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The Northeast Asia mountain glaciers in the near future by AOGCM scenarios

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Abstract

We studied contrasting glacier systems in continental (Orulgan, Suntar-Khayata and Chersky ranges located in the Pole of Cold of Eurasia area at the contact of Atlantic and Pacific influences and maritime (Kamchatka Peninsula) – under Pacific influence. Our purpose is to present a simple projection method to asses the main parameters of these glacier regions under climate change. To achieve this, constructed vertical profiles of mass balance (accumulation and ablation) based both on meteorological data for 1950–90s and ECHAM4 for 2040–2069 are used, the latter – as a climatic scenario. Also for selected key glacier systems other models were applied for comparison. The observations and scenarios were used to define the recent and future equilibrium line altitude (ELA) and glacier termini elevation for each glacier system.

The altitudinal distributions of ice areas were determined for present and future, they were used for prediction of the elevation spreading of glaciers in the system taking into account the correlation between the ELA and glacier-termini level change. We tested two hypotheses of ice distribution versus altitude in mountain (valley) glaciers – linear and non-linear. The results 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. Finally, we compare characteristics of the stability of continental and maritime glacier systems under global warming.

1 Introduction

Our approach involves the projection of (1) equilibrium line altitude (ELA) because at this level it is possible to reconstruct accumulation by calculated ablation due to their equality here (e.g. Braithwaite and Raper, 2007), and (2) glacier termini level because this is correlated with ELA change (e.g. Chinn et al., 2005). The projected ELA can be obtained as a value of the accumulation and ablation balance profiles intersection for glacier systems (regions).

The projection of glacier change, not only for individual glaciers but also for groups of them (glacier systems), is a very important goal of global environmental change studies (e.g. Dowdeswell and Hagen, 2004). The term "glacier system" is considered as a set of glaciers united by their common links with the environment: the same mountain system or archipelago and similar atmospheric circulation patterns; the glaciers are related to each other usually by parallel links from atmospheric inputs and topographical forms to hydrological and topographical outputs, and demonstrate common spatial regularities of glacier regime and other features. For each glacier system the balance scheme constructed from climate data is univocal.

Here we present a simple method for projection of change in the parameters of glacier systems and the application of this method for the region of the Northeast Asia. From them we have chosen to study the *continental* glacier systems of Northeastern Siberia – Orulgan (a part of Verkhonyansky Range in Fig. 1), the Suntar-Khayata and Chersky ranges – and the *maritime* glacier systems of Kamchatka – Sredinniy and Kronotsky ranges, and the Kluchevskaya, Tolbechek, Chiveluch volcano groups (see Fig. 1 and Table 1).

Observations of both these glacier regimes are available only for one or two benchmark glaciers, so we used data from the USSR Glacier Inventory[1] (1965–1982), which was based on areal photography of the glaciers (Orulgan Range – in 1958, 1963; Suntar-Khayata Mountains – 1945, 1959, and 1970; Chersky Range – 1970s, Kamchatka – 1950). The NE Siberia has undergone both winter and, to a lesser extent, summer warming since around 1960 until present, as well as the intensification of cyclone activity and precipitation (Ananicheva et al., 2003; IPCC, 1995). Due to these climatic tendencies the proportion (and amount) of solid precipitation here has been increasing (Ananicheva and Krenke, 2005). Significant warming is also observed in Kamchatka (Shmakin and Popova, 2006).

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[1] We used the following parts of the USSR Glacier Inventory: vol. 17 (Lena-Indigirka basins region), issue 2, part 2 (Orulgan), 1972, 43 pp.; issue 3, part 1, issue 5, part 2, issue 7, parts 2 and 3, 1981, 88 pp.; vol. 19 (North-East), part 3, 1981; vol. 20 (Kamchatka), parts 2–4, 1969, 74 pp.

2 Glaciers studied

Glacier regions (systems) analysed in this 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 (Fig. 1).

2.1 The Suntar-Khayata Range

The Suntar-Khayata Range serves 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., 2006). The main source of snowfall for the glacier systems is moisture that has been brought from the Pacific and the Sea of Okhotsk Sea, in particular in spring, summer and early autumn. For the northern glacier massif of the range, Arctic air invasions are also significant in winter.

2.2 The Chersky Range mountain system

The Chersky Range mountain system (which contains a number of ridges) occupies the inner part of NE 66 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) 68 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., 2006).

2.3 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.

2.4 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 the glaciated regions considered, 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 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 facing the Pacific 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.

3 Methods and data

Our method for assessment of the morphology and regime of glacier systems is based on changes of the mean ELA (which are defined by the ratio of accumulation and ablation mass-balance profiles, constructed by observed meteorological parameters) and relation of the ELA and glacier termini elevation level under climate-change scenarios. The method is consistent with both GCM and palaeo-analogue scenarios. We chose the ECHAM4/OPYC3 – GGa11, scenario, which predicts one of the greatest warmings by 2100 in comparison with other GCMs: thus we evaluate the maximum likely reduction of the glaciers. The model is a spectral transform model with 19 atmospheric layers, and the results used here derive from experiments performed with spatial resolution T42, which corresponds to about 2.8° longitude/latitude resolution (Bacher et al., 1998). The choice is conditioned by the purpose to understand how much the glacier systems of the NE Asia, which are now under warming, would change if regional climate change either persists at the current rate or is somewhat enhanced.

We considered 17 glacier regions (systems) from the two different climate and relief regions of Russian Asia-NE Siberia (7), and the Kamchatka Peninsula (10), using climatic data from the second half of the 20th century (http://www.meteo.ru) and climatic scenarios. Mean vertical mass-balance (accumulation and ablation) profiles for these regions were constructed and became the basis for our projection of glacier evolution. The intersections of the vertical balance profiles give the values of the present-day and projected future ELA. The method of balance profile construction is described in Sects. 3.1 and 3.2. By using the USSR Glacier Inventory[1] data for each system we constructed hypsographic schemes showing the distribution of ice covered area versus altitude (Fig. 2: examples of hypsographic schemes for the NE Asia). The ELA was assumed, when unknown, to be the arithmetic mean of the highest and lowest point of a glacier in the system. This assumption, based on the Gefer/Kurowski method (e.g. Hess, 1904; Kalesnik, 1963), is used where glaciers are in balance with climate, which can reasonably be assumed to be the case for the USSR Glacier Inventory[1] data (1950s to 1970s).

This assumption for deriving unknown ELAs was verified using again the USSR Glacier Inventory[1] for the Suntar-Khayata and Chersky mountain systems by comparison with mean values by aerial phography for each glacier. The errors are as follows: Suntar-Khayata: Northern massif – 2.1%, Southern Massif – 1.3%, Chersky System: 5.2% (Buordakh Massif), 6.5% (Terentyakh), and 3.2% (Erikit). The deviation error between values calculated by the Gefer/Kurowski method and those obtained empirically is therefore small.

In support, Braithwaite and Raper (2007) found that the ELA and median glacier elevation are very strongly correlated across a wide range of glacier conditions. The area share of elevation intervals occupied with ice, is assumed at this stage of the work to linearly decrease with altitude while a glacier is retreating. These elements constitute the essence of our new approach for assessing glacier-system change due to climatic fluctuations.

3.1 Precipitation/temperature data

The moisture supply conditions of the studied glacier systems vary widely from plentiful (monsoon type) in the eastern parts of Kamchatka (glaciers of the Kronotsky range) to least on the south-east of Orulgan. The Chersky and Suntar-Khayata ranges occupy an intermediate position in terms of glacier accumulation-ablation rate. Comparison of data obtained between the late 1950s and 2001 about the glaciers of northeast Asia and their regimes, shows they have undergone appreciable changes – as revealed through retreat of their termini, surface lowering, formation of new morainic deposits, etc.

These changes may largely be attributed to external factors since the high inertia of the given glaciers (due to their generally low energy of glaciation, low temperatures, and typical 200–500-m ice thickness) do not encourage fast changes in their position and regime. As the temperature regime of the Suntar-Khayata region in the 20th century is suggested to be the dominant factor of the large changes in glacier size (Ananicheva et al., 2003), we analyzed long-term temperature and precipitation records for thirteen meteorological stations within 62–72° N and 121–152° E. The analysis of these series trends was carried out using the non-parametric Kendall-Mann-Sneyers test, with preliminary transformation of the series due to their extraordinary amplitude. We revealed two phases of temperature fluctuations since the 1940s, with cooling and subsequent warming taking place up to now. For these phases the annual, winter and summer trends were calculated and their spatial distributions obtained (see Fig. 3).

In the mountains during cooling periods, the greatest temperature decreases occurred in autumn and spring, exacerbating and prolonging winter cooling; however, warming phases were concentrated in summer, which enhanced ablation. The comparison of schematic distributions of seasonal temperature trends for the past ~50 years, and the signs of these values in particular, specifies different "sources of intensification" for the winter and summer trends. The former increases from northwest to southeast, under the influence of warming, coming from the central part of Asia; the latter increases from NE to SW, under the influence of warming of the southern part of the Sea of Okhotsk, and rapidly disappears towards the Arctic Ocean.

Trends of total precipitation until 1992 are slightly negative for the majority of stations, while solid precipitation only slightly increased since 1970s, so temperature change is likely to have been the dominant climatic forcing factor on most of our studied glacier systems during the last few decades. We may expect different reactions of the glacier systems to climate warming. According to our chosen climatic scenario the mean summer temperature would increase by between 3.1° and 4.0 °C throughout the study region by 2040–2069, greatly exceeding the temperature difference between 30-year periods before and after the start of warming around 1960 (Ananicheva et al., 2002). The daily total precipitation given by this GCM was recalculated to solid precipitation (for the accumulation on glaciers) in monthly amounts, using the Bogdanova method (Bogdanova, 1976; Bogdanova et al., 2002). This estimates the solid-precipitation fraction according to mean monthly temperature and elevation, taking account of the model baseline and increased (projected) temperatures. In Northeastern Siberia under the scenario of intense warming, solid precipitation would tend to increase everywhere except the southern massif of Suntar-Khayata. The situation on Kamchatka is the opposite: solid precipitation would decline except in the south-east, where it might increase slightly.

To calculate the vertical distribution of present mass-balance components we used all available climatic data, which mainly cover the second half of the twentieth century. This timeframe corresponds to the baseline (1959–1990) period used for reference in the ECHAM4 scenario of climate change for the next 80 years. Our baseline period approximately corresponds to the state of the glacierization reflected in the USSR Glacier Inventory[1] and also partly covers the time preceding its compilation.

To complement rare meteorological-station data for high elevations (above 1000 m), we used the accumulation at the mean ELA for the each glacier group (10–15 glaciers), which was calculated from the Glacier Inventory[1] data or obtained from their maps (Krenke, 1982; Ananicheva and Krenke, 2005).

These maps were widely used in the Atlas of Snow and Ice Resources, published in Moscow (Kotlyakov, 1997). At the ELA, accumulation (C) is equal to ablation (A), with the latter dependent on summer mean temperature (see Eq. 2 below).

Among glacier regime characteristics related to high altitudes, A is considered more reliable than C because it is relatively easy to calculate based on air temperature, since temperature lapse rates are easier to define and therefore better known than precipitation lapse rates (e.g. Hanna and Valdes, 2001). Accumulation is then set equal to the ablation at the mean ELA. For each glacier system mentioned above, vertical profiles of A and C were constructed using the methods described below.

3.2 Present accumulation/ablation calculation

Accumulation was calculated based on solid precipitation measurements from weather stations; ablation by the relationship between it and mean summer air temperature.

For Northeastern Siberia, precipitation and temperature data were available only up to a height of 1400 m except for the high altitude (2068 m a.s.l.) station "Suntar-Khayata", which operated for 9 years (1957–1966) at the terminus of Glacier 31 in the northern massif of Suntar-Khayata Range. Based on this station's observations and data from an intermediate station at Nizhnya Baza (1350 m), located on the western slope of Suntar-Khayata Range, temperature lapse rates of –0.68 °C/100 m below 1000 m, –0.50 °C/100 m between 1000–1500 m and –0.60 °C/100 m above 1500 m were used for summer.

Weather stations on Kamchatka are situated within the altitude range of 100–400 m a.s.l. In situ meteorological observations in the Avachinskaya Volcano group (1963–1974 and 1975–1979) were made to a height of 1500 m. The temperature gradient everywhere increases with altitude. However, inversions are not characteristic for this region, in contrast to northeast Siberia (Matsumoto et al., 1999). Based on these observations, we adopted lapse rates of –0.35 °C/100 m between 100 and 1000 m, –0.55 °C/100 m between 1000 and 2000 m, and –0.60 °C/100 m above 2000 m (Vinogradov, 1975; Vinogradov and Martiaynov, 1980).

We extrapolated precipitation in northeast Siberia according to "Suntar-Khayata" station and in Kamchatka by precipitation gradients identified by observation at 1500 m, incorporating corrections based on C values at the ELA – with C, defined basing on its equality to A at this level. The next step was to construct a corresponding vertical A-profile for present-day climate (the baseline period). In northeast Siberia where glaciers are cold-based, superimposed ice prevails; therefore a significant fraction of meltwater refreezes and then melts again at the surface. In this case it is possible to use a regional variant of the "global" formula relating A to summer temperature (T_{sum}), presented by Krenke and Khodakov (1966, in Krenke, 1982), which was proposed by Koreisha (1991) and confirmed in calculations for Glacier 31 for reconstruction of the

Suntar-Khayata glaciation during the Holocene optimum (Ananicheva and Davidovich, 2002):

$$A = (T_{\text{sum}} + 7)^3 \tag{1}$$

where A is ablation in mm, and T_{sum} is the mean summer air temperature over glacier surface at the ELA.

This formula is obtained from the data of many glaciers (the graph is included in the latter). In Kamchatka, in maritime conditions we used a slightly modified variant of the formula (Krenke, 1982):

$$A = 1.33(T_{\text{sum}} + 9.66)^{2.83} \tag{2}$$

In both cases T_{sum} over the glacier surface (T_g) was obtained according to:

$$T_g = 0.85T_{\text{ng}} - 1.2, \tag{3}$$

where T_{ng} is the temperature over the rocky surface nearby (Davidovich and Ananicheva, 1996).

The calculation of accumulation profiles is made by a transformation with the help of a coefficient of concentration (K_c). The solid precipitation contribution for each month, and then annually was defined, as explained above, by the Bogdanova method (Bogdanova, 1976; Bogdanova et al., 2002). It varies from zero in summer months, to 70–99% in winter, early spring and late autumn, to 10–20% in late spring and early autumn. Then, to take account of the morphological type of a glacier in the glacier system, we introduced the concentration coefficient for snow drift, avalanche snow transfer onto glaciers, and its drift from volcano slopes. According to recommendations given by Krenke (1982), in the situation where cirque type glaciers prevail (such as in the Orulgan, Valagiskiy, Tumrok and Gemchen ranges) K_c is assumed to be 1.6. For the Chersky, Suntar-Khayata, and Sredinny ranges, where medium-sized valley glaciers dominate, K_c is assumed to be 1.4. For volcanoes covered by ice caps on the cones in combination with large valley glaciers, we used a K_c of 1.4 until the cone end, and then K_c is reduced from 1.0 to 0.6–0.7 on the slopes from which snow drifting prevailed.

For some glacier systems of Kamchatka we also used the mass-balance component profiles, obtained by Davidovich (2006) via the same approach. Examples of mass balance (accumulation and ablation) curves for both northeast Siberia and Kamchatka are given in Fig. 4.

3.3 Method of projecting glacier change

This section of the work involved the construction of projected ablation and accumulation curves, A_p and C_p, for the climate of 2040–2069, based on A and C for the present time period. For ablation/accumulation we used the assumption that the temperature shift, presented in the scenario for each grid point within which the given glacier system is located, spreads over the entire (real-surface) altitudinal range encompassed by that pixel. If the glacier system is covered by a number of grid points, we used the mean value of the temperature shift.

3.4 Projected accumulation/ablation calculation

For all glacier systems considered, the mean summer temperature increase from current conditions is projected to lie within the range 3.1°–4.0 °C. These summer temperature increases were incorporated in the calculation of A described above. We used the temperature increase at the ice-rock boundary because – due to microclimatic influences and the melt process – glacier surfaces depress air temperature compared with non-glacier surfaces and so experience a reduced warming rate.

We involved modeled daily precipitation to calculate monthly values of solid precipitation for both the baseline and projected time period using the Bogdanova (1976, 2002) method and the modeled (increased) temperatures. The purpose was to obtain ratio coefficients of solid precipitation for the projected time interval compared with present for all glacier systems. Note that in northeast Siberia, under the significant warming of the given scenario, solid precipitation is predicted to increase everywhere (coefficients are from 1.09 to 1.46) except for the southern massif of Suntar-Khayata (0.99).

In Kamchatka the situation is the opposite: solid precipitation will decrease slightly (0.74–0.96) except for the southeast where it rises slightly (1.08). Thus the southern parts of the region under consideration will be so warm that the solid precipitation will decrease due to the longer time period with positive temperatures.

In using these coefficients in the calculation of accumulation for the projected period, we assumed that this ratio did not change with altitude. As a result we obtained vertical curves of C_p for all glacier systems in 2040–2069.

The intersections with the scenario-based curves A_p are taken to obtain the mean ELA for 2040–2069 for the glacier system – $\mathrm{ELA_p}$. Its shift is rarely higher than the highest point of the area of accumulation (H_{high}) in the system (a scenario, which would mean that the ice should disappear).

3.5 The projection of the glacier termini shift

In other cases it is assumed that after adaptation of the glacier to the new climate in accordance with the Gefer/Kurowski method of ELA identification (ELA is the arithmetic mean of the highest and the lowest glacier points; Kalesnik, 1963), the elevation difference between the top of the glacier H_{high} and $\mathrm{ELA_p}$ is equal to the elevation difference between $\mathrm{ELA_p}$ and glacier terminus (H_{ends}). Under the assumption that the same is valid for whole glacier system, we derive the following formula for the altitude of the lowest glacier height position:

$$H_{\mathrm{ends}} = \mathrm{ELA_p} - \left(H_{\mathrm{high}} - \mathrm{ELA_p}\right) = 2\mathrm{ELA_p} - H_{\mathrm{high}} \tag{4}$$

Using this simple equation, 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 glacierzed area equals zero, and the highest point remains unchanged. The correlation change of the ELA is thus related to the glacier-termini level by this relationship.

The ice distribution at intermediate elevation steps changes in proportion to altitude from zero (at H_{high}) to unity (at H_{ends}) relative to the baseline period. This is a linear hypothesis assumption.

Projected ice areas for the glacier systems were multiplied by A_{p} and C_{p} to derive the distribution of projected ablation/accumulation versus altitude for the climatic conditions of the scenario (2040–2069). See Fig. 4, where projected balance profiles are indicated by the broken line.

The comparison of the projected profiles of mass-balance components with the highest and lowest elevations of the glaciers derived from the USSR Inventory[1] data (1940–1970) also enables us to estimate the change of the ratio of glacier morphology types and related parameters – not just glacier balance and area – under climate-change scenarios.

4 Results and discussion of the "linear assumption"

Using the ECHAM4 scenario described above, we obtained the following projected assessments of the ELA change. The shift upward of the ELA altitude, ΔH_{ela}, is less in the northern parts of northeast Siberia than in the south (230 m as against 500 m in the south). In Kamchatka ΔH_{ela} as a rule is more significant and depends on precipitation rate. The largest ΔH_{ela} (up to 1210 m) was found in the south of Ichinskiy Volcano, located in the "rain shadow" of the Sredinniy Range (Table 1). The change in glacierized area is anticipated to range from a complete disappearance of some minor glacier systems, to the preservation of 70% of the present area (Kluchevskaya volcano group) and 50% of the contemporary ice area (Shiveluch and Tolbachek volcanoes). Under the warming scenario as calculated by our approach, glaciers will not be present in the southern systems of northeast Siberia – the southern regions of Orulgan glaciers and the Suntar-Khayata Mountains, small mountain ranges of Kamchatka around Ichinskiy Volcano. Those glaciers covering the volcanoes of southeast Kamchatka and receiving intensive moisture supply due to the elevation of the peaks and proximity of the Pacific Ocean would preserve more than 40% of their area.

As for the intensity of mass exchange at the ELA, we can expect the following changes in ablation and accumulation during the projected period compared with the baseline period. ΔA and C at the ELA is greater for NE Siberia on the north of the Orulgan, Chersky, and Suntar-Khayata ridges, where precipitation due to warming will increase from 200 to almost 500 mm. Orulgan derives moisture from the North Atlantic; the Chersky – from both Atlantic and Pacific, while Suntar-Khayata ridges also receive moisture from the Pacific Ocean. In glacier systems of Kamchatka only the Kronotsky Range and volcanoes of the southeast part of the peninsula are characterized by high A, C from 200 to 450 mm at the ELA; these are areas of plentiful precipitation, and despite the solid precipitation portion reducing during warming, it would still be a large absolute value. In the rest of the Kamchatka systems $\Delta A, C$ will range from 30 to 150 mm as a result of reduced snow accumulation because of strong warming. The glaciers of the Shiveluch Volcano attain negative A-, C-values at the ELA due to the rather abrupt decrease of the solid-precipitation fraction. Judging from the glacier-balance averages both for the baseline and projected periods, the glacier systems have different sensitivities to current climatic conditions and predicted future climate change. Under a constant climate, when glacier mass balance is close to zero, the glacier will not change; but assuming the same constant climate, if mass balance is positive, the glacier will expand, while if it is negative it will shrink. The balance trend, stability or change, and its sign are controlled by climatic conditions. A glacier can "keep up" with climate change – in this case its balance also remains near zero as well as consistent with climate. Among the glaciations considered, only that of the Chersky Range has been in this state during the baseline period. Glaciers of the Orulgan, the western slope of Sredinniy Range, the Kluchevskya Volcano group and Tolbachek in Kamchatka were growing at that time. The rest have retreated.

For the 2040–2069 period, the northern region of Orulgan glaciers and glaciers of the Kluchevskya and Tolbachek volcanoes are predicted to come into equilibrium with climate. Despite the intensive warming scenario, the Chersky glaciers will still be consistent with climate: this is due to a combination of elevation, relief forms and corresponding glacier morphology and regime, leading to their quite slow movement and change. Glaciers of the Sredinniy and Kronotsky ranges, Shiveluch and southeast Kamchatka volcanoes will undergo accelerated retreat and provide evidence of a time lag when compared with the warming rate.

Verification of the results was done by comparing the calculation of parameters (ELA, glacier termini and glacier areas) projected for the period of the 1957 International Geophysical Year (IGY) until the modeled period 2010–2039 with data of actual glacier changes obtained based on *Landsat* satellite imagery (Ananicheva at al., 2006). In particular, the difference of glacier area of Suntar-Khayata between that defined by recent *Landsat* images and the Glacier Inventory[1] data (which are approximately centered on the 1957 IGY) turned out to be 19.3%. This implies that during the ~50 years (1957–2003) this mountain region lost about 20% of its glaciated area.

The calculation by our method for the modeled period showed about 30% areal loss for this region. Since ECHAM4 is considered to simulate a rather intense warming scenario and because the modeled time period is later then the *Landsat* image data (2003), we can say our method – even with its linear hypothesis of ice distribution versus altitude in the glacier system demonstrates good results.

5 Non-linear hypothesis of ice-distribution versus altitude under climate warming

Besides the linear hypothesis of the decrease of glacierization vs. altitude for four key glacier systems, we also applied a non-linear distribution of ice under warming. For this we obtained an empirical curve of the ice zones by altitude as the difference between 30-year surveys for four glaciers (two Alpine and two Scandinavian, all are of valley type, prevailing for the key glacier regions), Fig. 5.

According to the empirical ice distribution via altitude, the areas covered with ice will 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. The mass balance correspondingly will be larger under a non-linear distribution, but mostly negative. Thus, under the ECHAM4 scenario the glacierization of the studied regions will not come into equilibrium with climate and will keep decreasing.

For 2040–69 under a non-linear distribution of ice under warming, the elevation distribution of glaciers will shrink by 40% in northeast Siberia and 3–4 fold in Kamchatka. The glacierized area will decrease twofold on the Chersky Range, five times in Suntar-Khayata, and as much as in 80 times on Kronotsky volcano, it will be at the threshold of vanishing (Table 2).

5.1 Results of the application of Hadley and Japan model scenarios

We also tested four key glacier systems under projections with two other GCMs – Had CM2GSDX (minimal warming) and the Japanese Model – CCSRGSA1 (JJGSA), maximal warming (see Table 3).

Under the minor warming of the HadCM2 climatic scenario (Cullen, 1993) the elevation distribution of glaciers will be almost the same as now. The glacier area, which covers Ichinsky Volcano will not change, the rest will lose 10–35%. The accumulation-ablation at the ELA will show minor change, decreasing by 10–20%. In the Suntar-Khayata and on Kronotsky Range, despite a high moisture supply, the mass balance will remain negative; that means the glacierization will not come into balance with climate and will persistently decline. In Buordakh (Chersky) and on Ichinskiy Volcano under climate stabilization, the glaciers will be safe. The Japanese model CCSRGSA1 (JJGSA) (Nakajima and Tanaka, 1986) presents the most intensive warming for the regions mentioned. The elevation distribution of the glaciers in all systems (except Ichisky Volcano) will decrease 4–5 fold. In Ichinsky the shrinkage is only 25%; the volcano cone will remain under ice cover (due to its large area) and only small glaciers will disappear. Correspondingly, the area of glaciers of the Ichinsky Volcano will shrink till 22.1 km^2.The slope and cirque glaciers will remain unchanged.

In Chersky and Suntar-Khayata under this scenario the accumulation-ablation will increase because of snow accumulation. It will stay high on Kronotsky Range. The glaciers of all key regions will have negative mass balance and therefore disappear soon after 2070, in response to the high warming rate.

6 Conclusions

A new approach involving calculating the average ELA and glacier-termini level for present and projected future climate states has been used to assess glacier-system change due to predicted climate change. 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 predict that the upward shift of ELA, H_{ela}, is less in the northern parts of northeast Siberia (230 m as against 500 m in the south), while in Kamchatka H_{ela} as a rule is greater and depends on precipitation rate. Our calculations also predict the disappearance of some glacier systems, while others will preserve 70% of their present area.

Our simple climate-based approach allows the evaluation of the behavior of mountain glacier systems under specified climatic scenarios for any glacierized mountains worldwide and can serve as a tool for glacier morphology and regime forecasts for the medium-term future. The originality of our approach consists in the definition of glacier-climate characteristics for a glacier system, and we have applied this here for the first time to a projection of glacier-system change. By so doing, we have derived important information about the climate sensitivity of glaciers in northeast Siberia and Kamchatka Peninsula.

The future development of the glacier systems are defined by scenario choice and assumptions. The glacierization of northeast Siberia and Kamchatka will be considerably reduced under the ECHAM4 scenario: under a linear ice distribution versus altitude more than under non-linear. The HadCm2 scenario will lead to minor changes and the Japanese scenario leads to the disappearance of the major part of the glaciers.

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References

Ananicheva, M. D., Davidovich, N. V., and Mercier, J.-L.: Climate change in North-East of Siberia in the last hundred years and recession of Suntar-Khayata glaciers, Data of glaciologic studies, Moscow, 94, 216–225, 2003 (in Russian with English summary and figure captions).

Ananicheva, M. D. and Davidovich, N. V.: Reconstruction of the Suntar-Khayata glaciation's in the periods of Quaternary climatic optima, Data of Glaciological Studies, 93, 73–79, 2002 (in Russian with English summary and figure captions).

Ananicheva, M. D. and Krenke, A. N.: Evolution of Climatic Snow Line and Equilibrium Line Altitudes- North-Eastern Siberia Mountains in the 20th Century – Ice and Climate News, WCRP Climate and Cryosphere Newsletter, N 6, 1–6, July 2005.

Ananicheva, M. D., Kapustin, G. A., and Koreysha, M. M.: Glacier changes in Suntar-Khayatamountains and Chersky Range from the Glacier Inventory of the USSR and satellite images 2001–2003, Data of Glaciological Studies, Moscow, 101, 163–169, 2006 (in Russian with English summary and figure captions).

Bacher, A., Oberhuber, J. M., and Roeckner, E.: ENSO dynamics and seasonal cycle in the tropical Pacific as simulated by the ECHAM4/OPYC3 coupled general circulation model, Clim. Dynam., 14, 431–450, 1998.

Bogdanova, A. G.: Method of for calculation of solid and mixed precipitation proportion in their monthly standard, Data of Glaciological Studies, 26, 202–207, 1976 (in Russian with English summary and figure captions).

Bogdanova, E. G., Ilyin, B. M., and Dragomilova, I. V.: Application of a comprehensive bias correction model to precipitation measured at Russian North Pole drifting stations, J. Hydrometeorol., 3, 700–713, 2002.

Braithwaite, R. J. and Raper, S. C. B.: Glaciological conditions in seven contrasting regions estimated with the degree-day model, Ann. Glaciol., 46, 297–302, 2007.

Chinn, T. J., Heydenrych, C., and Salinger, M. J.: Use of the ELA as a practical method of monitoring glacier response to climate in New Zealand's Southern Alps, J. Glaciol., 172, 85–95, 2005.

Cullen, M. J. P.: The Unified Forecast/Climate Model, Meteorol. Mag., 122, 81–94, 1993.

Davidovich, N. V.: Kamchatka glaciation during the Holocene Optimum (2006), Data of Glaciologic Studies, 101, 221–229, 2006 (in Russian with English summary and figure captions).

Davidovich, N. V. and Ananicheva, M. D.: Prediction of possible changes in glacio-hydrological characteristics under global warming: south-eastern Alaska, USA, J. Glaciol., 42, 407–412, 1996.

Dowdeswell, J. A. and Hagen, J. O.: Arctic ice caps and glaciers, in: Mass Balance of the Cryosphere: Observations and Modelling of Contemporary and Future Changes, edited by: Bamber, J. L. and Payne, A. J., Cambridge University Press, 527–557, 2004.

Hanna, E. and Valdes, P.: Validation of ECMWF (re)analysis surface climate data, 1979–98 for Greenland and implications for mass balance modeling of the Ice Sheet, Int. J. Climatol., 21, 171–195, 2001.

Hess, H.: Die Gletscher, Braunshweig: F. Vieweg u. Sohn, 426 pp., 1904.

IPCC: Second Assessment Report, 1995, in: The science of Climate Change, edited by: Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., Cambridge University Press, UK, 572 pp., 1996.

Kalesnik, S. V.: Ocherki glyasiologii (Glaciological essays), Moscow, Ychpedgiz, 182 pp., 1963, (in Russian).

Koreisha, M. M.: Glaciation of Verkhoyansk-Kolyima Region, The USSR Academy of Sciences, Moscow, 143 pp., 1991 (in Russian).

Kotlyakov, V. M. (Ed. in Chief): World Atlas of Snow and Ice Resources, Institute of Geography, RAS, Moscow, 600 pp., 1997.

Krenke, A. N.: Mass exchange in glacier systems on the USSR territory, Leningrad, Hydrometeoizdat, 288 pp., 1982 (in Russian, extended English summary).

Matsumoto, K. Y., Shiraiwa, T., Yamaguchi, S., Sone, T., Nishimira, K., Muravyev, Y. D., Khomentovsky, P. A., and Yamagata, K.: Meteorological observations by automatic weather stations (AWS) in alpine regions of Kamchatka, Russia, 1996–1997, Cryospheric studies in Kamchatka II, Hokkaido University: Sapporo, 155–170, 1999.

Muraviev, Y. D.: Present-day glaciation in Kamchatka – distribution of glaciers and snow, in: Cryospheric studies in Kamchatka II, Institute of Low Temperature Science, Hokkaido University, 1–7, 1999.

Nakajima, T. and Tanaka, M.: Matrix formulation for the transfer of solar radiation in a plane parallel scattering atmosphere, J. Quant. Spectrosc. Ra., 35, 13–21, 1986.

Shmakin, A. B. and Popova, V. V.: Dynamics of climate extremes in northern Eurasia in the late 20th century, Izvestiya AN, Fizika Atmosfery i Okeana, 42, 157–166, 2006 (in Russian, English summary and figure captions).

Vinogradov, V. N.: Present glaciarization of the areas of active volcanism, Moscow, “Nauka”, 103, 25 pp., 1975 (in Russian, extended English summary).

Vinogradov, V. N. and Martiyanov, V. L.: Heat balance of Kozelskiy Glacier (Avachnskaya Volcano group), Data of Glaciological Studies, Moscow, 37, 182–187, 1980.

Table 1. Change of glacier systems characteristics in NE Siberia and Kamchatka up to the mid 21st century (ECHAM4, 2040–2069).

Glacier system	The shift of ΔH_{ela} (from base to projected period), m	The elevation range of the glacier system, m		Glaciated area, km^2, % of the left		Ablation and accumulation at the ELA, mm		Balance, cm yr^{-1}	
		Base period	Projected period	Base	Projected period, km^2 (%)	Base period	Projected period	Base period	Projected period
NE 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	–
CherskiyErikit 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
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
Ichinskiy Volcano (with account of blowout fromthe 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 model scenario used.

Table 2. Change of the main glacier system characteristics for a non-linear distribution of ice versus altitude under climate warming: ECHAM4scenario, 2040–2069.

The location of the glacier system	Base	The elevation distribution of the system, m		Base	The area of glacierization, km^2		Base	Ablation-accumulation at the ELA, mm		Base	Balance, cm/year	
		ECHAM4			ECHAM4			ECHAM4			ECHAM4	
		Linear	Nonlinear		Linear	Nonlinear		Linear	Nonlinear		Linear	Nonlinear
Chersky-Buordakh	1640	1288	1000	63	18	28.4	700	1050	1050	–2	–22.8	–0.05
Suntar-Khayata, North	1110	520	700	111	9	21.6	460	850	850	–40	–70	–59.1
Kronotsky Range	1150	260	300	91	26	1.04	3350	3800	3800	–48	–116	–4.8
Ichinsky Volcano	2080	780	600	29.3	6	6.68	1510	1550	1550	+17	+3	124.1

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 3. The change of the main characteristics for key glacier systems by three GCMs to 2040–2069. Nonlinear distribution.

The location of the glacier system	Base	The elevation distribution of the system, m			Base	The area of glacierization, km^2			Base	Ablation-accumulation at the ELA, mm			Base	Balance, cm/year		
		ECHAM4	Hadley	Japan		ECHAM4	Hadley	Japan		ECHAM4	Hadley	Japan		ECHAM4	Hadley	Japan
Chersky-Buordakh	1640	1000	1600	400	63	28.4	53.4	4.02	700	1050	660	1100	–2	–22.8	4.3	34.8
Suntar-Khayata, North	1110	700	1100	300	111	26.0	63.4	2.4	460	850	600	1200	–40	–59.1	–49.7	–150
Kronotsky Range	1150	300	1000	300	91	1.04	80.4	0.57	3350	3350	3600	3300	–48	–4.8	–10	–21.1
Ichinsky Volcano	2080	600	2080	1400	29.3	6.68	29.3	21.12	1510	1550	1470	1500	17	124.1	26.8	–30.9

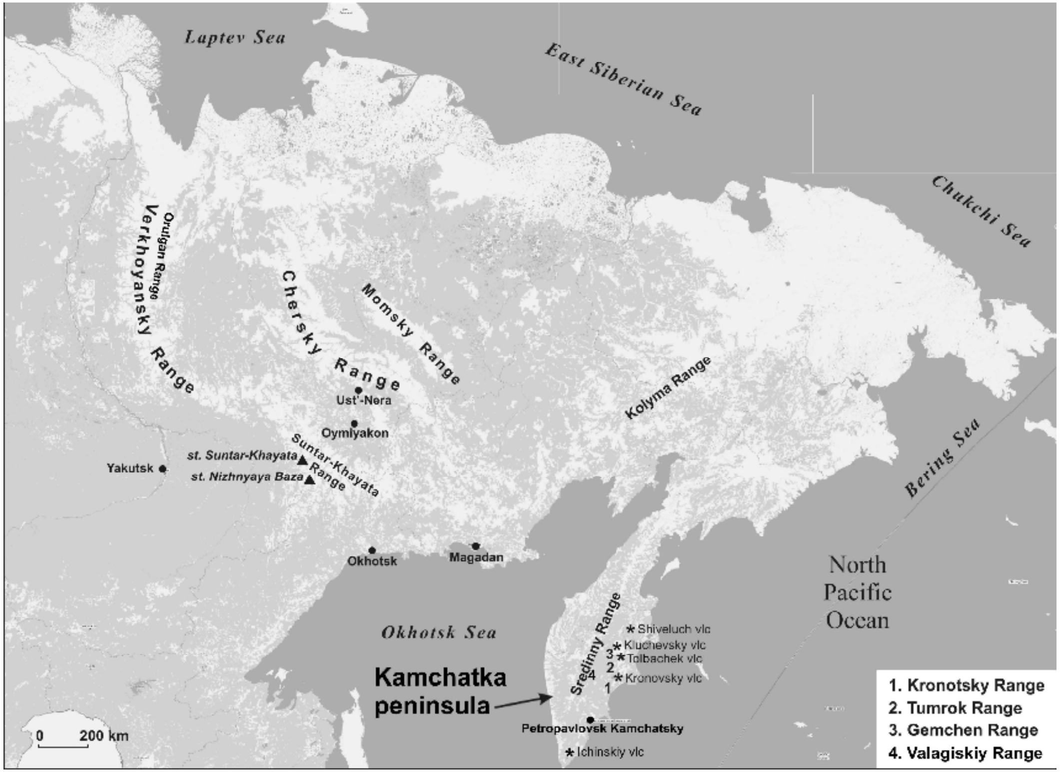

Fig. 1. Map of the study region.

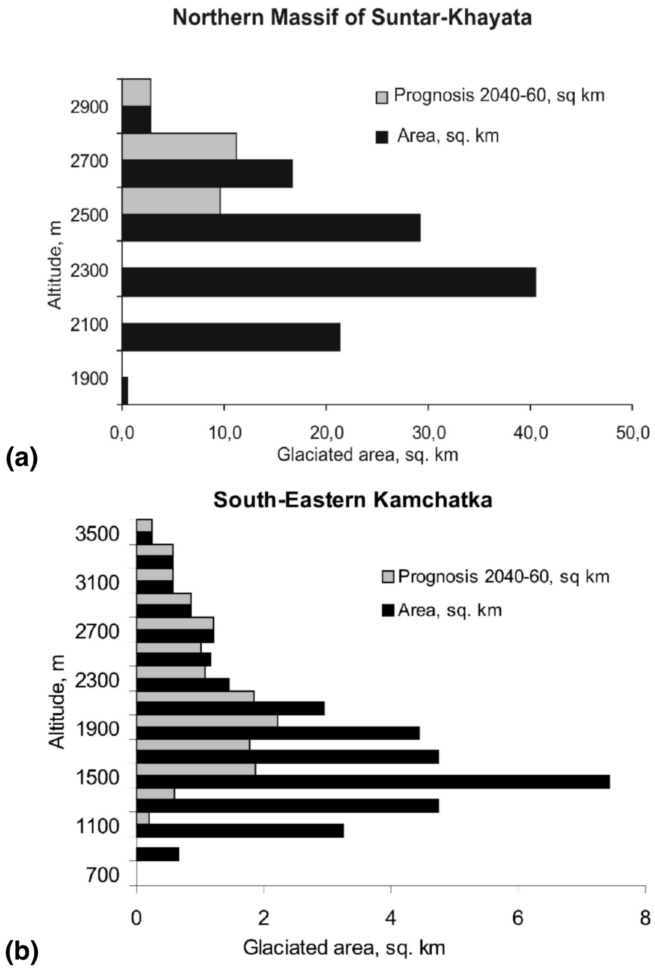

Fig. 2. Examples of hypsographic curves (distribution of ice area versus altitude for the north-east Siberia glaciers systems **(a)**, and Kamchatka **(b)**.

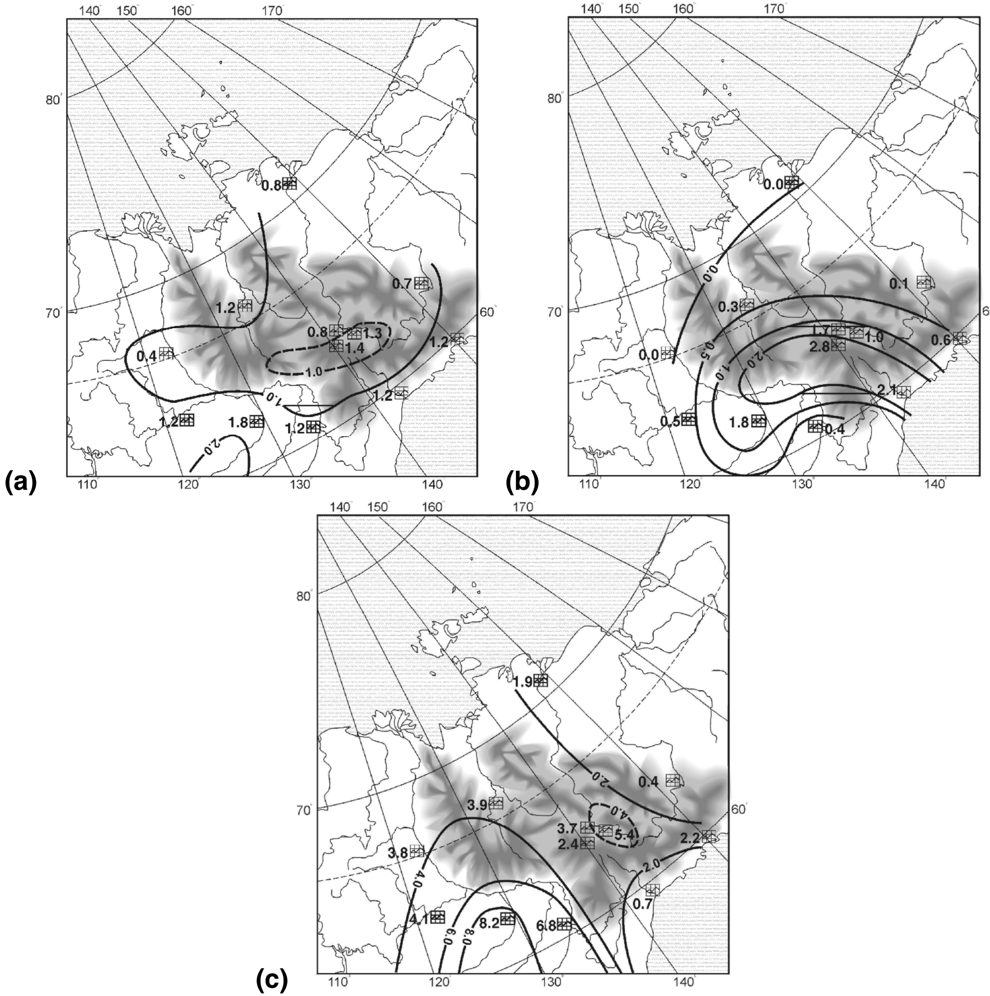

Fig. 3. Spatial distribution of positive temperature trends. **(a)** Annual values for the warming up to 1995, T°C/50 years, **(b)** summer trends for the same period, T°C/50 years, and **(c)** winter trends for the same period, T°C/50 years.

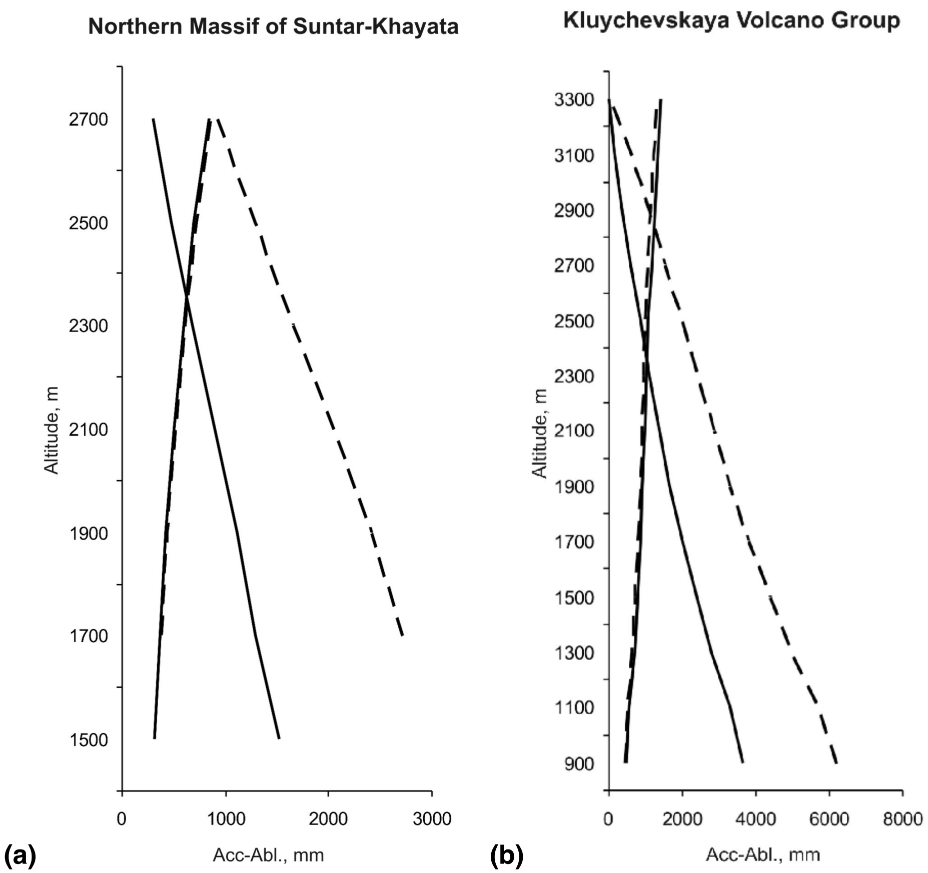

Fig. 4. Mass balance (accumulation and ablation, directed in oppositional way) vertical profiles for one glacier system of northeast Siberia – northern massif of Suntar-Khayata **(a)** and Kamchatka – Kluychevskaya Volcano **(b)**. Solid lines – baseline period, broken line – projection by ECHAM4.

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