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CHANGES IN EQUILIBRIUM LINE ALTITUDE OF GLACIER SYSTEMS IN NORTHEASTERN SIBERIA FOR THE LATE 20th–EARLY 21st CENTURIES

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Changes in the equilibrium line altitude (ELA) of glacier systems have been studied in the Suntar-Khayata, Chersky and Orulgan mountains, as well as over the whole territory of Northeastern Siberia, for three periods of time: 1930–1960, 1961–1990 and 1991–2012. Northeastern Siberia has undergone warming in the 21st century which became more rapid than in the previous fifty years. Records at most weather stations show increasing trends in mean annual and summer air temperatures and in total atmospheric precipitation but a decreasing trend in solid precipitation. The climate change leads to a rise of glacier ELA almost all over Northeastern Siberia and to an increase in ablation which is in balance with accumulation at this altitude. The ELA rise was from 100 to 450 mm, 200 ± 50 m on average, while the ablation (accumulation) increase was 50 to 250 mm in different periods. The glacier parameters inferred from climatic data are background values, which provide a general idea of current and potential changes in glacier systems in this poorly studied region.

Glacier, glacier system, equilibrium line altitude, climate, trend, cryosphere, Northeastern Siberia

INTRODUCTION

This study continues our previous research [*Ananicheva and Krenke, 2005*] on spatial variations of glacier system parameters. The publication of 2005 concerned simultaneous mapping of the climatic snow line (CSL) and the glacier equilibrium line altitude (ELA). Their variations were estimated proceeding from records of mean summer air temperatures (that control ablation) and solid precipitation (which, in turn, controls accumulation) at weather stations in Northeastern Siberia from 1930 to 2012. The study region, which includes ice-clad ranges of Verkhoyansk, Suntar-Khayata, and Chersky, and their surroundings (Fig. 1), remains poorly investigated in terms of glaciology. See Table 1 for a summary of data from twenty weather stations operated till present.

The Suntar-Khayata, Chersky, and Orulgan valley glaciers have been investigated since the International Geophysical Year [*Koreisha, 1963, 1991; Takahashi et al., 2011; Ananicheva and Karpachevsky, 2015*]. The new study focuses on recent variations in two key parameters of glaciers: the equilibrium line altitude (ELA) and ablation which is in balance with accumulation at this altitude. The ELA and ablation changes are estimated for the existing Suntar-Khayata, Chersky and Orulgan glacier systems, as well as for the whole territory of Northeastern Siberia. A glacier system consists of several related glaciers which share common links with the environment: have the same geological substrate, are exposed to the same atmospheric circulation, and cause joint impact on the local climate, surface runoff, and topography [*Krenke, 1982*].

Previously we [*Ananicheva and Krenke, 2005*] estimated CSL–ELA variations for two periods of 1930–1960 and 1961–1991. Since the beginning of the 1960s, the climate of Northeastern Siberia has shifted to warming. As follows from correlated CSL and ELA patterns of highland glacier systems, summer warming in the region remained moderate till 1992 (summer air temperatures grew for no more than 2 °C, or 0.5 °C on average) and was restricted to the central parts of ranges and the adjacent basins. Increase in winter temperatures and cyclonic activity led to increase in solid precipitation. This partly compensated the rise of the climatic snow line (chionosphere base [*Kalesnik, 1963*]), which is the surface of equal snow line altitudes where the potential snow accumulation is in balance with snow melting (snow equilibrium); the respective line for glaciers is the long-term mean altitude of ice equilibrium.

The warming trend has continued for time that elapsed after 1991. The trends of mean summer (T_{sum}) and annual (T_{year}) air temperatures and solid (P_{sol}) and liquid (P_{liq}) precipitation totals for fifty years (to 2012) were obtained from the available records of weather stations in the region. As shown by recently published maps (Fig. 1, *a*, *b* in [*Mavludov and Anani-*

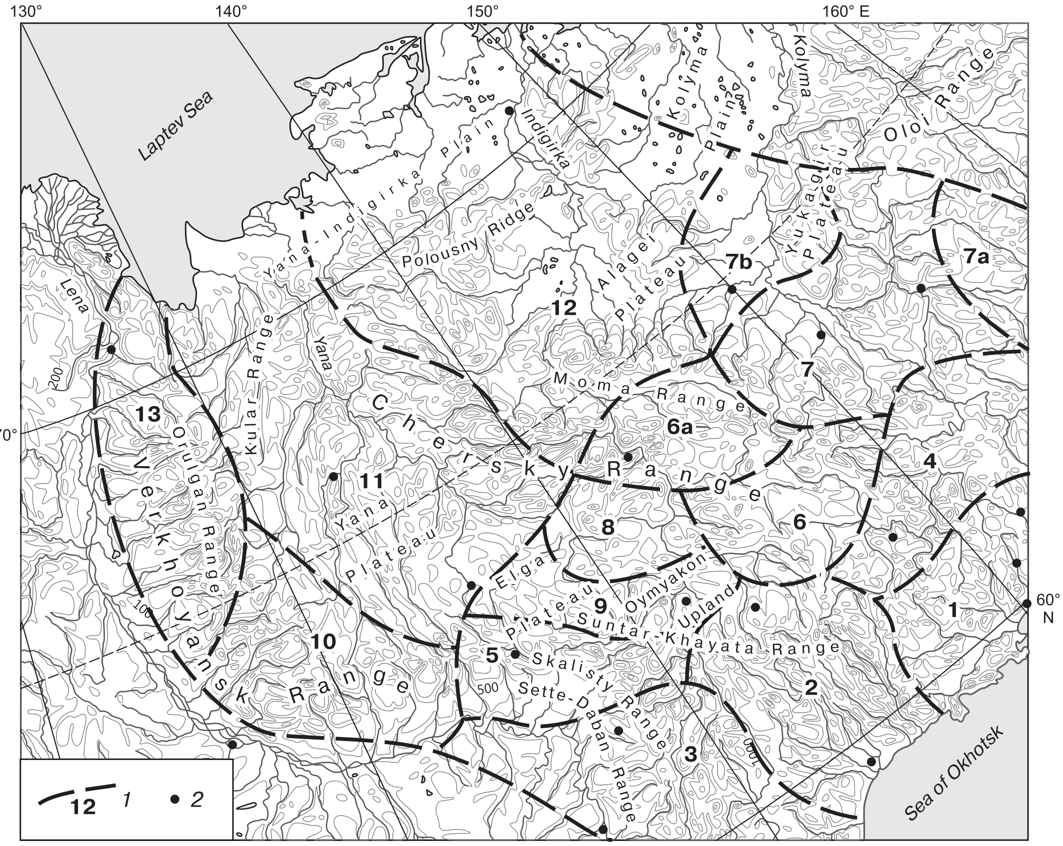


Fig. 1. Location map of areas where altitude profiles of summer air temperature (T_{sum}) and solid precipitation (P_{sol}) were obtained.

1 – boundaries and numbers of regions (Table 2), *2* – weather stations.

Table 1. **Weather stations used in this study (www.meteo.ru)**

Number	Name	WMO index number	Altitude, m	Latitude, degr	Longitude, degr
1	Agayakan	24684	777	63.20	141.44
2	Verkhoyansk	24266	137	67.34	133.24
3	Zapadnaya	24678	851	63.08	138.17
4	Zyryanka	25400	283	65.44	150.54
5	Iema	24477	660	65.18	135.48
6	Magadan	25911	50	59.50	150.70
7	Oymyakon	24688	740	63.15	143.09
8	Okhotsk	31088	6	59.22	143.12
9	Seimchan	25703	206	62.55	152.25
10	Srednekan	25705	260	62.27	152.19
11	Tompo	24671	400	64.17	135.52
12	Ust`-Moma	24382	195	66.27	143.14
13	Chokurdakh	21946	45	70.60	147.90
14	Susuman	24790	649	62.80	148.20
15	Viluisk	24641	107	63.80	121.60
16	Okhotsky Perevoz	24871	141	61.90	135.50
17	Kyusyur	21921	30	70.70	127.40
18	Tongulakh	24843	205	61.90	124.60
19	Korkodon	25503	102	64.45	154.40
20	Omolon	25428	264	65.20	160.50

cheva, 2016]), a large area of the Suntar-Khayta–Chersky mountains has been exposed to warming for years, though at quite low rates of 1 to 2 °C/50 yr for summer (T_{sum}) and 1 to 3 °C/50 yr for annual (T_{year}) values.

Warming for quite a long period after the publication of [*Ananicheva and Krenke, 2005*] has obviously affected the glacier systems of the region. This study focuses on most recent changes in their equilibrium line altitude (ELA), as well as in ablation (accumulation) at ELA for the 21st century.

Mapping of ELA as an indicator of highland climate and hydrological conditions was broadly used for imaging the regime of glaciers in the World Altas of Snow and Ice Resources (http://www.webgeo.ru/index.php?r=50&page=1&id=5723) and in the work by *Krenke* [*1982*]. According to *Krenke* [*1982*], the ELA of glaciers rises systematically southward from 200 m asl in the high Arctic (150 m in the southeastern Franz Josef Land) to 5000 m in the extreme south of the Former Soviet Union (5400 m in the southern windward slopes of the Zaalay Range, the Pamirs).

Ananicheva and Krenke [*2005*] calculated the CSL and ELA values for the past and present climatic conditions, using the approach of Gefer-Kurowski [*Krenke, 1982*] estimating the altitude of individual glaciers as the average (arithmetic mean) of their minimum and maximum elevations. The Gefer-Kurowski method, applicable to small and medium glaciers [*Braithwaite, 2015*], is extended in this study to a glacier system and used for mapping ELA over glacier areas in northeastern Russia.

Variations in air temperature and atmospheric moisture were estimated using the respective daily time series (data of All-Russian Research Institute of Hydrometeorological Information – World Data Centre, RIHMI–WDC, Obninsk), as well as monthly means measured at the Agayakan (777 m above sea level) and Suntar-Khayata (2068 m asl) weather stations which are the most proximal to the Suntar-Khayata glaciers (reports of the Yakutsk Weather Survey, Table 1). The weather station data were used to plot altitude profiles of air temperatures and precipitation sums. As a result, sixteen areas with unique altitude dependences of T_{sum} and P_{sol} were distinguished within the study region (Fig. 1).

The mean air temperature of summer (June through August) as a main control on the amounts of molten ice and solid precipitation was used to estimate accumulation at ELA. The amount of solid precipitation was calculated using empirical relationships between its percentage and air temperature [*Bogdanova, 1977*] obtained from measured data for different regions worldwide.

The distinguished sixteen areas (1 through 13, and 6a, 7a, and 7b) encompass large ranges and basins of the Verkhoyansk-Kolyma mountain province. Weather stations in these areas are located at 100 to 1500 m asl, except for one station at Glacier 31 in the Northern Suntar-Khayata mountains, which is as high as 2068 m asl (Table 2). Altitude profiles of ablation (accumulation) were calculated for each area from air temperature and precipitation data (see below for the calculation technique).

Table 2. **ELA rise in existing and potential glacier systems, Northeastern Siberia**

Number	Area	ELA, m			ELA rise, m		
		1930–1960	1961–1990	1991–2012	1930–1960/ 1961–1990	1961–1990/ 1991–2012	1930–1960/ 1991–2012
1	Yama River catchment	2450	2500	2500	50	0	50
2	Suntar-Khayata Range, Southern part, Yudoma River catchment	2450	2500	2550	50	50	100
3	Ulakhan-Bom and Sette-Daban Ranges	2750	2850	2900	100	50	150
4	Chersky Range, western Southern part	2250	2300	2400	50	100	150
5	Suntar-Khayata Range, Northern part	2350	2400	2550	50	150	200
6	Moma Range	2150	2100	2250	–50	150	100
6a	Chersky Range, eastern Southern part	2250	2300	2500	50	200	250
7	Omsukchan Range	1650	1750	2000	100	250	350
7a	Kedeon and Omolon river catchments	1700	1800	2150	100	350	450
7b	Yukagir Plateau	1800	1900	2250	100	350	450
8	Chersky Range, western Central part	2350	2300	2400	–50	100	50
9	Oymyakon and Elga Plateaus	2400	2450	2500	50	50	100
10	Verkhoyansk Range	2000	2100	2200	100	100	200
11	Verkhoyansk Plateau	2550	2600	2650	50	50	100
12	Momo-Selenyakh plain	1750	1850	1930	100	80	180
13	Orulgan Range	1700	1750	2100	50	350	400
	Average	2172	2219	2364	47	145	192

REGIONAL CLIMATE AND ITS VARIATIONS

The climate of Northeastern Siberia, as described in detail in [*Ananicheva and Krenke, 2005*], is remarkable by contrasts between very cold and dry intermontane basins and wetter ranges with more temperate conditions.

The 1930–1960 period included two cold spells: in the beginning of the 1930s within the territory from 59 to 63° N and in the earliest 1950s over the area between 63 and 73° N. The latter event lasted longer in the central and southwestern parts of Northeastern Siberia, but the Okhotsk Sea area has undergone warming already since the early 1950s. Warming, expressed mostly as higher winter air temperatures, spread almost all over the Verkhoyansk-Kolyma province (especially in the continental part or on most of Northeastern Siberia) in the early 1960s and lasted till the earliest 1990s.

The mean summer air temperature (T_{sum}) difference between the 1930–1960 and 1961–1992 periods reached 3.9–2.2 °C in the highest elevated mountains (central Chersky, Ulakhan-Chistai, and northern Suntar-Khayata Ranges) but was within 2 °C in the southern parts of these ranges, as well as in the southern Moma Range and the Kolyma Plateau [*Ananicheva and Krenke, 2005*].

According to records of weather stations in low mountains, annual solid precipitation in Northeastern Siberia mainly fell in mid-season (May, September, and October) and varied from 25 to 50 % of the total precipitation, depending on the climate severity. In mm, it was from 250 mm in the southern Moma Range and in the windward slope of the Verkhoyansk Range to 60–70 mm in intermontane basins. The amount of moisture was the greatest in the Suntar-Khayata mountains: 200–300 mm or up to 50–60 % of total precipitation [*Vasiliev and Torgovkin, 2002*].

The climate trends from the earliest 1990s through 2012 appear in the air temperature (T_{sum}, T_{year}) and moisture (P_{sol}, P_{year}) patterns. Data from all weather stations for 1991–2012 show warmer T_{sum} and T_{year} than for the previous period 1960–1990, with a mean annual temperature increase of 0.7 to 1.8 °C, higher in the northwestern part of the region. The mean summer air temperatures became 0.4 to 1.5 °C warmer, the difference being greater at the Eurasian pole of cold and in the northwest of the region, where the glacier systems are present. The total annual precipitation became 5–60 % higher, according to most records, while the solid precipitation reduced for 4–65 %, approximately in the areas where the T_{sum} and T_{year} increase was the greatest.

It is interesting to note that the atmospheric water cycle of the Arctic, including Northeastern Siberia, evaluated via seven global reanalyses covering the 1979–2013 period [*Dufour et al., 2016*] shows a decrease of moisture transport to the region in all models.

Thus, the climate trends of the recent decades are unfavorable for preservation, and more so, for advance of glaciers.

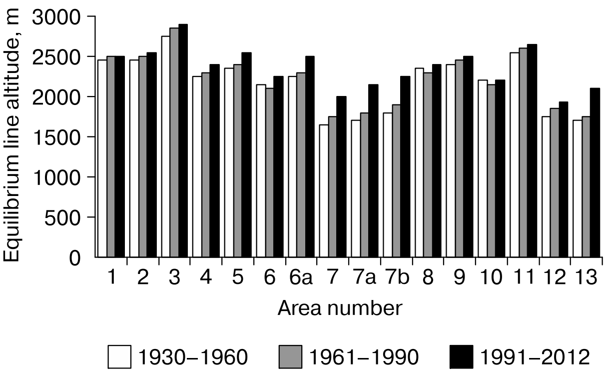


Fig. 2. Equilibrium line altitudes calculated for three periods of time.

METHODS FOR MAPPING ELA AND CALCULATING THE RESPECTIVE ACCUMULATION AND ABLATION

The altitude mass-balance profiles of accumulation and ablation were calculated for the sixteen areas from climate data that cover the large basins and ranges of the Verkhoyansk-Kolyma province. The intersection of these profiles corresponds to the equilibrium line altitude of glaciers, which either exist at present or are absent but would exist potentially if the altitude reached the value required for glacier formation. Data for each area were obtained from several weather stations located at elevations 100 to ~900 m asl, except one station at Glacier 31 (2068 m asl). The altitude variations of T_{sum} above 1000 m asl were assumed to be congruent to the profiles for this station, with regard to local temperature gradients for each area.

Ablation (A, g/cm^2) was calculated as [*Koreisha, 1991*]:

$$A = 0.1(T_{sum} + 7)^3.$$

It was estimated bearing in mind that glaciers in the region form by superimposed ice and taking into account the temperature difference at the transition to the glacier surface, found as [*Davidovich, 1983*]:

$$T_{gl} = 0.85T_{nongl} - 1.2,$$

where T_{gl} and T_{nongl} are the temperatures on the glacier and non-glacier (rocky) surfaces, respectively.

Accumulation (C, g/cm^2) was estimated using the coefficient of snow concentration (K_{sn}) on glaciers, which allows for snow redistribution from slopes and for snow drift and avalanche transport.

Table 3. **Ablation (accumulation) at ELA for glacier systems as a whole, mm/yr**

Number	Glacier system	1930–1960	1961–1990	1991–2012
1	Yama River catchment	500	500	750
2	**Suntar-Khayata Range, Southern part, Yudoma River catchment**	550	670	600
3	Ulakhan-Bom and Sette-Daban Ranges	350	500	700
4	**Chersky Range, western Southern part**	450	480	500
5	**Suntar-Khayata Range, Northern part**	450	580	650
6	Moma Range	550	600	650
6a	**Chersky Range, eastern Southern part**	440	500	540
7	Omsukchan Range	750	750	650
7a	Kedeon and Omolon river catchments	600	550	600
7b	Yukagir Plateau	700	600	600
8	**Chersky Range, western Central part**	350	350	400
9	Oymyakon and Elga Plateaus	370	440	400
10	Verkhoyansk Range	410	470	510
11	Verkhoyansk Plateau	600	600	550
12	Momo-Selenyakh plain	380	400	420
13	**Orulgan Range**	580	560	600

Note: existing glacier systems are in bold.

The K_{sn} value depends on the predominant glacier type in a group [*Krenke, 1982*] and is added to the amount of solid precipitation.

The resulting A and C altitude profiles perfectly fit the true variations only near ELA, because the equation which relates mean summer temperature and ablation was derived for this very altitude. Details of the method can be found in [*Ananicheva and Krenke, 2007; Ananicheva et al., 2010*].

The calculations led to ELA values which can make basis for a conventional ELA field for groups of both existing and potential glaciers.

The ELA values for three periods are compared in Fig. 2 and Table 2. The ELA error found as the least square deviation of points in the altitude profiles is ~50 m.

The ELA ablation and the respective accumulation were estimated for the same three periods, using mass balance profiles from climatic data (Table 3).

RESULTS AND DISCUSSION

The equilibrium line altitude rise has been the greatest in the northern Verkhoyansk Range, as well as in the eastern part of the region, including the Omsukchan Range, the Yukagir Plateau, and the Kedeon and Omolon river catchments: 350 ± 50 m by 1960–1991 and 450 ± 50 m by 2012 (in the case if the elevations were high enough for the formation of glaciers). The increase is the smallest in the southern Suntar-Khayata and Chersky Ranges (50 and 100 m, respectively), where more moisture comes from the Sea of Okhotsk. Although the 50 m rise or fall of ELA is within the accuracy of the method, it is evidence of changes in the glaciological level.

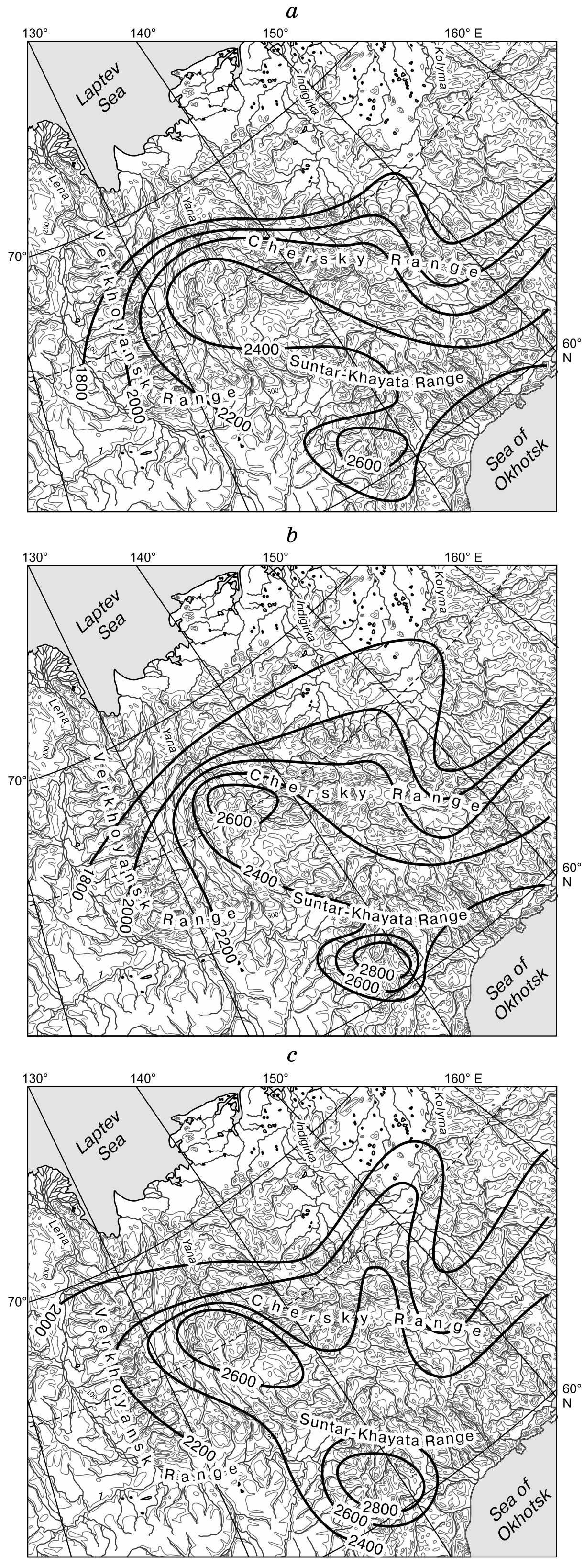
In any case, ELA changes depend on the amount of solid precipitation, which has followed a decreasing trend lately as shown by comparison of data for 1960–1990 and 1990–1212 (see above). The patterns of solid precipitation for the existing and potential glacier systems (Fig. 3) can provide an idea of the ELA spatial distribution in the three periods of time.

The ELA values vary smoothly over the area. The maps of Fig. 3 show that ELA reaches progressively higher elevations (a rise of 350–400 m the highest, 200 m on average); the "foci" of greater ELA rise become more prominent and expand under the ongoing warming; summer warming likewise increases with time, as one may see by comparing the periods before and after 1990.

ELA traces the sensitivity of glacier systems to long-period climate changes while the ELA spatial patterns display the spatial distribution of the climate change effect in highlands. The spatial variations of ELA difference between its values in different periods are evident from the respective patterns.

The map in Fig. 4 shows ELA changes for three periods relative to the previous time spans. The difference increases toward the Arctic seas and toward the northern Russian Far East where the climate change is more prominent, but is minor in the basin between the Suntar-Khayata and Chersky Ranges and south of them. The changes increase with time; the maximum difference has shifted inward the continent from the Okhotsk Sea coast by 2012, which is evidence of the warming trend and its influence on glaciation.

Zones of greater ELA changes correspond to zones of potential ice and snow hazard (glacial mud flows or collapse events, etc.). However, the ELA rise



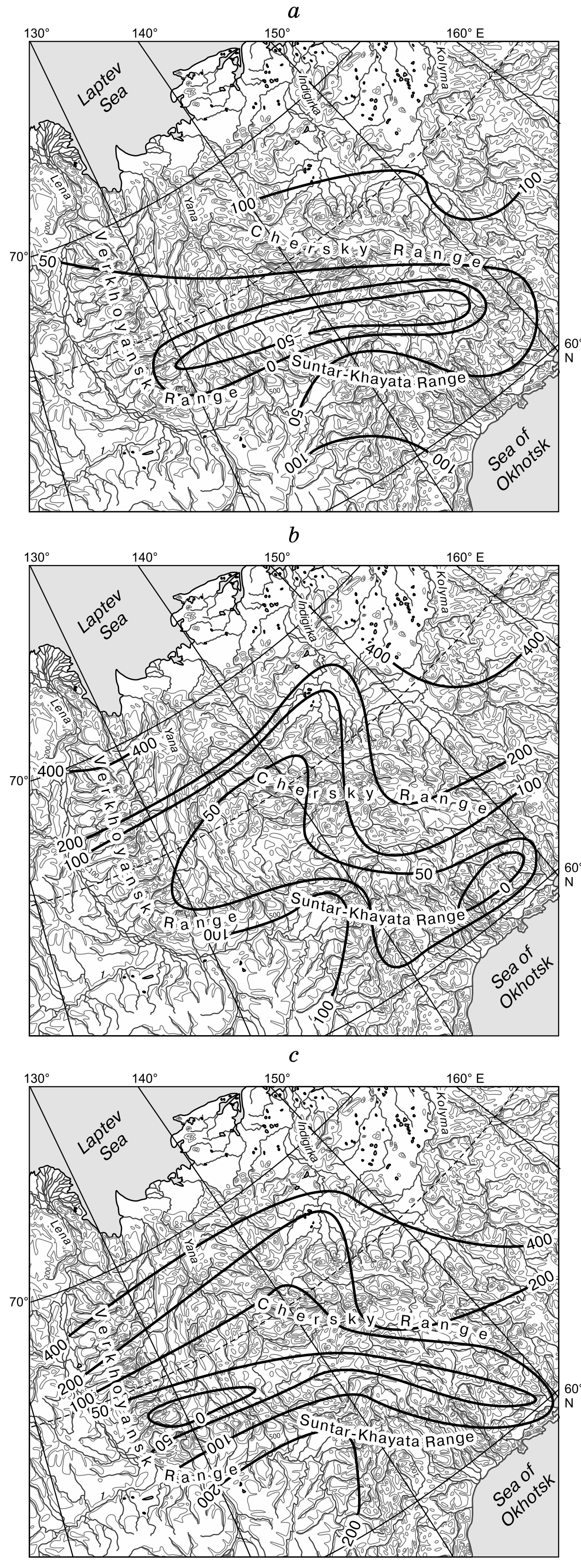


Fig. 3. ELA fields (m) for existing and potential glacier systems, for three periods: 1930–1960 (*a*); 1961–1990 (*b*); 1991–2012 (*c*).

Fig. 4. Changes in ELA (m) in 1961–1990 with respect to 1930–1960 (*a*), in 1991–2012 with respect to 1961–1990 (*b*), and in 1991–2012 with respect to 1930–1960 (*c*).

alone cannot be a reliable hazard indicator: prediction requires at least the knowledge of ablation and accumulation changes in glacier systems. The ablation and accumulation values at ELA (which are equal at this altitude) can be estimated from climatic data. They show increasing trends with time as ELA rises due to melting of glacier ice and retreat of glaciers.

Ablation (accumulation) at ELA was 350 to 750 mm/yr in 1930–1960 [*Ananicheva and Krenke, 2005*]. For the existing glacier systems, it was 400 to ~600 mm/yr (bold numerals in Table 3) in 1930–1960 and 350–580 mm in 1961–1990. Lately, these values increased to 400–750 mm/yr (400–650 mm for the existing systems).

The ELA ablation (accumulation) increase since the 1930s has been the greatest in the southern part of the region (Suntar-Khayata glacier systems) and the smallest in the north (till negative difference). It was greater in the more continental eastern part of the Chersky Range than in its western segment. Thus, the ELA rise and the ablation (accumulation) increase currently occur in the interior continental parts of mountain ranges and intermontane plateaus.

The glaciological parameters inferred from climatic data are the background values smoothly distributed over the area, which allows judging about the regime of glacier systems all over the region.

CONCLUSIONS

1. As a continuation of the previous study [*Ananicheva and Krenke, 2005*], the equilibrium line altitude and ablation (accumulation) at the respective altitude were estimated for three periods 1930–1960, 1961–1990, and 1991–2012 and analyzed in terms of recent change trends. ELA contour lines and increment in continental Northeastern Siberia were mapped for each period, for both existing and potential glacier systems.

2. The spatial distribution of ELA is controlled by climate: summer warming in the region was minor before 1991 and restricted to the central parts of mountain ranges and basins between them. The warming was attendant with increase in the amount of solid precipitation due to increasing mean winter air temperatures and cyclonic activity. In the 21st century, warming has accelerated: mean summer and annual air temperatures have increased all over the region, as well as total annual amount of moisture, while solid precipitation decreased, according to data from most weather stations. These trends are unfavorable for the preservation of glaciers.

3. Climate change has caused the rise of ELA all over the region, by 200 ± 50 m on average. The ablation (accumulation) values at the average equilibrium line altitude differed from period to period for 50 to 250 mm.

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References

Ananicheva, M., Karpachevsky, A., 2015. Glaciers of the Orulgan Range: assessment of the current state and possible development for the middle of the 21st century. Environ. Earth Sci. 74 (3), 1985–1995.

Ananicheva, M.D., Krenke, A.N., 2005. The evolution of climatic snow line and equilibrium line altitudes of glaciers in Northeastern Siberia in the 20th century. Mater. Glaciol. Issled. 98, 225–232.

Ananicheva, M.D., Krenke, A.N., 2007. Glaciological projection. Valley glaciers (case studies of Northeastern Russia and Kamchatka), in: Glaciation in Northern Eurasia in the Recent Past and in the Near Future. Nauka, Moscow, pp. 277–293. (in Russian)

Ananicheva, M.D., Krenke, A.N., Barry, R.G., 2010. The Northeast Asia mountain glaciers in the near future by AOGCM scenarios. The Cryosphere 4, 435–445.

Bogdanova, E.G., 1977. Methods for estimating the shares of solid, liquid, and mixed precipitation types in highlands. Mater. Glaciol. Issled. 30, 126–129.

Braithwaite, R.J., 2015. From Doktor Kurowski's Schneegrenze to our modern glacier equilibrium line altitude. The Cryosphere 9, 2135–2148.

Davidovich, N.V., 1983. The cooling effect of valley glaciers in mid-latitudes. Izv. AN SSSR, Ser. Geogr., No. 5, 74–82.

Dufour, A., Zolina, O., Gulev, S.K., 2016. Atmospheric moisture transport to the Arctic: assessment of reanalyses and analysis of transport components. J. Climate, No. 29, 5061–5081.

Kalesnik, S.V., 1963. Treatise on Glaciology. Geografgiz, Moscow, 551 pp. (in Russian)

Koreisha, M.M., 1963. Modern glaciation of the Suntar-Khayata Range: results of the International Geophysical Year. Glaciologiya, No. 11, 170 pp.

Koreisha, M.M., 1991. Glaciation of the Verkhoyansk-Kolyma Area. Izd. Mezhduved. Geofiz. Komiteta pri Prezidiume AN SSSR, Moscow, 143 pp. (in Russian)

Krenke, A.N., 1982. Mass Transfer in Glacial Systems within the USSR. Gidrometeoizdat, Leningrad, 288 pp. (in Russian)

Mavludov, B.R., Ananicheva, M.D., 2016. Glaciers of the northern Suntar-Khayata mountains: present state and dynamics since the latest 1950s. Led i Sneg (Ice and Snow) 56 (3), 345–357.

Takahashi, Sh., Sugiura, K., Kameda, T., Enomoto, H., 2011. Response of glaciers in the Suntar-Khayata Range, Eastern Siberia, to climate change. Ann. Glaciol. 52 (58), 185–192.

Vasiliev, I.S., Torgovkin, Ya.I., 2002. Spatial distribution of atmospheric moisture in Yakutia. Meteorologiya i Gidrologiya, No. 6, 23–32.

World Snow and Ice Resources. An Atlas. – URL: http://www.webgeo.ru/index.php?r=50&page=1&id=5723 (submittal date: 10.03.2017).

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