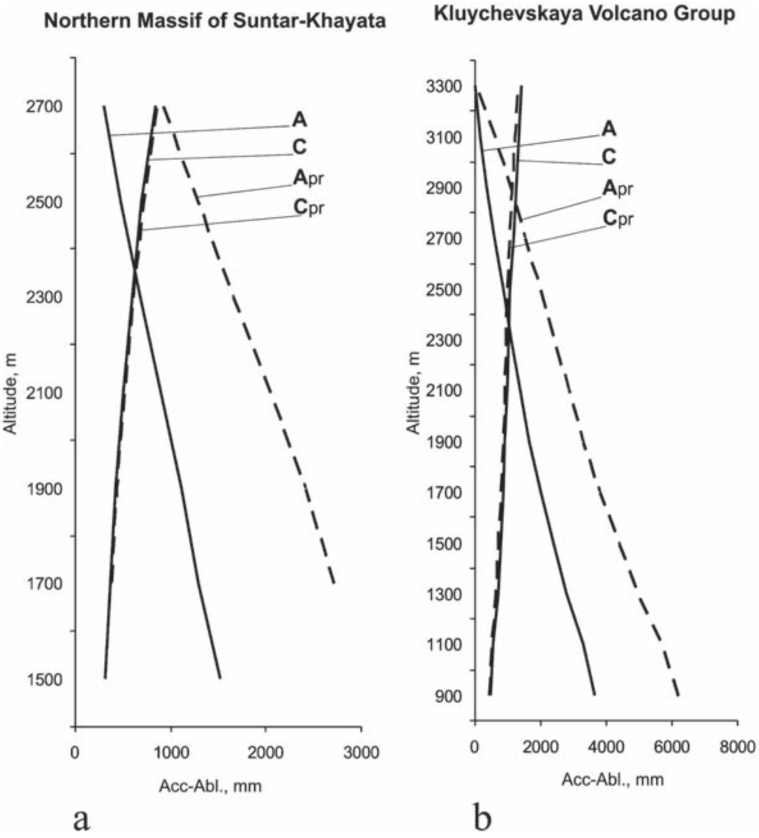

Fig. 4. Mass balance (accumulation and ablation, directed in oppositional way) vertical profiles for a glacier system of northeast Siberia – northern massif of Suntar-Khayata (a) and for Kamchatka – Kluychevskaya Volcano (b). Solid lines – baseline period, dashed line – projection by ECHAM4

that the temperature change, given in the scenario for each grid point within which the glacier system is located, spreads over the entire altitudinal range encompassed by the grid. Projected vertical balance curves are constructed by introduction of the GCM – scenario parameters. The intersections of them give the anticipated ELA values (Fig. 4).

We have chosen the ECHAM4/OPYC3 – GGa11 as a scenario, which predicts relatively greater warming by 2100 in comparison with other AOGCMs. The aim is to evaluate the maximum likely reduction of the glaciers for 2040–2069, additionally taking into account possible natural variability.

It is assumed that after adaptation of glaciers to new climate in accordance with the Gefer/Kurowski method of ELA identification, the elevation difference between the top of the glacier H_{high} and ELA_p (index p means projected) is equal to the elevation difference between $ELAp$ and glacier terminus (H_{ends}). Using the equation:

$$H_{ends} = ELAp - (H_{high} - ELAp) = 2ELAp - H_{high},$$

we obtained the projected distributions of ice against altitude for the glacier systems under consideration for the period 2040–2069. Their lowest point coincides with H_{ends}, where the glacierized area equals zero, and the highest point remains unchanged. The ice distribution at intermediate elevation steps changes in proportion to altitude from zero (at H_{high}) to 100% (at H_{ends}) relative to the baseline period. This is so called linear hypothesis assumption of projected ice distribution by elevation in the system.

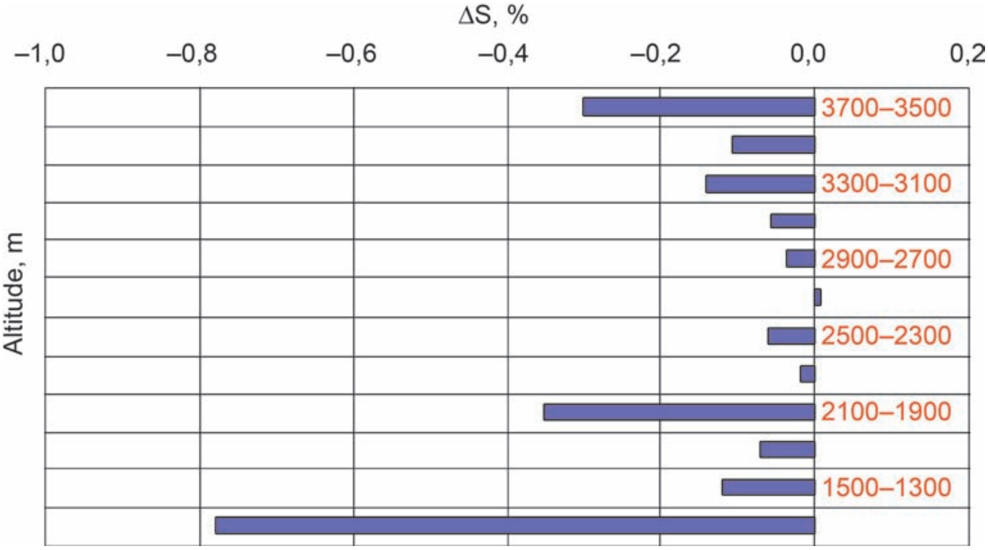

Fig. 5. The empirical curve of ice distribution versus altitude as a difference between 30-year surveys for four glaciers (two Alpine and two Scandinavian)

Projected ice areas for the glacier systems were multiplied by ablation and accumulation layer curves to derive the distribution of projected ablation/accumulation volume versus altitude for the climatic conditions of the scenario (2040–2069) [Ananicheva, Krenke, 2007].

More realistic than linear assumption is the analogy with the result of repeated (before and after warming) altitudinal surveys of glacier in terms of its ice distribution vs altitude. An empirical curve of the ice shrinkage as the difference between such surveys repeated after 30 years for four valley glaciers (two Alpine and two Scandinavian glaciers of the prevailing morphological type in the studied systems) has been obtained (Fig. 5). More in detail the method was discussed recently [Ananicheva et al., 2010].

Areas covered with ice by this regularity diminish less than by the linear hypothesis. The shrinkage in upper zones will be compensated with lesser area decrease in the central part of the system.

We also applied the method to project the development of glacier systems of Byrranga Mountains. The entire glacierization was divided into four systems. As a climatic scenario we used a new generation of ECHAM–ECHAM 5[1]. As a result we have got the projection of the ELA for each four systems to be above the peaks of topography up to 2060, i.e. the glaciers of Byrranga Mountains will disappear if this scenario is appropriate.

The results of the method application are estimates of the possible changes of the areas and morphological structure of Northeastern Asia glacier systems and their mass balance characteristics for 2049–60.

We have used this approach to study glacier systems with a wide spectrum of morphology and regime types, from small cirque glaciers of the Orulgan range to large dendritic glaciers of the Chersky Range, and specific volcano-glacier complexes of Kamchatka. The conditions of glacier nourishment vary widely and the reaction of these glacier systems to climate warming is found to vary considerably.

Calculation of projected changes shows that the shift of ELA upward will be less in the

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[1] http://www.mpimet.mpg.de/en/wissenschaft/modelle/echam/echam5.html

Table 5. Change of glacier systems characteristics in Northeastern Siberia and Kamchatka up to the mid 21st century (2040–2069)

Glacier system	The shift of ΔH_{ela} (from basic to projected period), m	The elevation range of the glacier system, m		Glaciated area, km^2, %		Ablation and accumulation at the H_{ela}, mm		Balance, cm yr^{-1}	
		Basic period	Projected period	Basic period, km^2	Projected period, km^2 (%)	Basic period	Projected period	Basic period	Projected period
Northeastern Siberia									
Orulgan Northern Knot	250	750	400	7	2(27)	740	1230	+23	0
Orulgan Southern Knot	500	760	0	12	0	580	0	+14	–
Cherskiy –Erikit knot	320	700	200	7	1 (10)	710	1020	+7	0
Cherskiy-Buordakh	300	1640	1280	63	18(29)	700	1050	- 2	–11
Cerskiy-Terentykh	300	1520	1180	28	8 (29)	720	1130	+2	+ 6
Suntar-Khayata, North	350	1080	520	111	26(23)	620	850	-26	–70
Suntar-Khayata, South	500	1110	60	22	0.4(2)	460	650	-40	–30
SUM				**250**	**55.4 (22)**				
Kamchatka									
Sredinny Range Eastern Slope	600	2850	2160	124	24(20)	1430	1460	-44	–170
Sredinny Range Western Slope	570	1900	1330	264	55(21)	1430	1470	+20	–44
Shiveluch Volcano	600	3240	2720	30	16(52)	1160	1080	–36	–50
Kluchevskaya Group	420	3950	3660	124	85(69)	1000	1100	+31	–4
Tolbachek Volcano	580	3085	2680	70	33(47)	1200	1350	+50	+3
Tumrok and Gemchen ranges	430	1020	0	11	0	1710	0	–81	–
Khronotskiy Range	510	1150	260	91	9(10)	3350	3800	–48	–116
Valaginskiy Range	610	1000	0	9	0	1400	0	–40	–
Volcanows of South-Eastern Kamchatka	300	2660	2340	34	14(41)	1350	1550	–44	–60
Ichinskiy Volcano	740	2080	780	29	6(22)	1510	1550	+17	+3
SUM				**786**	**242(30.8)**				
SUM totally				**1036**					
Ichinskiy Volcano (with account of blow-off from the slopes)	1210*	2080	0	29	0	1510	800*	+17	–

* The projected elevations are higher than the real topography, so the glaciation in these cases will not exist under the scenario used.

northern parts of northeast Siberia (230 m as against 500 m in the south), while in Kamchatka ELA change as a rule is greater and depends on precipitation rate. Our calculations also predict the disappearance of southern Orulgan and Suntar-Khayata glacier massifs as well as some Kamchatka (Ichinsky volcano and others) systems (it happens if ELA shifts above mountains tops), while others (Kluchevskaya volcano) will preserve 70% of their present area (Table 5).

We also tested four key glacier systems under projections by Had CM2GSDX (minimal warming) and the Japanese Model – CCSRGSA1 (JJGSA), maximal warming. The Had CM2 scenario will lead to minor changes and the Japanese scenario leads to the disappearance of the major part of the glaciers.

The results are certainly sensitive to the choice of the forcing GCM, downscaling method and glacier mass balance model.

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