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Scientific note

Northern Eurasia glacier response to global climate change

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Abstract: One way to predict climate change in the future is reconstruction of former climates. This approach is called the method of paleoanalogues. In this paper the climatic reconstructions for Holocene optimum (scenario 1) and Eemian Interglacial (scenario 2) are used as paleoanalogues of possible future climate warming. Two techniques worked out by authors have been applied to calculate the change of the equilibrium line altitude (ELA): (1) based on calculations of ablation and accumulation on the Novaya Zemlya ice cap (the sufficient paleodata situation) and (2) on the other ice caps of the Eurasian Arctic (the insufficient paleodata situation). The latter involves the term "lower bottom of chionosphere" which under some assumptions is transformed into the ELA of each ice cap under climatic conditions of the Holocene and Eemian Interglacials.

According to these scenarios, the greatest changes of air temperature will be in the Arctic. For example, under global warming appropriate to scenario 1, the mean summer temperature in the Novaya Zemlya archipelago will rise by 4℃; according to scenario 2—by 8℃. By both scenarios the archipelagoes of Franz Joseph Land, Novaya Zemlya and Severnaya Zemlya will undergo the greatest warming in Northern Hemisphere. Annual precipitation will also reach maximum increase in this region (+100 mm under scenario 1 and +200 mm under scenario 2 in comparison with present values).

1. Introduction

Despite the last decades' trend toward retreat of glaciers, they are still a dominant factor in many high mountain landscapes and, in particular, on Arctic islands. More than 50% of the Arctic archipelagos are covered by ice caps and ice domes. The behavior of glacier systems in the lasting climatic trend toward warming in high latitudes is an important current research topic. Many papers on this topic have been published. Proposed scenarios of climate change involve different GCM schemes; however reconstructions of paleoclimates for interstadials (time between global glacier advances) and their use as possible analogous for future climate change represent an important direction in modern glacioclimatology.

In this paper paleoclimatic reconstructions of the Holocene optimum (5–6 thousand years ago) and Eemian Interglacial (120 thousand years ago) were used as scenarios for investigation of glacial response to possible climate change under two variants of global atmosphere warming. These reconstructions give spatial distributions of precipitation and air temperature (the climatic parameters which play the most important roles in glacier development) for the whole Northern Hemisphere, with distinct regional differences.

2. Scenarios and methods

Calculations of the Arctic glaciers' response were carried out using the "principle of uniformity", that assumes contemporary relationships between glaciological and climatological parameters to be the same both in the past and future. Now glaciers exist in a wide corridor of the warmth and moisture alignment: from cold and dry conditions (where snow accumulation is lower than 50–100 mm per year, and mean summer temperature is -4, -6°C) to warm and humid ones (where snow accumulation is 3000–4000 mm annually and mean summer temperature is $+5$, $+6$°C). Actual data collected until the present time provide reliable links between glacier and climate characteristics for different types of glaciations.

The equilibrium line altitude (ELA), the basic glacier indicator, the level where annual accumulation equals annual ablation, directly depends on climate, first of all on the temperature and moisture regime. To obtain these parameters we used the following equations:

$$A = 1.33(t_{\mathrm{sum}} + 9.66)^{2.85}, \tag{1}$$

$$C = X_{\mathrm{year}} \bullet P \bullet K_{\mathrm{sn}}, \tag{2}$$

$$X'_{\mathrm{year}} = 9t_{\mathrm{sum}}^{2} + 296t_{\mathrm{sum}} + 645, \tag{3}$$

A—total melting (ablation), in mm, t_{sum}—mean summer temperature, °C, C—annual accumulation in mm, X_{year}—annual precipitation at any altitude, mm, P—solid precipitation share in X_{year}, %, which depends mostly on mean monthly temperature, K_{sn}—coefficient of snow concentration on glaciers. X'_{year}—winter mass balance plus summer precipitation at the ELA, mm.

Formula 1 is a modification of a well known relation between snow melting and mean summer air temperature (Krenke and Khodakov, 1966), recalculated for the ELA zone (Krenke, 1982). Formula 2, summarizing empirical experience, has been widely used while compiling the World Snow and Ice Resources Atlas (Kotlyakov, 1998).

The third formula was derived from observations on 70 different glaciers at their ELA in various climatic belts presented in Ohmura *et al.* (1992).

Paleoclimatic scenarios are presented as maps which have been compiled from field data (Frenzl *et al.*, 1992) The points of sampling are not uniformly distributed throughout Northern Eurasia, so for some regions the spatial picture of climatic parameters was obtained by interpolation between rather scarce data. Therefore the degree of reliability for these areas is lower in comparison with those with dense sampling. This circumstance compelled the authors to use two different methods.

In case of sufficient data, we used the technique described in Davidovich and Ananicheva (1996). Specifically, we applied this technique to the Novaya Zemlya ice cap reconstruction in Holocene and Eemian Interglacial. This method involves calculation of the ablation vertical profiles for the glacier region by Formula 1 with the help of air temperature lapse rates and temperature discontinuities at glacier margins. When reconstructing climatic characteristics of the Novaya Zemlya islands, we assumed the annual distribution of temperature and precipitation over the ice cap to be similar to the present-day one. The latter is distinctly maritime: the temperature extremes (minimum and maximum) take place in March and August, while the precipitation minimum occurs in February–March and maximum in August–September.

At present, the vertical gradient of air temperature over the existing ice cap, is noticeably greater (due to the cooling effect of the ice surface) than in free lower atmosphere and changes in reverse way through the year, with a winter minimum approaching the value of the dry adiabatic gradient. So for paleoreconstructions of warm periods we took the mean seasonal values 0.4℃/100 m in winter and 0.6℃/100 m in summer as the cooling effect of ice cap then was minimized. The mentioned method of treating the temperature discontinuities at the glacier surface is given in the same paper.

Since solid precipitation is not derived from paleogeographical data, this value was obtained by a nomogram, developed by E.G. Bogdanova of the State Geophysical Observatory (Bogdanova, 1976). The nomogram makes it possible to derive the solid precipitation component from the total amount by monthly air temperature and absolute altitude of the glacier (mean).

Paleo-temperatures and paleo-precipitation at different altitudes were calculated separately for 1) the modern ice sheet which occupies about 65% of Northern island's area in the middle and northern its parts, and 2) mountain glaciers which occupy about 7% of Southern island of the archipelago in its north. The two regions differ not only in the glaciation type, but also in subglacial landforms.

Vertical curves of glacier paleo-accumulation and paleo-ablation were built by Formulas 1 and 2. For the Novaya Zemlya ice cap the K_{sn} was assumed to be 1. The cross-section of the curves indicates the position of the ELA of the ice cap and mountain glaciation area in the two chosen time periods in the past.

The other approach was defined and used by Kononov and Ananicheva (1998) for the reconstruction of the former glaciation in Scandinavia *for the case of insufficient paleoclimate data.* A wealth of paleoclimate proxy data (lake level, pollen, diatoms, sediment stable isotopes, etc.) lies in the lowlands and intermountain basins outside the regions of interest. How can we exploit this resource of paleoclimate proxies in order to reconstruct mountain glaciation in the Arctic? This question was a primary motivating force for development of this approach.

For the reconstruction of glaciation in mountain areas (Arctic ice caps are located on elevated topography) we should identify the background value of some factor which combine both climatic and glaciologic components, can be obtained for region having past paleodata on climate, and can be extrapolated over wider (in particular mountain) territory. We consider that such factors can be obtained with the help of what we call the "chionosphere". The term was proposed by S.V. Kalesnik to describe the area (part of troposphere) where stable snow cover can persist all year round and glaciers can exist on the ground surface in favorable (elevated) relief forms (Kalesnik, 1963). This sphere of potential rather than actual glacierization should have a combination of warmth and moisture that permits annual solid precipitation on the horizontal surface to exceed their melting. The lower boundary of this sphere (H_h) corresponds to the climatic snow line, since in the free atmosphere climatic factors (temperature and precipitation) determine this level. While H_h touching the ground surface the relief factor enters into interaction, and then after glaciation

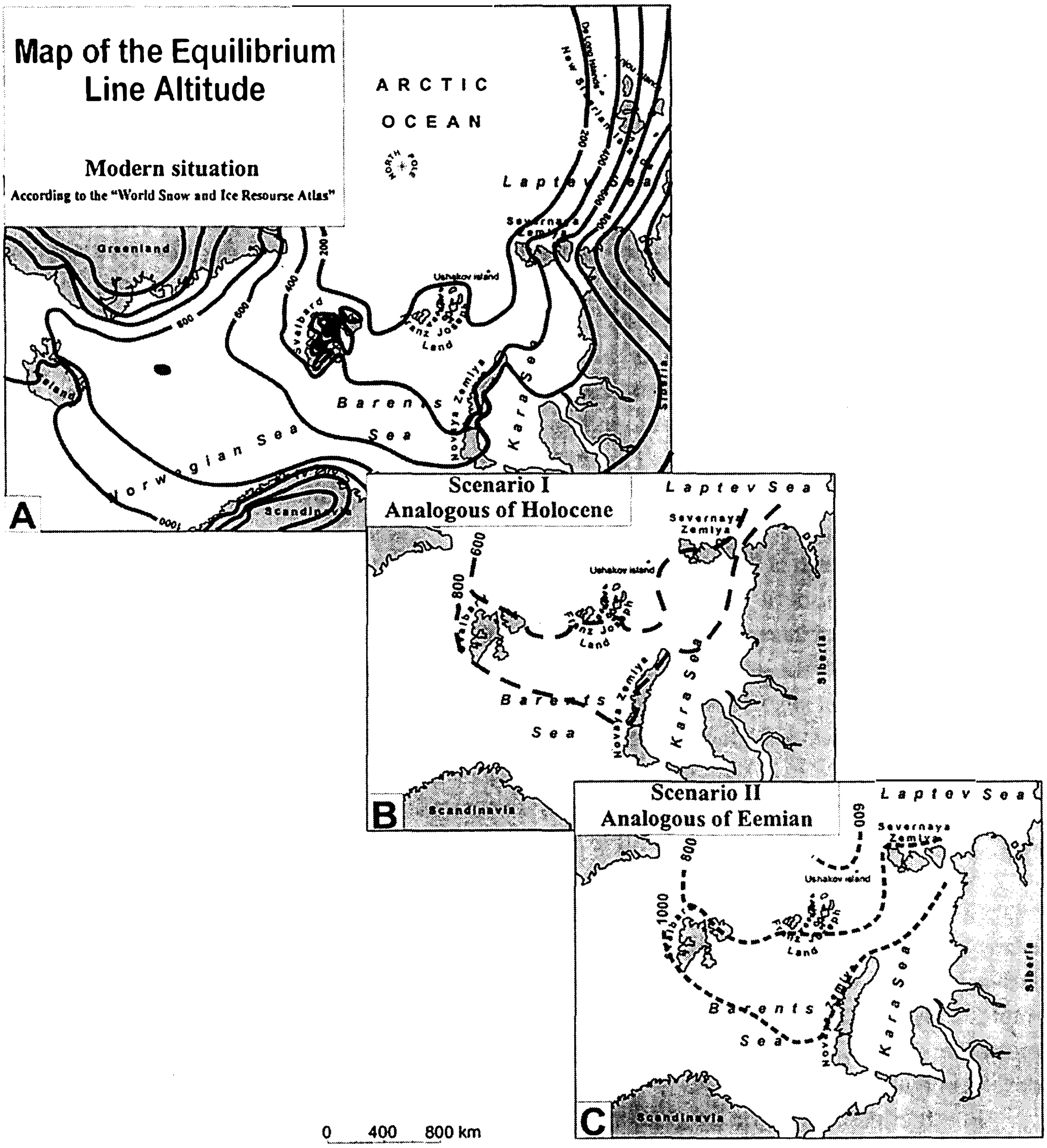

Fig. 1. Equilibrium line altitude of glaciation in the Eurasian Arctic at present time (A), reconstructed according to the paleoclimatic scenarios for Holocene Optimum (B) and Eemian interstadial (C).

has arisen, the glacier factor adds. In the latter case the lower boundary of the chionosphere "forms" ELA on glaciers. This method also supposes the use annual precipitation values as the analogue of accumulation.

The altitude of the chionosphere bottom over the major part of North polar area varies from 200–250 m to 1300–1500 m a.s.l. The chionosphere is at high altitude where it is cold and dry, in Greenland and the Canadian Arctic Archipelago, and is lowest over Arctic islands near the sea ice edge. Its elevation under the central part of the Russian Arctic is 300–400 m. The altitude of the bottom boundary of the chionosphere is indicated by present-day equilibrium line altitudes (Fig. 1a, solid line).

If we can calculate the lower boundary of the chionosphere over plains and foothills we can extrapolate/interpolate to obtain average height for the wider territory including mountain regions. So in more detail the algorithm of calculations includes the following stages:

—Identification of the chionosphere lower boundary in the free atmosphere under the nearest place with sufficient paleoclimatic data and making the isoline "field" of the H_h;

—Interpolating or extrapolating the calculated H_h values over (mountain) regions, taking into account their local features;

—Transformation of the H_h values into ELA and constructing contours of the mountain ranges situated higher than the ELA;

—Determination of the whole glacier area which depends upon morphological and morphometric characteristics of both low and high mountain belts.

As has been said, H_h is not a direct equivalent of ELA, indeed in a previous paper (Kononov and Ananicheva, 1998) was shown that the relief forms have the greater effect on the ELA deviation from H_h. However, analysis of the difference between the presently observed ELA position on ice sheets of the Arctic archipelagoes and H_h, calculated by the described method has revealed that the influence of the relief cut in this region is insignificant and H_h can be considered to be the analogue of the ELA.

Paleoclimatic reconstructions as usual provide information about seasonal air temperature and annual total precipitation at the ground surface. In paleoglaciologic modeling it is acceptable to use mean summer temperature t_{sum} and annual precipitation X_{year} for while calculating mean annual ablation and accumulation.

The lower boundary of the chionosphere in free atmosphere was calculated by transformation of Formula 3: mean summer air temperature which corresponds to total precipitation, received by paleodata, is defined for the ELA. In this way we simulate the climatic situation as if the lower boundary of the chionosphere is located in a given place near the surface. Then, comparing values of the mean summer air temperature at the ELA and actual temperature (according to paleodata) at the ground surface, we obtain a temperature deviation, from which, together with the air temperature gradient, we can calculate an altitude where the deviation equals zero. This altitude coincides with the bottom boundary of the chionosphere. Taking the subsequent stages of the calculations (see above) we estimate the position of the glacier ELA and, as a result, the character and extent of glaciation in the past.

The method error (20%), caused by the series of assumptions, is acceptable in paleo-reconstructions but in case of forecasting seems too big. The main reason for the error lies in the assumption of correspondence between annual total precipitation and melting, calculated with Formula 1. In this paper this error is reduced by using Formula 3, since for this equation annual precipitation was measured at the equilibrium line altitude. Both described methods have been used for the Novaya Zemlya ice cap change under the paleoscenarios, the results were close.

3. Simulation of possible climate change in the Eurasian Arctic

Contemporary data on insular Arctic glaciation, collected for the newly published World Atlas of Snow and Ice Resources, were used for building the empirical relationship of the ELA and area of ice caps or reticular glaciers as the most widespread types in the Arctic. This relationship helps to estimate areas of former glaciation as well as possible glacier extent under climate change in the future. Depending on the lower chionosphere boundary position glaciers can occupy the whole island (for example, Ushakova Island) or some of its area (other glaciated islands of the Russian Arctic).

In accordance with the paleoscenarios, the major changes of air temperature took place in the high latitude belt. In the region of the Novaya Zemlya archipelago, for example, the mean summer air temperature will be 4°C higher in the conditions of the global hemisphere

Table 1. Changes of some glaciological parameters for islands of the Eurasian Arctic under global warming by scenario 1.

Glacier region	Equilbrium line altitude (H) m a.s.l			Area under glaciers (S), km^2		
	Present-day	Forecasted	ΔH	Present-day	Forecasted	$\Delta S/\Delta\%$*
West Spitsbergen, Svalbard	500	800	300	23719	7750	15969/67
Nordaustlandet, Svalbard	350	700	350	11135	2500	8635/78
Frans Josef Land	250	550	300	13735	0	13735/100
Novaya Zemlya	500	850	350	23645	5800	17845/75
Ushakova Island	150	450	300	325	0	325/100
Severnaya Zemlya	450	600	150	18325	7350	10975/60

*The percentage of glacier reduction (Δ, %) is given in the dominator as compared with the present glacier area.

Table 2. Changes of some glaciological parameters for islands of the Eurasian Arctic under global warming by scenario 2.

Glacier region	Equilbrium line altitude (H) m a.s.l			Area under glaciers (S), km^2		
	Present-day	Forecasted	ΔH	Present-day	Forecasted	$\Delta S/\Delta\%$*
West Spitsbergen, Svalbard	500	900	400	23719	4250	19469/82
Nordaustlandet, Svalbard	350	800	450	11135	0	11135/100
Frans Josef Land	250	720	470	13735	0	13735/100
Novaya Zemlya	500	1100	600	23645	~500	23100/98
Ushakova Island	150	650	500	325	0	325/100
Severnaya Zemlya	450	850	400	18325	0	18325/100

*The percentage of glacier reduction (Δ, %) is given in the dominator as compared with the present time.

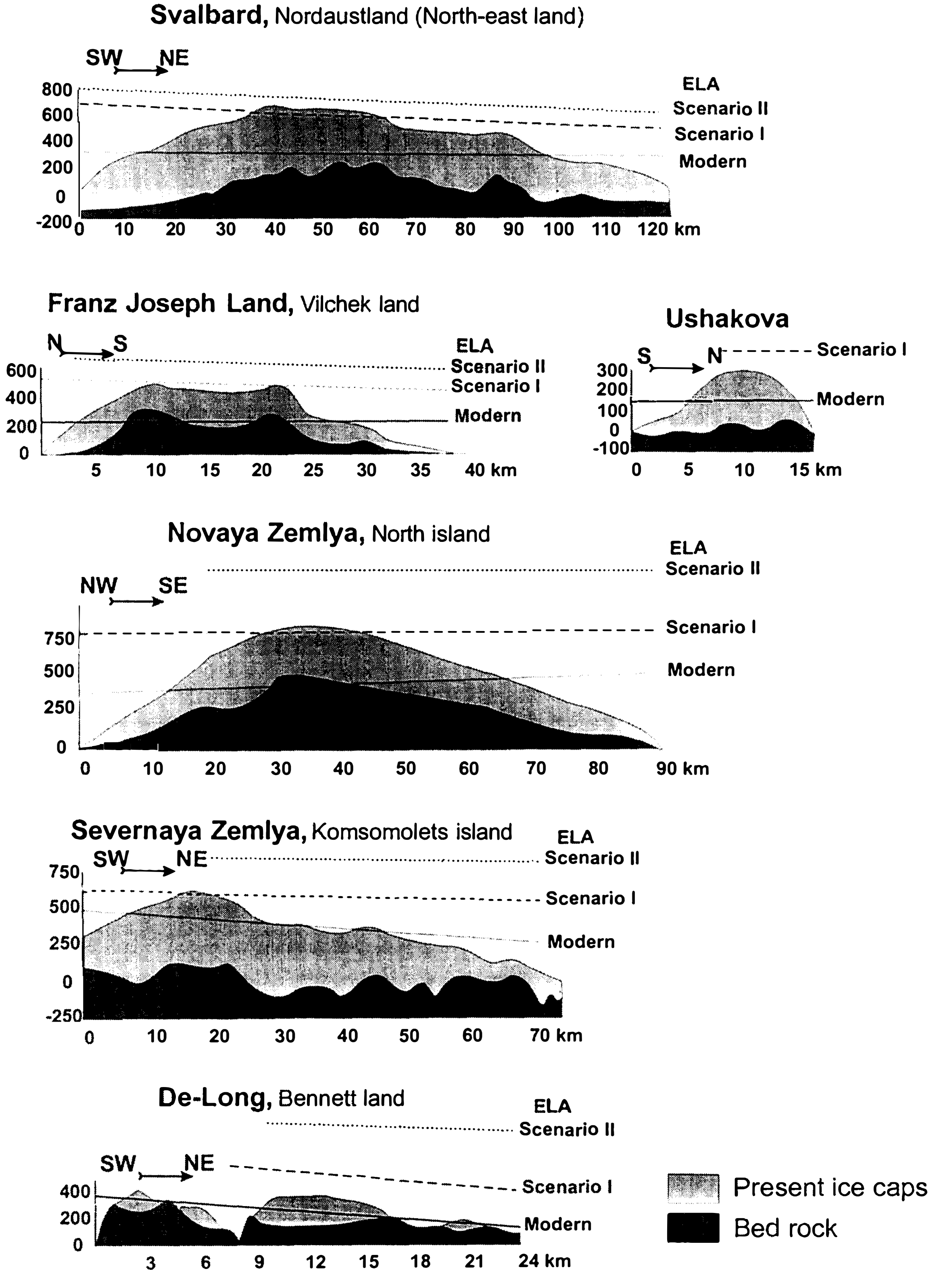

Fig. 2. The equilibrium line altitude change on glaciers of different Arctic islands according to the accepted paleoscenarios (the cross-sections are taken as presented in the World Atlas of Snow and Ice Resources, 1997)

temperature increase in the Holocene (scenario 1). Under global warming at 2°C, similar to the Eemian interstadial (scenario 2) it will be higher here at 8°C than at present. However, in the belt between 20–40°N, regional climate will not change, and some mountain regions will face cooling. In general, within the Eurasian Arctic, the areas of most warming according to both scenarios will be the Frans Josef Land, Novaya Zemlya and Severnaya Zemlya archipelagos. Here annual precipitation will increase (+100 mm by scenario 1 and +200 mm by scenario 2) as compared with the present quantity. Calculation by the above stated methods gave forecasts for the main characteristics of insular Arctic glaciations for scenarios 1 and 2 (Tables 1 and 2).

From deviations of the calculated ELA values (ΔH) and glacier areas (ΔS), given in the tables, we can judge possible glacier situations in the Eurasian Arctic islands. We may say with certainly that under global warming according to scenario 1 (and also–scenario 2) the ice caps of Frans Josef Land and Ushakova Island will disappear completely; the remaining islands' glaciations will undergo significant reduction. The ELA of Frans Josef Land and Ushakova Island will exceed the tops of the archipelagos relief, resulting in removal of their ice caps. On other islands' ice caps the ELA shift upward by scenario 1 will be from 150 to 350 m (Fig. 1b, broken line); by scenario 2, from 400 to more than 600 m (Fig. 1c, dashed line). The maximum shift of the ELA is characteristic for the Novaya Zemlya and North-East Land (in the North-East of Svalbard Archipelago) as these ice caps are located in areas of great ocean influence and maritime climate type. Figure 2 graphically represents the shift of the ELA under both scenarios for those ice caps which will undergo complete degradation even under scenario 1.

The glaciation of Novaya Zemlya will undergo great reduction (75%) and will be replaced by mountain-valley glacier complexes (the same result is obtained by the first method, mentioned above). West Spitsbergen and Nordaustlandet will lose about 80% of their glaciated areas. The Severnaya Zemlya glaciers will cover only 40% of the present areas. On this archipelago small ice caps may survive only on the islands October Revolution and Bolshevik, maximum elevations of which exceed the forecasted ELA (600 m).

If warming corresponds to scenario 2 (Table 2, Fig. 1, dashed line, see also Fig. 2), ice caps will disappear from all of the Eurasian Arctic, because the ELA will exceed the maximum bedrock elevations everywhere.

Results of solid precipitation and melting calculation in this region also corroborate this statement (the reduced solid precipitation will not be able to compensate for sharply increased melting).

The glaciation of Svalbard will be survive only as a mountain-valley type glacier on West Spitsbergen Island. Possibly a mountain-valley glaciation will survive on the most elevated area–the southern part of the Northern Island.

In general we can conclude that glaciers will persist on those islands of the Eurasian Arctic which are favorable for their existence—elevated relief forms and topography. The glaciers of flat islands (Frans Josef Land, Nordaustlandet, Ushakova Island) will undergo intensive reduction under the "coolest" scenario 1 and disappear completely under the warm scenario 2.

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