ISSN 1068-3739, Russian Meteorology and Hydrology, 2020, Vol. 45, No. 5, pp. 368–376. Allerton Press, Inc., 2020.
Russian Text The Author(s), 2020, published in Meteorologiya i Gidrologiya, 2020, No. 5, pp. 118–130.

Modern Deglaciation of the Altai Mountains: Effects and Possible Causes

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Received March 4, 2020
Revised April 7, 2020
Accepted April 7, 2020

Abstract—The analysis of satellite images revealed by 25% decrease of the Altai mountains' glaciation area over last 50 years. In 2008–2017, deglaciation rate increased twice. This tendency is in good agreement with an observed increase in the Katun River flow by 9% in 2008–2017 as compared to 1940–1968 (under invariable total precipitation). The analysis of trends of main meteorological parameters based on weather station data and the ERA-Interim reanalysis demonstrated that statistically significant warming in the region occurs only during the warm season and does not exceed 0.5 C/10 years. For this reason, "atmosphere–glaciers" turbulent heat transfer has increased by 4 W/m^2 in last two years, that caused an annual melting layer increase by 100 mm water equivalent (w.e.). However, the main reason for the Altai mountains' deglaciation is an increase of downward solar radiation flux, which amounted to 5 W/m^2 per decade and increased the melting layer by 365 mm w.e. per year. A positive trend in net radiation agrees well with a decrease in cloud amount, which is associated with an increase in the moisture divergence flux and geopotential height and with the weakening of zonal winds in the middle troposphere.

DOI: 10.3103/S1068373920050088

Keywords: Glaciations of the Altai Mountains, mountain meteorology, glaciology, regional climatology, ERA-Interim reanalysis

INTRODUCTION

In the recent decades, there has been a rapid glaciation reduction in the main mountain-glacier regions of the world, its trend is 0.5–1%/year [21]. According to the projections based on the IPCC scenarios, glaciers will completely melt in some mountain systems by the early 22nd century [23]. This may result in the catastrophic freshwater shortage for the countries whose climate is characterized by lack of moisture (Kyrgyzstan, Tajikistan, Kazakhstan, Peru, Chili, etc.). The reduction of area and volume of glaciers drives interannual runoff redistribution as well as region-dependent changes of mountain landscapes and frequency of mudflows [27, 38]. In addition, mountain glaciers melting makes significant contribution to global seas level change [23]. The above problems initiate the studies whose final goal is to simulate mountain glacier dynamics and to reveal the physical mechanisms of the modern deglaciation which depend much on the specific of a mountain-glacier region. The studies dealing with the inventory of mountain glaciers and the investigation of their dynamics were successful enough 30–40 years ago [2, 10]. However, the new approaches based on the joint analysis of satellite data and numerical atmospheric models' outputs allow a more detailed study of deglaciation causes in different regions of the globe. For example, the main factor of the modern glacier reduction in the Caucasus region is a positive trend in net radiation. It is associated with a decrease in total cloud amount, which is evidently initiated by the increasing frequency of anticyclones [37]. The catastrophic degradation of Kilimanjaro glaciers is primarily determined by the growing precipitation deficiency [28]. The main factor of deglaciation in the Indonesian mountains is a rapid growth of the contribution of liquid precipitation to the annual total amount, that is linked to the essential change in the altitude of glaciers equilibrium line so that most of glaciation is located below it [30]. In the tropical Andes, glaciers shrink against a background of rapidly increasing temperature and equilibrium line altitude [32]; the similar situation seems to be developing in the polar Urals [7]. The deglaciation in the Alps is determined both by the positive trend on the heat budget components [36] and by the negative anomaly of precipitation, which is partly linked to the prevalence of the positive phase of the Atlantic Multidecadal Oscillation over the last decades [24].

First data on the degradation of the Altai mountain glaciers were published in [8, 35]. In the same time, the estimation of main climatic values in the South Siberia mountains were carried out. For instance, the modern change in the glaciation-climate regime is caused by the intensification of zonal circulation patterns [9]. In [11], the Altai deglaciation in the recent 40 years is linked to the abnormal high values of average annual temperature, especially due to the summer temperature rise. The similar assumptions based on the statistical analysis of observational and model data are made in [35].

The present research provides an updated estimate of the change in the area of the Altai mountain glaciation in 2007–2018 as compared to 1968. A rather detailed meteorological interpretation of the Altai glacier shrinkage in the 21st century as compared to the Greater Caucasus is given [10, 37]. Both mountain systems are located sublatitudinally in the southern part of the temperate climate zone. This geographic similarity causes a unity of the heat budget structure with the prevalence of the radiative factor of melting [4, 14, 15], that allows expecting the similarity of the mechanisms for the modern deglaciation.

DATA AND METHODS

The method for the glaciation area estimation. The glaciation of the Altai Mountains being the highest part of the Altai-Sayan mountain system was chosen as a research object (Fig. 1). This territory is characterized by the combination of the vast planation surface with the high-mountain Alpine terrain. The glaciers are non-uniformly distributed across the territory and are grouped around three main mountain massifs: the Katun, Northern Chuya, and Southern Chuya ranges, whose altitudes exceed 4000 m. In this area, various and numerous forms of modern glaciation are common, among which valley and corrie-valley glaciers with the vast firn areas dominate [2, 5, 6].

Data of Sentinel-2 satellite observations on August 15, 2017 were used to estimate the modern size of glaciers in this mountain country. These images provide the simultaneous coverage of the whole analyzed territory. The images from CORONA (September 3, 1968) and ALOS PRISM (August 13, 2008) satellites were selected for evaluating trends in the glaciation area on the same territory. Both image sets allow comparing changes in the glacier boundaries both over the large (half-century) time period and for the recent decade. The spatial resolution of Sentinel-2, CORONA, and ALOS PRISM images is 10, 3, and 2.5 m. The images obtained at the end of the ablation period of the corresponding year, when the area occupied by the snow cover on glaciers and surrounding slopes was minimal (most often, in the middle of August), were used. This provided the control of initial data uniformity. Immediately before the procedure for the glacier boundary interpretation, all satellite images were subjected to orthotransformation and were composed in the UTM WGS 84 map projection. The Sentinel-2 images were used as the base ones. The root-mean- square error of the image composition did not exceed 5.3 m. The vectorization of glacier boundaries was performed manually using the ArcInfo 10.2.2 software (https://doc.arcgis.com/ru/). The interpretation errors due to the effects of clouds and snow cover may be neglected, because the influence of these factors was almost absent in the selected images. If the glacier boundary interpretation was hampered by the shadows from the neighboring mountain slopes, the contrast stretching function was applied (in the framework of the ENVI 5.0 software package). The ASTER GDEM V3 digital elevation model (https://asterweb.jpl.nasa.gov/gdem.asp) was used to detect the positions of ice divides in the glacier reservoirs. An important source of errors in the determination of the Altai glacier boundaries in the ablation zone is morainic deposits, whose area varies from 3 to 20%. The comparison of the results of interpretation of glaciers' boundaries based on satellite data with the data of ground-based measurements performed by the authors revealed that the presence of the morainic cover on the glacier surface makes additional contribution of 0.3% to the error of estimating the changes in their area [35]. The error caused by the subjective factor was assumed equal to 1.7% in accordance to the data presented in [29]. The minimum value of the glacier area, which was taken into account in the interpretation algorithm, is determined by the Sentinel-2 image resolution and is equal to 0.1 km^2. The error of the area determination was estimated using the ratio of the area of the buffer zone along the glacier perimeter to its area within the boundary; it varied in the range from 2.3 to 7.8% depending on the glacier size.

The method for the climate change assessment. The monthly mean values of surface air temperature with the 0.75 0.75 resolution from the ERA-Interim reanalysis [18] and the values of monthly total

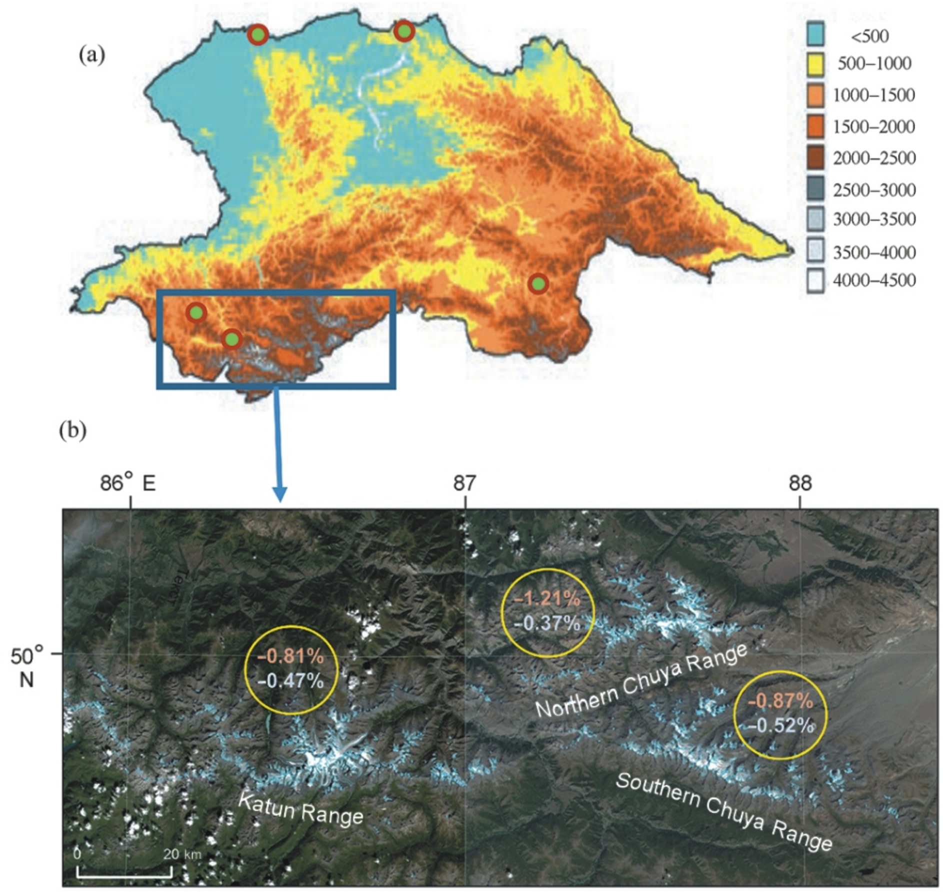

Fig. 1. The dynamics of the high-mountain Altai glaciation and meteorological data availability: (a) the Altai-Sayan region (the color scale is altitude above sea level, m) and its coverage with meteorological observations (the green circles are representative and long-series weather stations); (b) the area of the Altai mountain glaciation, the average annual trends towards its decrease (the yellow circles) over the periods of 1968–2009 (white) and 2008–2017 (pink).

precipitation from the CRU TS 4.02 (Climatic Research Unit Time-Series version 4.02) dataset with the 0.5 0.5 resolution were analyzed [20]. The affirmative results of using reanalyses data and variously gridded datasets to assess the meteorological regime and climate changes in the high-mountain regions has been discussed in many papers (for example, [1, 14, 19, 28, 35]). The present study focuses on the analysis of modern changes in the glaciation area and climate of the Altai Mountains; therefore, the period of 1979–2017 was chosen. This time period is characterized by rather homogeneous density of the global observation network and considerable amount of satellite data. The coefficient of linear trend is used as a measure of climatic and glaciological changes. The significance of regression was checked by the *F*-test, and the significance of correlation coefficients was checked by the *t*-test with the significance level of 0.05. The trends in temperature and precipitation over the period of 1979–2017 were also analyzed using the data of five weather stations situated in relative proximity to the Altai mountain ranges (Fig. 1). Considerable attention was given to these trends, as they are based on observational data. However, due to the low density of meteorological network in the region, the ERA-Interim data on temperature and the CRU TS data on precipitation for 1979–2017 were used as a basis. The quality assessment for these data for the mountain regions was performed in [1, 37] for the Caucasus region, a high correlation with field data was revealed (the normalized correlation coefficient is 0.75–0.85 for air temperature and 0.55–0.65 for precipitation). Due to the macrogeographic similarity of the two mountain systems (the Caucasus and Altai mountains), the quality of gridded datasets is assumed approximately identical. This assumption is corroborated by the close values of the trends obtained from the data of gridded datasets and five weather stations (www.meteo.ru). To reveal the mechanisms of climatic anomalies which favor the glaciation degradation, the quantification of changes in such characteristics as total column water vapor (the mass of water vapor in the air column with the section of 1 m^2 from the surface to the atmosphere top), moisture flux divergence, 500 hPa geo-

Table 1. The area of glaciers in the Altai Mountains and the average annual rate of its change in 1968–2017

Range	S, km^2			S, % per year		
	1968	2008	2017	1968–2008	1968–2017	2008–2017
Katun	267.3	217.6	198.0	0.47	0.53	0.81
Southern Chuya	165.0	130.9	118.0	0.52	0.58	0.87
Northern Chuya	151.9	129.5	112.9	0.37	0.52	1.21
Total	584.2	477.9	428.9	0.46	0.54	0.93

potential height anomaly, and vorticity at this level was performed. All these parameters were also taken from the ERA-Interim [18].

THE RESULTS OF ASSESSING THE DYNAMICS OF GLACIATION AND CLIMATE IN THE ALTAI MOUNTAINS

The glaciation dynamics in the recent 50 years. Based on the results of satellite image interpretation, three time sections of the boundaries of the Altai Mountains glaciers were constructed in vector format, which corresponded to their state in 1968, 2008, and 2017. This allowed quantifying the area of glaciation and its changes (Fig. 1, Table 1). The obtained data indicate the clearly pronounced deglaciation in the Altai Mountains; the average annual rate of the glaciers' area reduction in the recent decade is almost twice higher than the trend typical of the period of 1968–2008 (Table 1). The values of the trends are region-dependent: the maximum values are typical of the Southern Chuya Range (0.52%/year) and the minima are typical of the Northern Chuya Range (0.37%/year). This is evidently associated with the average long-term differences in total precipitation: under the same positive temperature trend, the slopes of the Southern Chuya Range are characterized by more arid conditions than the Northern Chuya Range. As a result, the glaciers of the Southern Chuya Range are more sensitive to the warming, their area decreases 1.5 times faster. In general, over last 50 years the Altai glaciation area reduced by about 25% (Table 1), such changes may be called catastrophic. If the modern trends stay, the glaciers in the Altai Mountains will completely melt in 100 years. The similar estimates for the mountain systems of the temperate climate zone based on the IPCC scenarios were made in [23]. The results of the previous estimates of the glaciers reduction for the Katun Range based on the ASTER satellite images in 2004 and 2012 also demonstrated an increase in the deglaciation rate by 1.5–2.0 times [8]. The obtained data allow supposing that the radical change in the Altai Mountains glacier regime occurred at the turn of the 20th and 21st centuries. One of the main reasons for these changes is the climate forcing.

The temperature and precipitation trends for the warm and cold seasons. The analysis of temperature trends based on station and reanalysis data demonstrates that the Altai-Sayan region and the nearby areas of Mongolia, China, and Kazakhstan are generally characterized by the statistically significant increase in average temperature for the warm season (May–September), whose mean value is 0.3 C/10 years (0.5 C/10 years in June and July) (the figure is presented in the supplementary materials at the website http://link.springer.com). In the cold season (from November to March), there are no statistically significant trends from station and ERA-Interim data (except for three stations near the eastern border of the study region). The absence of the winter warming in southern Siberia and even the growth of the frequency of negative temperature anomalies in these regions [22, 25] are in good agreement with the Arctic sea ice reduction being most clearly manifested in the Barents Sea [13, 33]. A significant decrease in the temperature gradient between the high and middle latitudes due to the accelerated warming in the Arctic may lead to the weakening of zonal circulation in the mid-latitudes and, as a result, the winter cooling in the inland areas of the Northern Hemisphere [34].

There were no statistically significant trends in annual and seasonal precipitation amounts from observational and CRU TS dataset (see the figure in the supplementary materials at the website http://link.springer.com). The analysis of weather station data revealed a significant precipitation increase during the cold season observed in northern China and in the steppe regions of southern Siberia (in the east of the study area). A significant increase in winter precipitation was detected according to CRU data in the Western Sayan mountains located near Altai. However, this tendency is not observed from station data analysis. No significant changes in precipitation are registered during the warm season either.

Despite a relatively small trend in summer temperature in the high-mountain Altai regions, its anomaly in 2008–2017 as compared to 1980–1990 was equal to about 1 C. The additional energy influx due to an increase in the sensible heat flux resulting from the air temperature rise by 1 C will be approximately equal to 4 W/m^2, that is equivalent to the melting of 100 mm of ice in water equivalent (mm w.e.). This estimate was performed similar to [37], where the anomalies of turbulent sensible heat flux are evaluated using the aerodynamic formulas [4, 15] assuming that wind speed and temperature of the ice surface do not significantly change during summer. In reality, the growth of downslope windstorm frequency can be an important additional reason for the increase of turbulent heat transfer between ice and air [17].

The changes in the radiation regime for the warm and cold seasons. Another important manifestation of the regional response to global warming in the Altai Mountains is a change in the radiation regime. The analysis revealed that the net radiation over the Altai-Sayan mountain country does not almost change in winter, whereas its statistically significant growth is registered during the warm season (see the figure in the supplementary materials at the website http://link.springer.com). According to the ERA-Interim data, the mean value of the trend in net radiation over the Altai Mountains during May to September is 5 W/m^2 per decade. Thus, during last 10 years the mean values of downward short-wave radiation flux in warm season in the high-mountain Altai regions can be 15 W/m^2 higher than in 1980–1990. In terms of the glacier heat budget, this means that during the melting season, whose active phase in the high-mountain Altai continues from June to August, the horizontal surface (not taking into account the exposure and inclination angles) receives 120 MJ/m^2 of additional energy, that is equivalent to the melting of 365 mm of ice in water equivalent. The radiation budget anomaly made a significantly greater contribution to melting than the summer increase in surface air temperature. The positive trend of radiation budget in the Altai mountains can be caused by increase in downward short-wave and long-wave fluxes (the second fact may be driven by increase in moisture content and anthropogenic emissions of greenhouse gases) [31]. Assuming a relative constancy of high-mountain landscapes, it may be considered that their reflectivity and heat radiation have slightly changed (this is indicated by the ERA-Interim data). The trend in the downward long-wave radiation over the Altai Mountains did not exceed 1 W/m^2. Therefore, the main reason for radiation budget increase is probably the growth of the incoming short-wave radiation, which is in good agreement with a decrease in cloudiness in the warm season.

It should be noted that the reanalysis data should be used very carefully, especially if we consider such values as the net radiation and cloudiness, which are characterized by a high level of errors. On the other hand, the studies [14, 18, 37] demonstrated that reanalyses data, including ERA-Interim, generally well simulate the real pattern of long-term variability of clouds and net radiation. Some papers, in particular, [31] discuss a trend towards an increase in net radiation, which is typical of modern climate change and is registered from in situ data.

The possible hydrological response to the deglaciation. Data on ice area changes coupled with the estimates of possible melting increase which is driven by heat budget anomaly, can be used to calculate a possible contribution of the Altai deglaciation to the runoff. The basin of the Katun River upstream Tyungur village is used as an example, because long-term observational data series on runoff, including average monthly and annual discharges are available for it (https://gmvo.skniivh.ru). The total area of glaciation in the selected part of the basin is currently equal to ~115 km^2 and has been reduced by 26% in the last 50 years (Table 2). Based on average long-term data on the main components of the mass balance for the representative glacier Malyi Aktru (www.wgms.com) and assuming the measured values typical of the glaciers of the Katun basin, it is possible to evaluate the average long-term glacier component of river flow. According to measurement data, the average values of summer mass balance for the Malyi Aktru glacier in 1970–1990 were equal to –950 mm w.e., that corresponds to the typical values for the mountain glaciers in Northern Eurasia [39]. According to the Kara-Tyurek high-mountain weather station data (www.meteo.ru) recalculated by the typical alpine rain-rate gradient [16] in the altitude range 3000–3500 m, the mean total summer precipitation on glaciers' surface is about 350 mm. Assuming that most of precipitation falling to the glacier surface in summer is added to the river runoff, we found that the average long-term melting layer in summer amounts to 1300 mm w.e. If the joint contribution of the anomalies of incoming solar radiation and surface temperature in summer in the recent 10 years is added to this value, we get the heat budget increase in 2008–2017 by 19 W/m^2 (or, in terms of the summer season, 151 MJ/m^2), that is equivalent to the melting of additional 465 mm w.e. Thus, due to the radiation and temperature effects in 2008–2017 the melting layer could increase by 36% as compared to 1980–1990. It follows from the observational data that the mean water discharge of the Katun River in the area of Tyungur village averaged for July and August in 2008–2017 will grow by 9% as compared to the period of 1940–1968 against a background of almost unchanged total precipitation in summer (Table 2). Assuming that in July and August in the upper part of

Table 2. The factors which determine the hydrological regime of the Katun River in the upper reaches (Tyungur village) in different periods from 1940 to 2017

Parameter	Station	Months	Period		
			1940–1968	1968–2008	2008–2017
S, km^2			155	122.6	115.1
R, mm	Kara-Tyurek	November–April	110	113	130
	Ust'-Koksa	November–April	109	110	127
	Kara-Tyurek	July, August	120	118	112
	Ust'-Koksa	July, August	160	147	143
Q, m^3/s	Tyungur	April–June	585	–	632
	Tyungur	July, August	400	–	436
Q_{year}, m^3/s	Tyungur		270	–	288

Note: The analyzed periods do not correspond to the WMO recommendations, their choice is determined by the availability of data on the glaciations area in the upper reaches of the Katun River obtained by the authors (1968, 2008, 2017), as well as by the availability of data on water discharge (these data are absent for the period of 1968–2008). S is the total area of 225 glaciers in the upper part of the Katun River basin (upstream of the Argut River mouth) in 1968, 2008, and 2017; R is total precipitation; Q is mean water discharge; Q_{year} is average annual water discharge.

the Katun River basin the snow cover is kept only in the mountain glacier accumulation zone, the observed river flow increase is logically linked to the increasing ice melting due to the positive trend in the heat budget.

DISCUSSION OF RESULTS

Climate change in the high-mountain Altai region over the last decades come to the statistically significant summer warming against a poorly varying precipitation regime. The main reason for the catastrophic deglaciation in the Altai Mountains is the positive trend in net radiation, which agrees well with the negative trend in total cloudiness. The interpretation of these results comes to the estimation of trends in meteorological parameters, which are inseparably linked to the changes in atmospheric circulation conditions: 500 hPa geopotential height, zonal component of wind speed, and vorticity at this level, moisture flux divergence (Fig. 2). A statistically significant positive trend in geopotential height in the middle troposphere is observed in most of Russia, except for the Urals and Western Siberia, during the warm season (May–September) (Fig. 2a). Over the southern areas of Siberia, including the Altai, positive geopotential height trends are statistically significant and are equal to 5 gpdam/10 years. At the same time, a statistically significant decrease in the zonal component of wind speed is registered over the southern areas of Siberia, as well as over Central Asia, Mongolia, and China, whereas no essential changes occur over the northern part of Eurasia (Fig. 2c). An increase in the integral moisture flux divergence over the Altai (Fig. 2d) and a certain growth in the relative vorticity (Fig. 2b) should also be noted. The combination of the factors presented in Fig. 2 indicates that a possible reason for the cloudiness reduction and, consequently, for the net radiation growth in the south of Siberia, in particular, over the Altai Mountains is an increase in the frequency of anticyclonic conditions in May to September.

Paper [3] provides a fairly complete review of the frequency of anticyclones in Russia (including blocking episodes). For instance, it is shown that a sharp increase in the number of anticyclonic days over Mongolia and southern Siberia occurred in the 1970s–1990s. This result is in good agreement with basic conclusions presented in [12]. So, a tendency towards the decrease of zonal circulation and intensification of meridional synoptical phenomena has been registered in the last 20 years over Northern Eurasia and southern Siberia. Among them, blocking anticyclones that cause temperature anomalies and the growth of short-wave radiation in summer can be an important factor. On the other hand, paper [9] analyzes the Katz circulation index and shows that the zonal circulation over southern Siberia, on the contrary, has intensified over last decades. However, most researchers (for instance, [34]) did not note a fact of westerlies intensification over Siberia. On the contrary, its weakening is registered, that leads to the increase in the frequency of stationary planetary waves [33] and in the probability of long-term cold anomalies in the winter season and prolonged and intense summer warming. The results obtained in the current study generally confirm this well-known hypothesis.

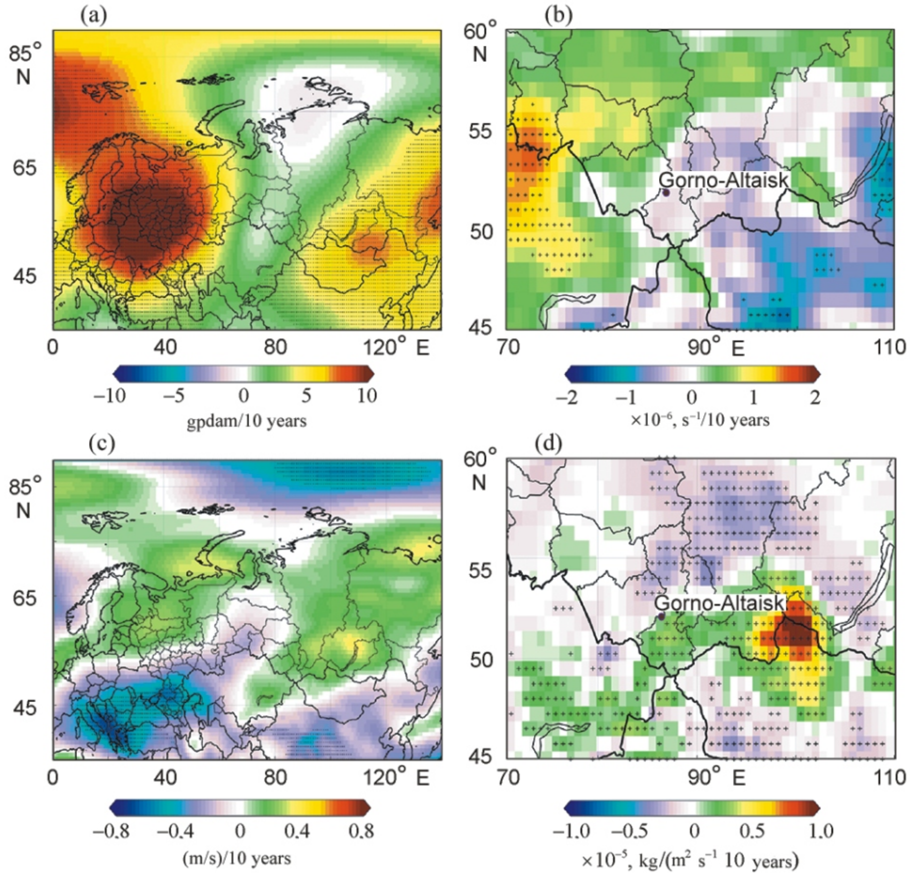

Fig. 2. The coefficients of linear trend in (a) the 500 hPa geopotential height, (b) relative vorticity, and (c) zonal component of wind speed on the 500 hPa geopotential height and (d) moisture flux divergence in the water column derived from the ERA-Interim data for the Altai-Sayan region, 1979–2017 for the warm period (May–September). The areas with statistically significant trends (the level of 0.05) are shaded.

The phenomenon of increasing anticyclone frequency in the Northern Hemisphere mid-latitudes is associated by some researchers with expansion of the Hadley cell downward branch to the north [26]. This effect may explain a growth in the number of anticyclonic days in the North Caucasus [34] but it is hardly true for the central part of Northern Eurasia. The mechanism of westerlies weakening seems to be more logical, that may lead to the increase in the frequency of blocking anticyclones [33]. The issue of the mechanisms of formation of anomalous regime of anticyclonic circulation in the mid-latitudes remains open due to the relatively poor exploration of the dynamics and climatology of anticyclones in general [3].

CONCLUSIONS

This research demonstrated that the Altai mountains' deglaciation has decreased by ~25% over the last 50 years, and the deglaciation rate has increased by 1.5–2 times since the beginning of the 21st century. This process has been observed against a background of the statistically significant rise in the warm-season temperature (by 0.3 C/10 years on average), whereas the winter temperature regime has not essentially changed. The similar results for the Altai temperature trends are discussed in [35]. The precipitation regime also remained almost unchanged in the Altai Mountains. An increase in summer surface air temperature led to the positive anomaly of the heat influx to the ice surface due to the turbulent heat transfer, which was equal to 4 W/m^2 in 2008–2017 as compared to 1980–1990. Another important factor in this period was the positive anomaly of net radiation due to the downward shortwave radiation, which amounted to 15 W/m^2. Thus, the total anomaly of heat budget in 2008–2017 reached 19 W/m^2 and was evidently a reason for the melting layer growth by 465 mm w.e. It is shown that the observed increase in runoff in the Altai Mountains by 9% in July and August (for the case of the upper reaches of the Katun River) against a background of invariable amount of precipitation is in good agreement with the performed estimate for the positive anomaly of the melting layer.

The positive trens of radiation budget is evidently determined by the statistically significant decrease in cloudiness. The latter highly correlates with the increase in the integral moisture flux divergence and with the intensification of downward air movement. These tendencies correspond to the statistically significant positive trend in geopotential height in the middle troposphere and to the weakening of zonal circulation over Central Asia, Mongolia, and northern China. Combination of these factors indicates the increase in the frequency of anticyclonic conditions over southern Siberia in summer, which leads to the positive trend in net radiation. As a result we observe the deglaciation rate growth. This mechanism is important because radiation budget plays the main role in the heat balance of glaciers in the south of the boreal zone [4, 13]. This can explain the similarity of causes for deglaciation in the Altai and North Caucasus [34]. The issue of the genesis of anticyclone frequency increase in southern Siberia, which caused the intensification of glacier melting, remains open. One of the most substantiated versions is a decrease in the interlatitude temperature gradient in the middle troposphere related to the Arctic warming, which led to the westerlies weakening, to the increase in the frequency of stationary planetary waves and, hence, of blocking anticyclones [11, 31, 33].

FUNDING

The estimation of the Altai glaciation trends was performed in the framework of the Governmental Assignment theme 0148-2019-0004, the calculation of trends in meteorological parameters was carried out in the framework of the Governmental Assignment theme 0148-2019-0009, the analysis and interpretation of results, as well as the estimates of the contribution of the radiation factor to the deglaciation was supported by the Russian Foundation for Basic Research (grant 20-05-00176).

SUPPLEMENTARY MATERIALS

Supplementaty materials are available for this article at DOI: 10.3103/S1068373920050088 and are accessible for authorized users.

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