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Glacier changes in the Siberian Altai Mountains, Ob river basin, (1952–2006) estimated with high resolution imagery

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Abstract
The Siberian Altai covers about 70% of the area of all south Siberian glaciers, which provide fresh water to the upper tributaries of the Ob and Yenisey rivers. The observed air temperature has increased by 1.2 °C over northern Eurasia during the last 120 years, affecting the degradation of the Siberian Altai glaciers. In this study, we estimated glacier area changes in the Aktru River basin (44.8 km^2), located in the central Altai mountains. We used the 1952, 1966, 1975 and 2006 remote sensed images with 0.6–3.0 m spatial resolution (aerial photographs, Corona and PRISM satellite images) and differential GPS (DGPS) data. From 1952 to 2006, the total glacier area in the Aktru basin shrank by 7.2% (1.2 km^2). During the last three decades, the rate of glacier area loss increased by a factor of 1.8, thus resembling trends in other mountain systems of Eurasia (Alps, Tien Shan). The glacier area changes were caused mainly by increase of summer air temperature by 1.03 °C (from 1951 to 2000) at elevations below 2500 m, which intensified the melt of the glacier's ice in the ablation zone. At elevations above 2500 m (upper accumulation zone), the summer air temperature increased by only 0.83 °C.

Keywords: glacier, climate change, Siberian Altai, remote sensing

1. Introduction

The Siberian Altai is located in the most northern periphery of the central Asia mountain system and the southern periphery of the Asian Arctic basin (figure 1). The highest part of the Siberian Altai mountains (Katun, South Chuya and North Chuya ranges) holds about 70% of the area of all south Siberian glaciers which provide fresh water to the upper tributaries of the Ob and Yenisey rivers [1]. The observed air temperature has increased by 1.2 °C over northern Eurasia during the last 120 years [2]. During the last 30 years the temperature rise was more intense (0.6 °C, between the 1970s and 2005), which has contributed to the widespread mass loss of Asian glaciers [3–6], and has also affected the glaciation of the Siberian Altai.

Our study focused on the Aktru River basin, Siberian Altai, where intensive observations of glaciers, climate and river runoff regime have been conducted since the 1960s (figure 2). The time series of annual mass balance observations (snow accumulation and ice ablation) of the Aktru basin glaciers are the longest in Siberia and have been used as a regional representative for global estimations of glacier mass balances [7, 8].

The Aktru basin glaciers started to retreat at the end of the Little Ice Age (approximately 1850s), as estimated from the terminal moraines radiocarbon analysis [9]. In 1911, for the first time, Russian geographer Vasiliy Sapozhnikov documented positions of the glacier termini in the Aktru basin [10]. From 1936 to 1952, Mikhail Tronov continued these observations [11, 12], and in 1952, the measurements

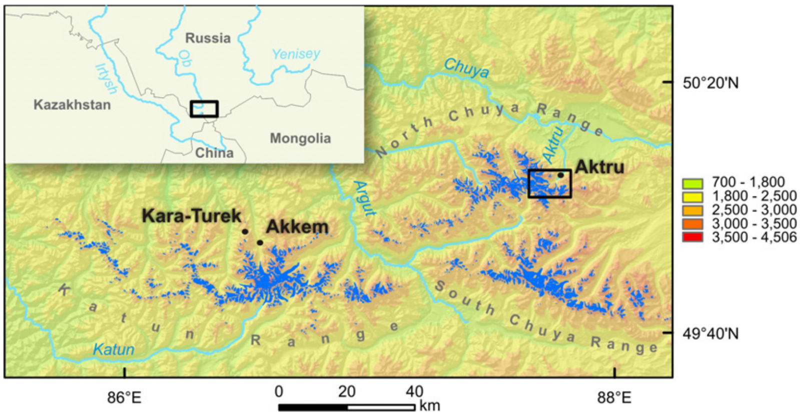

Figure 1. Location map of Siberian Altai mountains and glaciation and the Aktru River basin. Black dots indicate meteorological stations in the region.

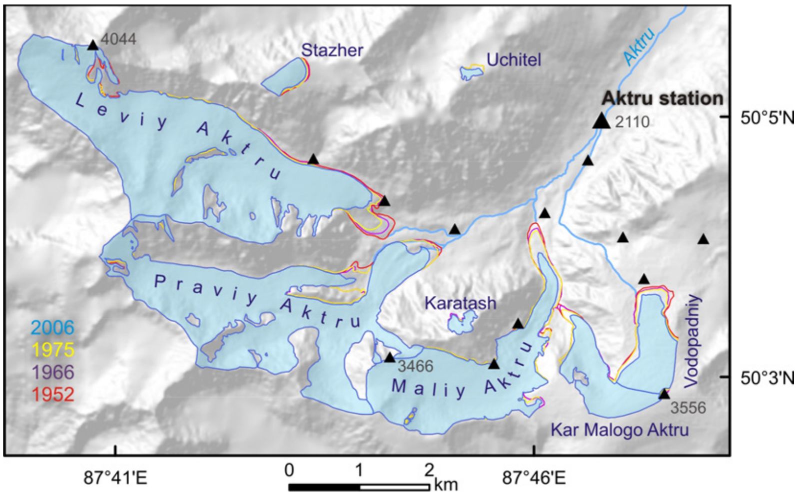

Figure 2. Map of Aktru River basin with multitemporal glacier boundaries. The DGPS surveyed ground control points that we used for co-registering remote sensed images are shown as black triangles.

were taken annually and became a part of the Tomsk State University glacio-climatological monitoring program [13–16]. Additionally, between 1977 and 1980 the lower parts of the glaciers were mapped using terrestrial (ground-based) photogrammetry [12]. However, accurate estimates of the area changes of the Aktru basin glaciers were unknown, possibly lowering the accuracy of the glacier mass balance and glacial runoff calculations. Since 1952, when a 1:25 000 topographic map was compiled, the mapping of glaciers in the Aktru basin has not been repeated. Furthermore, detailed studies of glacier area changes were not conducted anywhere else in the Siberian Altai.

Recent advancements in high resolution (1–5 m) remote sensing showed significant usefulness for monitoring mountain glaciers (see for example [17–19]). Launched in January 2006, the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) provided the first low-cost imagery at a resolution of 2.5 m, comparable to that of traditional aerial photography. Also, the US government recently declassified a large image data set from the 'Corona' reconnaissance satellite missions flown from 1959 to 1980 (see for example [20]). The PRISM and Corona images together with historical aerial photography provide a unique opportunity for high resolution repeated glacier mapping.

In this study we estimated area changes of the Aktru basin glaciers using the 1952, 1966, 1975 and 2006 remote sensed images with 0.6–3.0 m spatial resolution. We removed image geometric distortions and co-registered the imagery using a differential GPS (DGPS) surveyed set of ground control points (GCPs) and a digital elevation model (DEM). Next, we digitized the multitemporal glacier boundaries using visual interpretation of the imagery assisted with a large archive of ground photographs. After presenting our results, we discuss our observations of the area changes of the Aktru basin glaciers along with the Altai region climatological data.

2. Study area

The Aktru River basin is located in the highest part of the Northern Chuya Range (2100–4044 m). The basin area is

Table 1. The morphological types, areas and area changes of the Aktru basin glaciers.

Name	Morphological type	Area in 2006 (km^2)	1952–2006 area loss (%)	Proportion of the total area loss (%)
Leviy Aktru	Valley	5.89	−5.7	30.8
Praviy Aktru	Valley	4.66	−5.4	23.1
Maliy Aktru	Valley	2.61	−8.6	21.2
Kar Malogo A.	Cirque–valley	0.78	−7.5	5.5
Vodopadniy	Ice-cap–valley	0.70	−20.0	15.2
Stazher	Cirque	0.18	−14.6	2.6
Karatash	Hanging	0.08	−5.3	0.4
Uchitel	Niche	0.03	−28.7	1.2
Total		14.9	−7.2	100

Table 2. The remote sensed data used in the study and corresponding residual errors after geometric corrections.

	Date of acquisition	Resolution (m)	GCP RMSE (m)
Aerial photographs, block of 3	3 September 1952	3	1.8
Corona KH-7 photograph	19 August 1966	0.6	0.4
Aerial photographs, block of 8	21 August 1975	1	1.3
Landsat ETM+[a]	22 July 2000	15, 30	12.0
ASTER[a]	10 September 2004	15	7.0
PRISM	6 September 2006	2.5	2.4

[a] Supplementary images.

44.8 km^2, of which glaciers occupied 35.9% in 2006 (table 1). Three large valley glaciers constitute 88% of the total glacier area. The other 12% represents smaller glaciers of different morphological types.

The location of the study area in the center of Asia has defined the continental climate conditions. Long term (1972–1994) mean minimum/maximum annual temperatures vary between −18 and 10 °C at the Aktru meteorological station (2110 m). The average annual precipitation is about 540 mm, 81% of which occurs from April to October. The Atlantic Ocean is the main moisture source for the Siberian Altai. At the same time, one third of the Siberian Altai precipitation originates from internal moisture sources, which refer to evaporation from continental sources, such as the closed Aral and Caspian drainage basins, or local river basins [21]. One of the main factors determining the climatic regime is the interaction between the Siberian High and the western cyclonic activity. During winter, the strong impact of the Siberian High prevents the entrance of moisture to the alpine areas of the Siberian Altai, resulting in low winter precipitation (about 17 mm month^{-1}). North-western cyclones and local convection result in a precipitation summer maximum (up to 90 mm month^{-1}). The most conspicuous feature of the glacio-climatic regime in the Siberian Altai is the coincidence of summer maximum precipitation with the melting of glaciers and snow.

3. Data and methods

Table 2 summarizes the images that we used in this study. To accurately estimate glacier area changes, both the spatial resolution and accuracy of remote sensed imagery should be consistent with time. First, we minimized the glacier change errors by using images of similar high spatial resolution (0.6–3.0 m). Second, using DGPS surveying, we established a network of ground control points (GCPs) that are identifiable on every image dataset. After image geometric corrections, we achieved GCP residuals less than 3 m (one standard deviation). We delineated the Aktru glacier boundaries using manual digitizing assisted with stereo viewing.

3.1. Remote sensed data

Two aerial topographic surveys were conducted in 1952 and 1975. We digitized paper prints of the 1952 photographs at 300 dpi (3 m resolution) and the 1975 photographs at 600 dpi (1 m resolution). The instability of the paper base introduced distortions of 0.2–0.6 pixel (about 0.2–1.7 m in ground distances of the digitized images).

A film of the Corona photograph taken on 19 August 1966 by the KH-7 surveillance system was scanned at 3600 dpi (0.6 m resolution). The image covers the entire Aktru basin and clearly depicts large boulders, individual trees and details of glacial and periglacial relief.

Current glacier areas were estimated using a 2.5 m panchromatic PRISM image that was acquired on 6 September 2006, only a month after our GPS field work. In addition, we used supplementary Landsat ETM+(2000) and ASTER (2004) images.

3.2. GPS field survey data

To quantify glacier area changes, the images from different dates must be co-registered using ground control points (GCPs). Such GCPs typically represent immobile features that are accurately identifiable on the images.

During two field trips, one in 2005 and one in 2006, we established a geodetic network throughout the study area

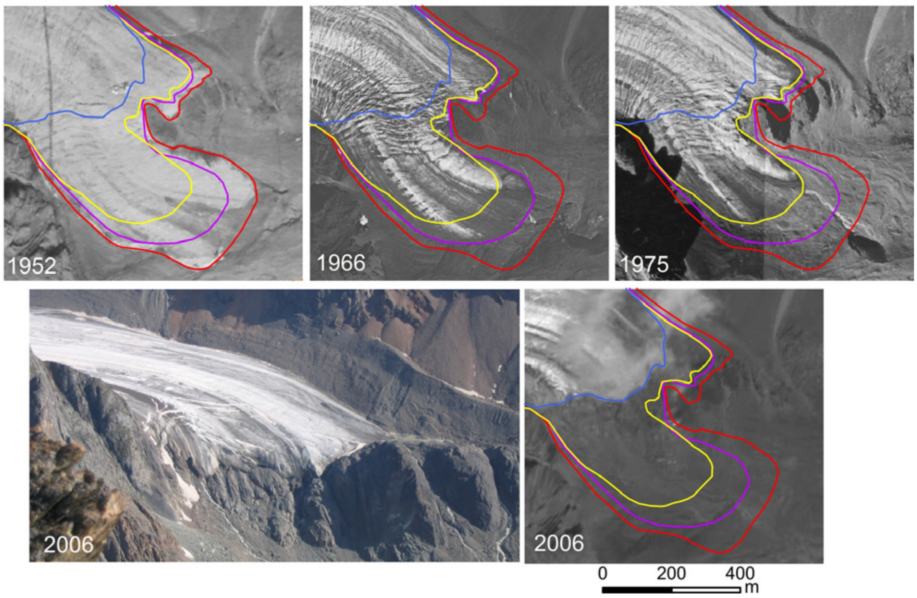

Figure 3. Multitemporal boundaries of the Leviy Aktru glacier terminus overlaid on the orthorectified imagery. On the 2006 PRISM image a light cloud partly obscured the glacier boundary. The lower left image is an oblique photograph taken during the 2006 field work.

(figure 2). We surveyed a set of 14 GCPs using a DGPS with 0.2 m accuracy. Given the 54 year overall time span between the images, we considered only relatively permanent targets—large boulders on stable moraines, distinct rock peaks and abrupt shores of lakes. Also, we surveyed longitudinal profiles of the Vodopadniy, Maliy Aktru and Leviy Aktru glaciers as well as sections of the glacier boundaries to verify accuracy of the 2006 PRISM image.

3.3. Image processing and glacier delineation

We corrected the images for geometric distortions due to terrain and sensor imaging geometry (orthorectification) using Leica Photogrammetry Suite 9.1 software. For this we used the GCPs and a DEM that we generated using digitized contour lines from the 1:25 000 topographic map. The residual GCP errors are less than 3 m (table 2).

The glacier boundaries were manually digitized from the orthorectified images (figure 3). The images were taken at the end of summer and in most cases they show well defined glacier boundaries. The lower part of the Praviy Aktry glacier is covered by debris, and we used stereo viewing with the image stereo pairs (Stereo Analyst software) to identify the characteristic V-shaped depression between the glacier body and the lateral moraines to identify the glacier boundary. To validate the glacier boundaries determined by visual interpretation of the remote sensed imagery, we also used our archive photographs taken from 1963 to 2006.

In areas where steep rock faces meet with a relatively flat glacier body, local shifts of glacier boundaries of up to 40 m are visible on the consecutive images. The shifts occurred due to avalanche snow deposits that are highly variable and depend mostly on the snow accumulation of the preceding winter. In such cases, we used the lowest glacier boundary for the calculations.

The 2006 PRISM image was taken after light snowfall on higher altitudes that masked the upper glacier boundaries on high flats next to the Vodopadniy and Maliy Aktru glaciers. In the absence of well defined topography, the thin snow cover caused unrealistically large shifts of the visible glacier boundaries. These parts of the 2006 glacier boundaries were edited using satellite images of lower resolution (Landsat 2000, ASTER 2004) and the 2006 GPS measurements.

4. Results and discussion

The total glacier area in the Aktru basin decreased by 7.2% (1.2 km^2) from 1952 to 2006 (figure 2, table 1). 83% of the observed area change occurred due to retreat of glacier termini at elevations between 2200 and 3100 m. At the upper glacier areas, in accumulation zones, the glacier area decreased mostly on steep slopes (40°–60°) with a thin ice cover.

The area changes of the glaciers vary from −5.3% to −28.7% between 1952 and 2006 in the Aktru basin. The large range of values reflects the fact that a glacier response to regional climate change is modified by local factors—glacier morphology, snow accumulation conditions and the glacier exposure. Below we discuss the individual changes in detail.

- *Karatash* (−5.4%, 3274–3535 m) is a small hanging glacier at the top of the north face of Karatash Peak. The mass loss of the glacier strongly depends on ice stability rather than climate change: the ablation of the glacier ice occurs mainly through avalanches.
- *Praviy Aktru glacier* (−5.4%, 2400–3758 m). A thick debris layer covers the lowest 30% of the ablation area of this large valley glacier. The debris strongly inhibits

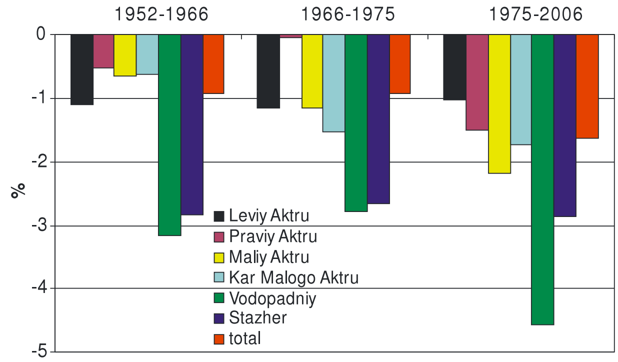

Figure 4. Ten-year averaged rates of area loss of the Aktru basin glaciers (not including Karatash and Uchitel glaciers).

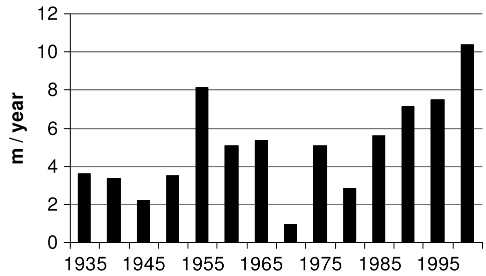

Figure 5. Five-year averaged rates of terminus retreat of the Maliy Aktru glacier.

ice melting and modifies the glacier's response. Instead of retreating gradually, the glacier terminal areas collapsed in separate events.

- *Vodopadniy glacier* (−20.0%, 3040–3556 m) is one of the seven outlets descending from a continuous ice cap that occupies Kupol Mountain (3556 m). Vodopadniy experienced relatively high mass loss due to less favorable snow accumulation conditions [22].
- *Uchitel* (−28.7%, 3030–3148 m) is a very small semi-glacier whose mass balance strongly depends on its shade location. The average altitude of the glacier (3080 m) is the lowest among the Aktru basin glaciers, making the Uchitel glacier particularly vulnerable to climate change.

The glacier area loss in the Aktru basin occurred mostly due to the three largest glaciers (75% of the total area loss), but area changes of the smaller glaciers may have stronger impact on a regional scale. In 1952 the small Aktru glaciers with an area of less than one square kilometre occupied only 13% of the total Aktru basin glacier area, but they account for 25% of the glacier area loss in the Aktru basin from 1952 to 2006. Since such small glaciers occupy 27% of the total glacier area in the Siberian Altai [23–27], we may expect their impact on the regional glacier area loss to be more significant than in the Aktru basin. Paul *et al* [28] reported that glaciers less than one square kilometre in area account for 44% of the total area loss in the Swiss Alps from 1973 to 2000, despite the fact that they cover only 18% of the total 1973 area.

The average decadal loss rate of the Aktru basin glaciers remained practically the same during the first two periods (1952–1966, 1966–1975), but during the last 31 years, the rate nearly doubled, with the area loss accelerating from 0.9% to 1.6% per decade (figure 4). The rates of the Maliy Aktru terminus retreat also reflect the tendency of the accelerated glacier area loss during the last decades (figure 5).

The observed acceleration of the Aktru glacier area loss rate since 1975 resembles trends in other mountain systems of Eurasia. For example, in the Akshiirak glacierized massif, in central Tien Shan, this rate increased by a factor of 2.7 from 1977 to 2003 (−8.6%) in comparison to the 1943–1977 (−4.2%) period [6]. Although the glaciers in the Alps lost only 1% of their area from 1970 to 1985, over the next 13 years, the glaciers suffered an area loss that was seven times faster than the decadal mean from 1850 to 1973 [28].

5. Climatic factors

Climate change characteristics in regard to glacier state usually consider changes in mean air temperatures and mean annual precipitation. Since data for the Aktru meteorological station (2110 m) are available only from 1972 to 1994, we also analyzed records of monthly air temperature and precipitation for Akkem (2050 m) and Kara-Turek (2600 m) meteorological stations from 1951 to 2000. Akkem and Kara-Turek stations are located in the Akkem River basin, the central part of the Katun Range, about 90 km to the southwest from the Aktru basin. We found that the mean summer air temperatures are highly correlated: Aktru–Akkem ($R = 0.83$) and Aktru–Kara-Turek ($R = 0.86$), while the total annual precipitations are correlated moderately: Aktru–Akkem ($R = 0.59$) and Aktru–Kara-Turek ($R = 0.57$) (figure 6).

The main cause of the observed glacier area loss in the Aktru basin is an increase in summer air temperatures. Instrumental measurements on the Maliy Aktru glacier showed that its annual mass balance is highly correlated to ablation ($R = -0.94$) which, in turn, is highly correlated to the mean summer air temperature at Aktru station ($R = 0.93$) [22]. The temperature records of the meteorological stations showed that the rise of summer air temperature at the lower elevations was more intensive than at the higher elevations. From 1951 to 2000, at elevations below 2500 m, the summer air temperature increased by 1.03 °C, while at elevations above 2500 m, the air temperature increased by 0.83 °C. The precipitation profiles on figure 6 show a positive trend at higher elevation, while at the lower elevations the precipitation trend is insignificant. Therefore, at elevations above 2500 m, the increase of summer mean temperature of 0.017 °C yr^{-1} in the Siberian Altai was partly absorbed by the increase of annual precipitation of 3.2 mm yr^{-1}. At the lower elevations, the increase of summer air temperatures of 0.064 °C yr^{-1} was not accompanied by a significant increase of annual precipitation.

6. Conclusion

The combination of historical and modern high resolution imagery enabled us to estimate area changes of the Aktru

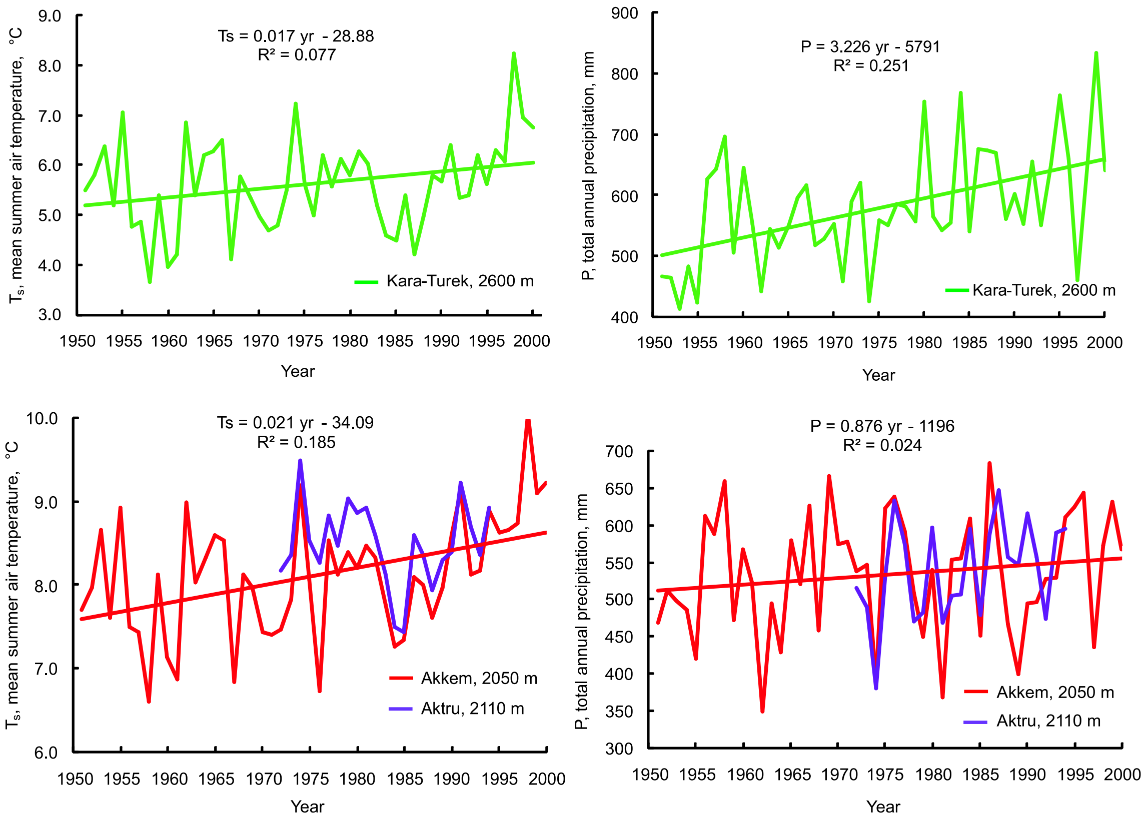

Figure 6. Mean summer air temperature and total annual precipitation at Aktru, Akkem and Kara-Turek meteorological stations.

glaciers between 1952, 1966, 1975 and 2006. We orthorectified the remote sensed images with DGPS data and achieved residual errors that are less than 3 m. From 1952 to 2006 the Aktru basin glaciers lost 7.2% of their area. In the last three decades, the rate of area loss accelerated by a factor of 1.8 (from 0.9% to 1.6% per decade). The changes were caused mainly by the increase of summer air temperature by 1.03 °C at elevations below 2500 m and 0.83 °C at elevations over 2500 m from 1951 to 2000.

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