Glacier changes in the central and northern Tien Shan during the last 140 years based on surface and remote-sensing data

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ABSTRACT. This research presents a precise evaluation of the recession of Akshiirak and Ala Archa glaciers, Tien Shan, central Asia, based on data of geodetic surveys from 1861–69, aerial photographs from 1943, 1963, 1977 and 1981, 1 : 25 000 scale topographic maps and SRTM and ASTER data from 2000–03. The Akshiirak glacierized massif in the central Tien Shan contains 178 glaciers covering 371.6 km^2, and the Ala Archa glacier basin in the northern Tien Shan contains 48 glaciers covering 36.31 km^2. The Tien Shan glaciers retreated as much as 3 km from the 1860s to 2003. Area shrinkage of Akshiirak and Ala Archa was 4.2% and 5.1%, respectively, from 1943 to 1977, and 8.7% and 10.6%, respectively, from 1977 to 2003. The volume of the Akshiirak glaciers was reduced by 3.566 km^3 from 1943 to 1977 and 6.145 km^3 from 1977 to 2000. The total reduction of the Tien Shan glaciers is 14.2% during the last 60 years (1943–2003). The northern and central Tien Shan have not experienced a significant precipitation increase during the last 100 years, but they have experienced an increase in summer air temperatures, especially observable since the 1970s, which accelerated the recession of the Tien Shan glaciers.

1. INTRODUCTION

Glaciers are sensitive objects that can indicate global climatic changes. Correct evaluation of glacier area and volume change has wide practical application in water-resource, water-supply and hydropower assessments. Despite the low amount of precipitation and extremely dry climate in central Asia, the Tien Shan hold one of the greatest concentrations of glacial ice in the mid-latitudes, and they constitute a vital source of water for more than 100 million people living in this region. Over the last 150 years, since the end of the 'Little Ice Age', and notably since the 1970s, the glaciers of central Asia have tended to retreat rapidly due to an increase in air temperatures and changes in precipitation partitioning (more rain than snow at high elevations) that have caused the glaciers to have a mainly negative mass balance, which has also changed river runoff regimes (Glazirin, 1996; Aizen and others, 1997, 2006; Glantz, 1999; Denisov and others, 2000; Agrawala and others, 2001; Aizen, 2003). An increase in air temperature and melting of glaciers has a significant impact on desertification of the central Asian lowlands, on glacier outburst floods and on mudflows in the upper valleys (Aizen and others, 1997, 2006; Sarsembekov, 2000). Furthermore, the stability of the central Asian hydrological systems relies on the stream-flow buffering capacity of the glacial ice.

Changes in the glacial coverage area in high mountains were poorly documented until aerial photography and particularly satellite imagery provided new techniques for remotely sensed glacier monitoring. Since the mid-1980s, the role of satellite glacier monitoring has been widely recognized. World Glacier Monitoring Service (WGMS; Haeberli and others, 2000) and Global Land Ice Measurements from Space (GLIMS; Bishop and others, 2004) are two international projects aimed at studying glacier fluctuations. Presently, as access to remote-sensing data has become less complex, many researchers have used it to study land-surface objects, but not all researches are as accurate as could be. Recent research based on remote-sensing data revealed significant glacier recession (Khromova and others, 2003) which seemed speculative and thus required further validation.

The main objective of our research is precise evaluation of the Tien Shan glacial recession using modern remote-sensing techniques in combination with earlier geodetic and meteorological data, and aerial photographs. We therefore compiled >50 years of meteorological data, >100 years of data from land-surface topographical surveys, topographic maps and modern data from on-site global positioning system (GPS) observations, in addition to remotely sensed data from the Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (SRTM). Together, these have provided unique information for interpreting climatic events and glaciological consequences. Furthermore, the authors report on numerous field studies they have completed in the Tien Shan in the last 25 years, particularly in the Akhsiirak and Ala Archa areas, which allow validation of past and present glacier positions on the remotely sensed images with great accuracy.

This research did not set itself the task of comparing glacier changes in different mountain systems of the world. Obviously, there are differences and similarities in alpine glacier fluctuation. For example, glaciers in the Alps are more vulnerable and retreat faster than Tien Shan, Pamir or Tibetan glaciers due to lower absolute elevations (Paul and others, 2004). Glaciers of Tibet, the Himalaya and central Asia can be more stable and may even advance (Liu and others, 2006; Narama and others, 2006). Therefore, an accurate estimation of the real glacier-covered area in the

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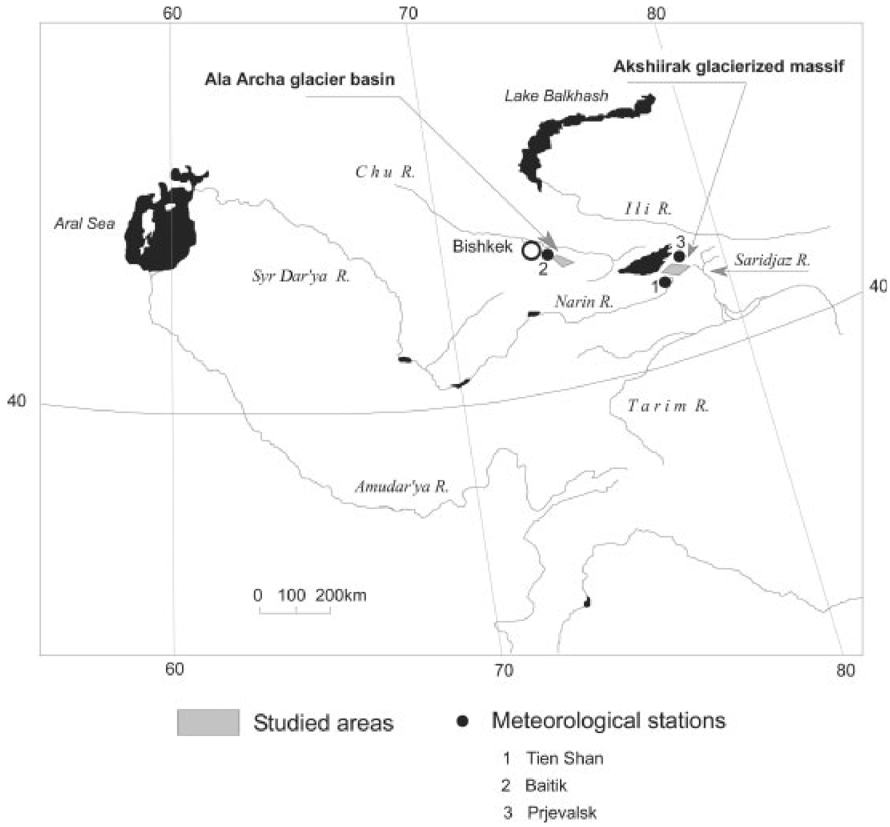

Fig. 1. The Tien Shan study areas.

past and at present is very important in understanding the impact of global climate change on water resources in arid and semi-arid regions.

2. AREA OF RESEARCH

For our analysis we selected two Tien Shan glacierized basins located approximately 800 km from each other that have different climatic regimes (Fig. 1). Both basins have rich glaciological data for the same period of time and have been the focus of many studies since the 19th century (Venukov, 1861; Kaulbars, 1875).

Akshiirak glacierized massif

The Akshiirak glacierized massif (41°40′–42°05′ N, 78°00′–78°32′ E), the second largest glacierized massif in the Tien Shan, is composed of 178 glaciers with an area of 371.6 km^2 (in 2003) and an altitudinal extent of 3600–5000 m a.s.l. (Figs 1 and 2). Large valley glaciers form 87% of the Akshiirak glacierized area. The Akshiirak subcontinental glacier system receives 350 mm of annual precipitation, with 45% occurring in three summer months. Akshiirak glaciers feed two large central Asian rivers: the Narin river, the headwaters of the Syr Dar'ya river, and the Saridjaz river, a tributary of the Tarim river in northwestern China.

Ala Archa glacierized basin

The Ala Archa glacierized basin is located at the northern edge of the Tien Shan mountain system (42°24′–42°36′ N, 74°24′–74°34′ E) and contains 48 glaciers covering an area of 36.31 km^2 (2003). Ala Archa glaciers are spread through an altitude range of 3300–4800 m a.s.l. (Figs 1 and 2). Approximately 83% of the Ala Archa glacier area consists of large valley glaciers, with about 76% of the total glacier-covered areas located between 3700 and 4100 m a.s.l.

The Ala Archa glaciers receive 700 mm of annual precipitation, mainly during spring to summer months (48% from April to June) (Aizen, 1988a, b; Aizen and others, 2000), and they feed the closed drainage basin of the Chu river, which is the major irrigation and water-supply source for northern Kyrgyzstan and southern Kazakhstan.

3. DATA AND METHODS

Tacheometric surveying, aerial photographs and topographic maps

Akshiirak

The first tacheometric surveying of Akshiirak glaciers was accomplished by expeditions of the Russian Imperial Geographical Society in 1869 (Kaulbars, 1875). At the beginning of the 20th century, tacheometric and terrestrial photogrammetric measurements were repeated by expeditions of the Russian Academy of Sciences (Vorob'ev, 1935; Avsyuk, 1953; Zabirov and Knijnikov, 1962). These measurements were applied only to the ablation area of the large valley glaciers in the northwestern part of Akshiirak massif. One of the present authors (V.A. Kuzmichenok), using aerial photographs, carried out the first comprehensive study of Akshiirak glacier area and volume changes between 1943 and 1977. The 1943 and 1977 glacier boundaries were transferred to intermediate 1 : 10 000 scale topographic maps by traditional stereophotogrammetry using the same set of ground-control points (GCPs) that were used to produce the 1 : 25 000 scale military topographic maps. Two

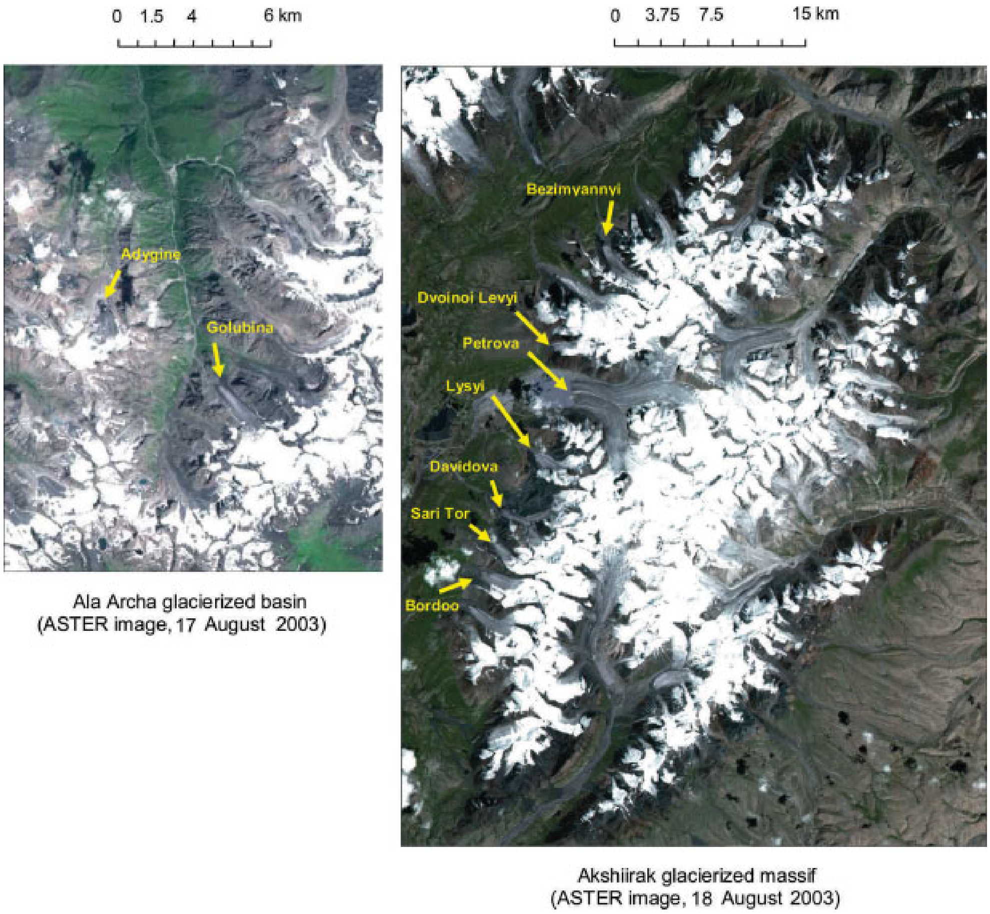

Fig. 2. ASTER images of Ala Archa basin and Akshiirak massif, 17 and 18 August 2003.

digital elevation models (DEMs) with 100 m resolution were also generated by point-by-point stereophotogrammetric measurements for estimation of surface changes. The DEM vertical accuracies of 2.8 m for 1943 and 2.7 m for 1977 were estimated by repeat measurements and comparison along map sheet boundaries (Kuzmichenok, 1985). The results were published in a 1 : 50 000 map (Kuzmichenok, 1990a, b, 1991), which contained generalized 1943 and 1977 glacier boundaries and 10 m surface change contour lines. The present positions of seven Akshiirak glacier termini were corrected using large-scale aerial photographs from 1995, acquired from AeroMap US Inc.

Table 1. Akshiirak glacier area (a), volume (b) and climatic (c) changes 1943–77–2000/03. ΔS is area change, ΔV is volume change, ΔH is thickness change, ΔT is warm-season (May–September) air-temperature change and ΔP is annual precipitation change at the Tien Shan station (3614 m) computed as annual linear trend multiplied by number of years in the time period

(a)						
	1943–2003		1943–77		1977–2003	
	ΔS (km^2)	ΔS (%)	ΔS (km^2)	ΔS (%)	ΔS (km^2)	ΔS (%)
	–53.10 ± 0.031	**–12.5**	**–17.95** ± 0.013	**–4.2**	**–35.15** ± 0.028	**–8.7**
(b)						
	1943–2000		1943–77		1977–2000	
	ΔH (m)	ΔV (km^3)	ΔH (m)	ΔV (km^3)	ΔH (m)	ΔV (km^3)
	–23.4 ± 6.0	**–9.711** ± 0.014	**–8.3** ± 3.9	**–3.6** ± 0.008	**–15.1** ± 8.2	**–6.1** ± 0.016
(c)						
	1943–2003		1943–77		1977–2003	
	ΔT (°C)	ΔP (mm)	ΔT (°C)	ΔP (mm)	ΔT (°C)	ΔP (mm)
	1.0	**–48**	**0.12**	**–15**	**0.88***	**–33**

*Statistically significant.

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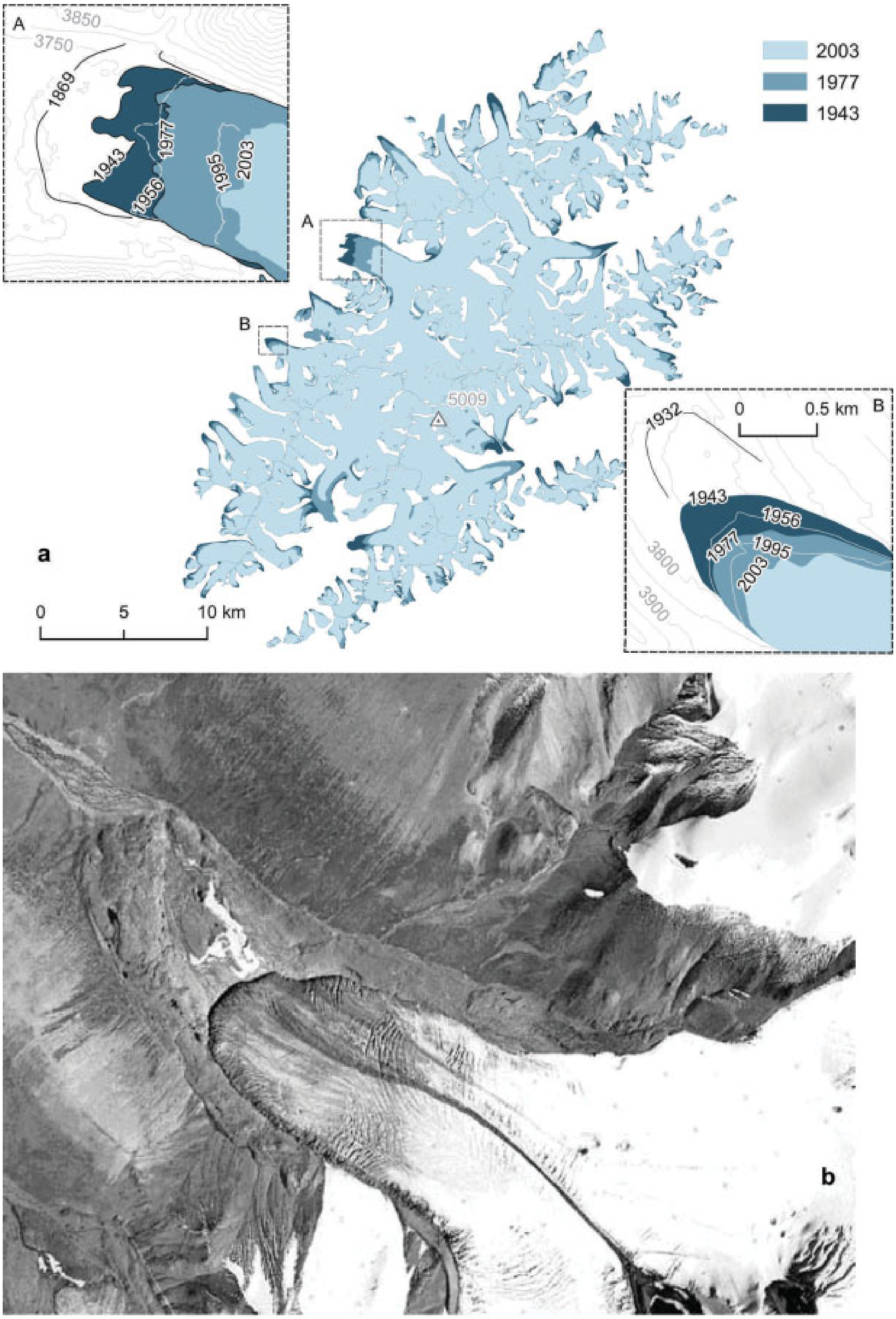

Fig. 3. (a) Akshiirak glacier area changes, 1943–2003. Inset (A) shows Petrova glacier terminus positions since 1869, and inset (B) Davidova glacier terminus positions since 1932. (b) Aerial photograph showing Davidova glacier terminus in 1977 before the glacier's surface elevation and terminus advanced in 1978.

Ala Archa

The first tacheometric surveying of the Ala Archa glaciers termini positions were conducted in the mid-19th century (Venukov, 1861). Several tacheometric surveys also took place during the 20th century (Agricultural Report, 1915; Beznosov, 1916; Korzjenewski, 1933; Visnevski, 1937; Marichek, 1950; Freifeld, 1952; Il'in, 1954; Aizen and Kalinichenko, 1979; Aizen and others, 1983). These measurements did not cover all the glaciers in the studied areas, and therefore were used only for intermediate updating of the position of some glacier boundaries. Thus, complete information about all glacier area changes in the Ala Archa basin was obtained using aerial photographs (1963, 1981) and satellite remotely sensed data for the last 40 years only. An issue of the Glacier Inventory of the USSR (Katalog Lednikov SSSR, 1973) contains information on glacier-covered areas in the Ala Archa basin, which was generated from aerial photographs of 1963. Change in glacier-covered area between 1963 and 1981 was evaluated by Aizen (1984).

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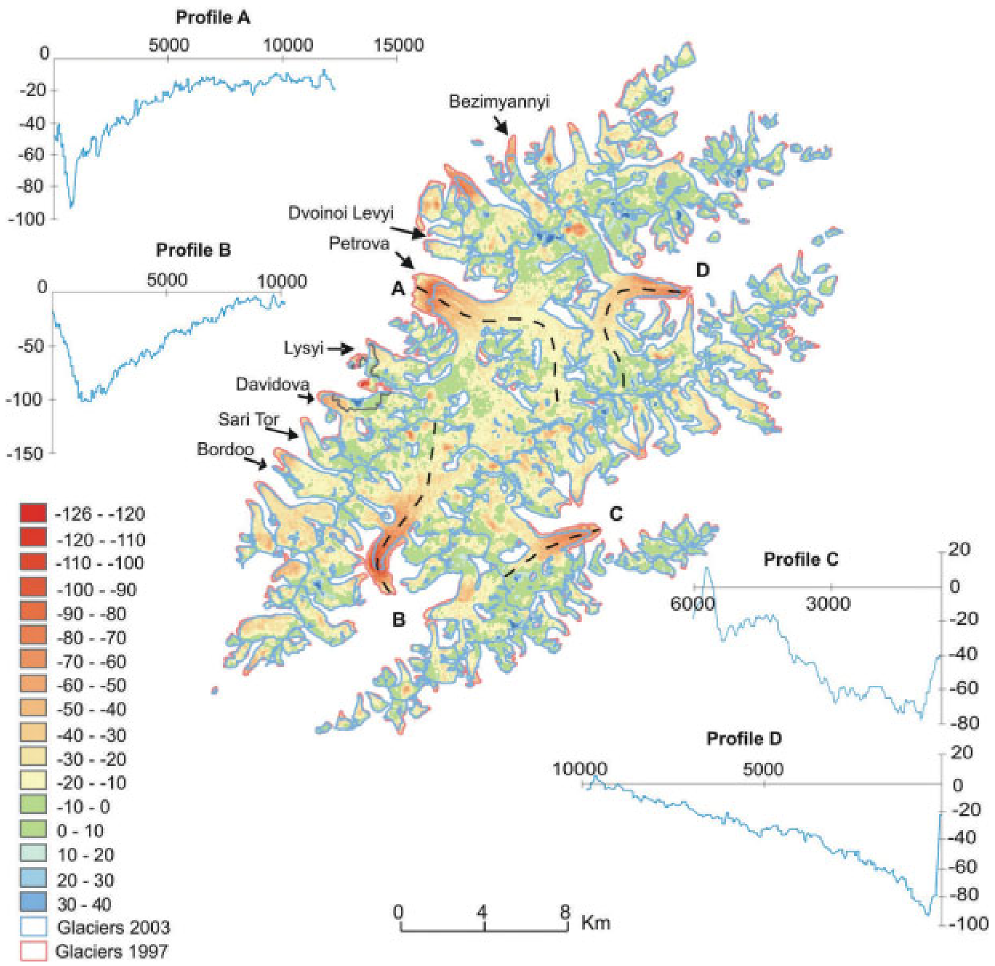

Fig. 4. Akshiirak glacierized massif surface elevation changes (m) evaluated from aerial photographs (1977) and SRTM data (2000) and terminus positions determined from aerial photographs (1977) and ASTER image (2003). A–D are longitudinal sections of the glacier surface elevation change.

Graphical renditions of the Akshiirak and Ala Archa tacheometric surveying during the period 1861–1950 were registered to 1 : 25 000 scale modern topographic maps by affine transformation using common relief features (moraines, rocks, etc.) and, in some cases, survey benchmarks determined on site. The estimated transformation accuracy is 30–40 m and up to 100 m for the earliest surveys.

Remote-sensing data and DEMs

The present glacier-covered area and the glacier boundaries in Akshiirak and Ala Archa were determined from ASTER images acquired on 17 August (Ala Archa) and 18 August (Akshiirak) 2003 (Fig. 2). Both images were clear of clouds and revealed glacier surfaces near the end of the ablation period when glacier boundaries are most visible. The raw L1A ASTER images were orthorectified with orthobase photogrammetric software. GCPs were collected from the topographic maps of 1977 (Akshiirak) and 1963 (Ala Archa) and identified on the ASTER images. The nominal vertical accuracy of the maps is 3.3 m and horizontal accuracy is 5 m. For the orthorectification, 15 m resolution DEMs were generated for Aksiirak and Ala Archa from the 30 1 : 25 000 scale topographic maps that cover all the glaciers and surrounding areas. The 10 m contour lines and spot elevations were manually digitized and processed with the ANUDEM algorithm available in the ArcGIS 9 software package. The orthorectification root-mean-square error (rmse) of the 28 GCPs of the Akshiirak ASTER image is 9 m, and for the 20 GCPs of the Ala Archa ASTER image it is 10 m. To achieve maximum accuracy for the glacier boundaries, manual digitizing on false-color composites of visible/near-infrared (VNIR) bands was used. True hardware-enabled stereo viewing with nadir 3N and backward-looking 3B bands was applied to delineate glaciers in problem areas (debris-covered termini and shadows). The accuracy of digitized 2003 glacier boundaries was confirmed by 2002 on-site GPS measurements on seven glacier termini in the Akshiirak massif.

To estimate the glacier volume changes in Akshiirak from 1977 to 2000 (Surazakov and Aizen, in press), we used an unedited version of 3 arcsec SRTM data acquired in the C-band and processed by NASA–Jet Propulsion Laboratory (JPL), USA (Rabus and others, 2003), and the 1977 DEM. For accurate comparison with the 1977 DEM, the SRTM data were transformed from the World Geodetic System 1984 (WGS84) to the 'Pulkovo' Russian 1942 datum with 2 m accuracy. Accuracy of the surface change measurements was estimated on flat depressions surrounding Akshiirak massif and glacier-free outcrops. More than 110 000 SRTM points were compared to the 1977 DEM to validate the accuracy. The standard deviation of differences is 6.3 m on slopes <25°. The glacier surface-elevation changes on steep slopes (>25°) were linearly interpolated using a triangular irregular network (TIN) with the SRTM

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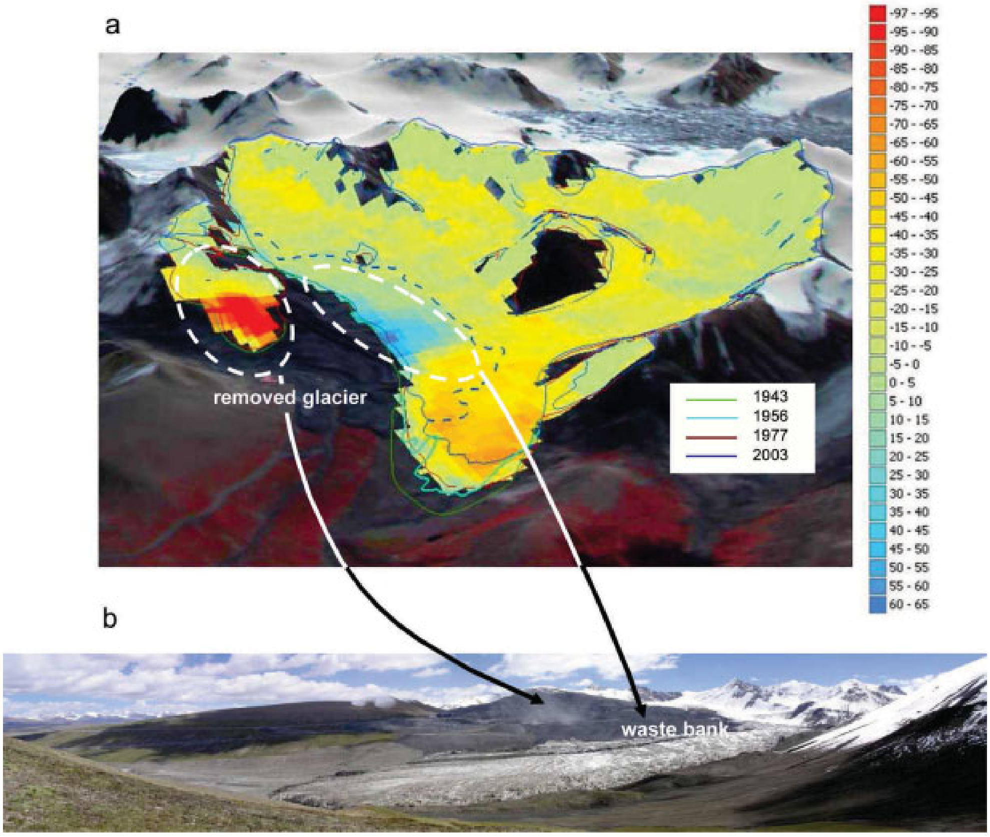

Fig. 5. Davidova glacier surface elevation changes (m) evaluated from aerial photographs (1977) and SRTM data (2000) and terminus positions determined from aerial photographs (1943, 1977), photogrammetry (1956) and ASTER image (2003). Areas shown with white dashed lines in (a) are excavated ice (red colour) and ice deposited to glacier body waste bank (blue colour).

points of flat areas and the glacier boundaries as zero change. After correction for penetration of the radar signal into snow and ice (Rignot and others, 2001), the estimated overall error of glacier surface change from 1977 to 2000 is 8.2 m. The modern rates of surface change were confirmed by comparing SRTM data with 2003 Ice, Cloud and land Elevation Satellite (ICESat) laser altimetry data (Surazakov and Aizen, in press).

4. RESULTS

Central Tien Shan (Akshiirak glacierized massif)

In 1943, Akshiirak glacier covered 424.7 km^2. From 1943 to 1977 the glacial area shrank to 406.8 km^2 (–4.2%), and it decreased to 371.6 km^2 by 2003 (–8.7%). In total, Akshiirak glaciers have lost 12.5% of their surface area from 1943 to 2003 (Table 1a). The rate of area reduction increased from 0.53 ± 0.0004 km^2 a^{-1} during the first period (1943–77) to 1.35 ± 0.001 km^2 a^{-1} during the second period (1977–2003). The rate of glacier thinning also changed from 0.24 ± 0.12 m a^{-1} to 0.69 ± 0.37 m a^{-1}. The volume of Akshiirak glaciers has been reduced 9.7 ± 0.01 km^3 since 1943 (Table 1b), which is approximately equal to 29% of initial glacier volume estimated as difference between the glacier surface elevation in 1943 and the radio-echo sounding glacier thickness measurements in 1986–87 (Kuzmichenok, 1990, 1996).

However, the glacier recession during the first period was not uniform. For example, 7 of the 178 Akshiirak glaciers advanced between 1943 and 1977 and an increase in surface elevation was observed on 32 glaciers. In the second period (1977–2003), all Akshiirak glaciers experienced recession. The four glaciers with areas <1 km^2 completely disappeared by 2003, and one glacier has been removed by Kumtor Mining Co. to access a gold-bearing lode (Figs 2–5).

We cannot represent all Akshiirak massif glacier behavior in this paper, so only a few of the 178 glaciers were selected for discussion (Table 2; Figs 2 and 3):

Bordoo glacier (1.25 km^2) advanced 270 m from 1943 to 1955 and then retreated 700 m by 2003.

Sari Tor glacier (3.05 km^2) retreated 70 m from 1932 (Kuzmichenok and Kasenov, 2002) to 1943. From 1943 to the mid-1970s this glacier was stable but it retreated 310 m from 1977 to 2003.

Davidova glacier (10.75 km^2) terminus was advancing before 1932 (Kuzmichenok and Kasenov, 2002), but by the mid-1940s it was retreating (Figs 3 and 5). The second advance of the glacier terminus was recorded in 1978 when the glacier terminus developed a 40 m high steep front edge and advanced 30 m relative to 1977, while its surface elevation increased 50 m (Fig. 3b). However, the glacier terminus did not reach the 1956 margin. From the end of the 1980s the retreat of the glacier terminus accelerated, particularly on the right side of the tongue (down-ice view), and by 2000 the surface elevation of the glacier tongue had decreased 70 m. By the mid-1990s, the right side of the glacier terminus had been buried under a bank of waste from the

Table 2. Termini changes of seven Akshiirak glaciers

Period	Length change Total m	Length change Annual $m\,a^{-1}$	Notes
Bordoo glacier			
1943–55	+270	+22	On central axial line
1955–77	–190	–9	On central axial line
1977–2003	–510	–20	On central axial line
Sari Tor glacier			
1932–43	–70	–6	Only the left part; right part is unchanged
1943–57	0	0	Within limit of accuracy of topographic surveys
1957–77	0	0	Within limit of accuracy of topographic surveys
1977–95	–220	–12	On central axial line
1995–2003	–90	–13	On central axial line
Davidova glacier			
1932–43	–540	–49	Left part
	–600	–55	Right part
1943–55	–280	–23	On central axial line with drift to left part
1955–77	–110	–5	On central axial line with drift to left part
1977–95	–90	–5	Left part
	–390	–22	Right part
1995–2003	–170	–24	Left part
	–160	–23	Right part
Lysyi glacier			
1932–43	–120	–11	Uniform recession
1943–77	–310	–9	Uniform recession
1977–95	–190	–11	Uniform recession
1995–2003	–70	–10	Uniform recession
Petrova glacier			
1869–1943	–700	–9	On central axial line
1943–56	–550	–42	On central axial line
1956–77	–400	–19	On central axial line
1977–95	–720	–40	On central axial line
1995–2003	–290	–41	On central axial line
Dvoinoi Levyi glacier			
1943–77	–220	–6	Average value
1977–2003	–160	–6	Average value
Bezymyannyi glacier			
1932–43	–20	–2	On central axial line
1943–56	+340	+26	On central axial line
1956–77	–170	–8	On central axial line
1977–2003	–150	–6	On central axial line

gold mining identified by SRTM data as an increase in surface elevation (Fig. 5).

Lysyi glacier (4.17 km^2) has retreated 690 m during the past 70 years, and the average surface elevation lowered 32 m from 1943 to 2000. The surface of this glacier has also been covered by a bank of waste from the gold mining and by blocks of ice that were removed from a hanging glacier to accommodate gold mining.

Petrova glacier (65.33 km^2) is one of the largest glaciers in the Akshiirak massif, and its glacier terminus descends to its moraine lake. From 1869 to 2003, this glacier gradually retreated >2.5 km, and the surface of the glacier terminus has lowered >100 m. The average surface elevation lowered 19.3 m from 1943 to 2000.

Dvoinoi-Levyi glacier (2.1 km^2) receded 380 m from 1943 to 2003, separating from Petrova glacier, and the average surface elevation lowered 24.1 m from 1943 to 2000.

Bezimyanniy glacier (4.83 km^2) has exhibited some surging behavior. The glacier terminus stagnated before 1940, and by the mid-1950s it had advanced 340 m. Since then it has receded. By 2003 the elevation of the middle part of the glacier terminus had risen 35 m, although the elevation of the area above this point decreased 40–45 m (Fig. 4).

Northern Tien Shan (Ala Archa glacierized basin)

From the mid-19th century to the beginning of the 20th century, the termini of the Ala Archa glaciers retreated 1.0 km on average from <2800 m a.s.l. to 3100 m a.s.l. (Venukov, 1861; Langwagen, 1908). They then stagnated approximately at the same level until 1910–15 (Agricultural Report, 1915; Korzjenewski, 1933). However, these results were based on information for large glaciers. According to the tacheometric surveying (Visnevski, 1937; Marichek, 1950; Freifeld, 1952), from 1915 to the end of the 1940s the glaciers retreated another 0.5 km, reaching 3200 m a.s.l. Comparing these data with the aerial photographs of 1963, we found that Ala Archa glacier margins were stationary during this period. In 1963, Ala Archa glaciers covered 42.83 km^2. By 1981, the glacier area had shrunk to 40.62 km^2 (5.2% from 1963) and glacier termini had retreated to 3500 m a.s.l. By 2003, the glaciers had lost another 10.6% of their area, shrinking to 36.31 km^2 (Table 3; Fig. 6). Table 4 presents the recession of the terminus of Golubina glacier, the largest glacier in the Ala Archa basin, from 1861 to 2003.

Golubina glacier (5.8 km^2) occupied an altitudinal range of 3300–4400 m a.s.l. (2003) and has a north-northwest orientation (Figs 6 and 7). In 1861, the Golubina glacier terminus lay in a deep canyon at 2900 m a.s.l. (Venukov, 1861). From 1861 until 1913, the glacier terminus retreated to 3050 m a.s.l. In 1949, the glacier terminus was at 3150 m a.s.l and by 1963 it reached 3250 m a.s.l. Between 1958 and 1982, when glaciological observations and tachymetric surveys on Golubina glacier were conducted on a regular basis, small annual oscillations of the terminus position up to 80 m occurred, and growth of the glacier surface elevations of 25–40 m occurred along the central axial line (1971, 1974, 1976) (Aizen and others, 1983). From 1958 to 1972, the Golubina glacier mass balance was positive (Aizen, 1988b), but since 1973 its mass balance has been predominantly negative (Aizen and others, 1983, 1988a, b). Consequently, the glacier began to retreat more rapidly, and from 1981 to 2003 it retreated 260 m and thinned 25–30 m on average along the longitudinal section, while glacier area shrank 0.2 km^2.

Thus, from 1861 to 2003, glaciers in the Ala Archa basin retreated 1.5 km on average. In the last 40 years from 1963 to 2003, the total Ala Archa glacier-covered area shrank 6.52 km^2, or 15.2%. From 1963 to 1981, nine small glaciers <1 km^2 in area totally disappeared (Aizen, 1984).

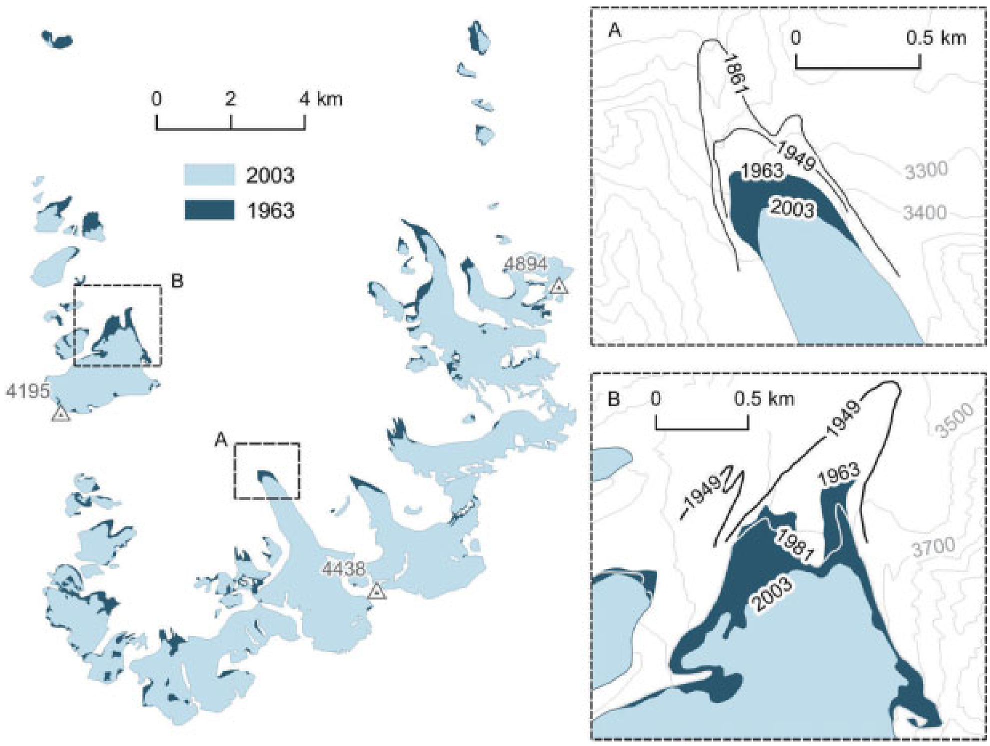

Fig. 6. Ala Archa glacier area changes, 1963–2003. Inset (A) shows Golubina glacier terminus positions since 1861, and inset (B) Adigine glacier termini positions since 1949.

5. DISCUSSION

Our research presents a long-term (about 140 years) estimation of the northern and central Tien Shan glacier changes based on a complex of geodetic ground surveys and remote-sensing data, which quantified the spatial and temporal regime of the glaciers (Tables 1–4). There has been a definite trend of glacier recession over the last 140 years and especially since the mid-1970s, which indicates an abrupt climate-change effect. The Tien Shan, located in the center of the large Eurasian continent, have spring–summer precipitation maxima, which preserve glaciers from intensive melt during the ablation period by increasing the glaciers' surface albedo. At the same time, the main factor controlling the glacier regime is the impact of air temperature which affects the type of precipitation, the duration and the intensity of snow and ice melt throughout altitudinal belts. The modern increase of air temperature, which is also observed in the Tien Shan's alpine areas, extends the period and intensity of melt and the glacier recession (Aizen and others, 1997).

Analysis of data from the station located closest to the Ala Archa glaciers shows no significant trends in observed annual precipitation or warm-season (May–September) temperature for the period 1913–2000 or 1963–2000 at Baitik station (1580 m a.s.l.), Ala Archa basin (Fig. 8a). However, a significant negative trend in annual precipitation is observed during the period 1963–81 (29% of average), while air temperature significantly increased during the 20 year period 1981–2000 (0.93°C) (Fig. 8a; Table 3), which extends the period of glacier ablation and consequently accelerates glacier recession (Fig. 8c; Table 4).

Analysis of data from the station located closest to the Akshiirak glaciers shows there is no significant trend in annual precipitation in the central Tien Shan for the last 60 years (1943–2003) of instrumental observations (Tien Shan station (3614 m a.s.l.)) (Fig. 8b). However, warm-season air temperature increased by 1.0°C for the same period (Table 1). The increase in air temperature, especially observable since the 1970s, accelerated the recession of the Tien Shan glaciers (Fig. 8b; Table 1).

Table 3. Ala Archa glacier area changes: change of area, rmse and relative change of area. ΔP is annual precipitation change, and ΔT is warm-season (May–September) air-temperature change at the Baitik station (1580 m) computed as annual linear trend multiplied by number of years in the time period

1963–2003			1963–81: $\Delta P_{63-81} = -138$ mm*				1981–2003: $\Delta T_{81-2000} = 0.93$°C*				
Area change km^2	rmse	% area change	Area in 1963 km^2	Area change km^2	rmse	% area change	Area in 1981 km^2	Area change km^2	rmse	% area change	Area in 2003 km^2
–6.52	0.027	–15.22	**42.83**	–2.21	0.029	–5.16	**40.62**	–4.31	0.025	–10.61	**36.31**

*Statistically significant changes.

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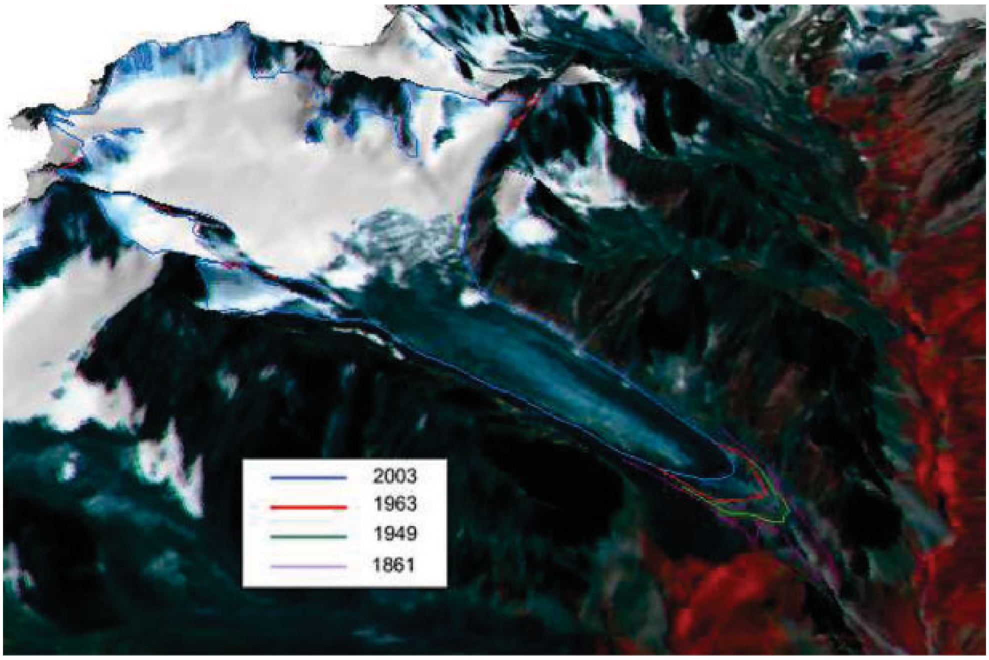

Fig. 7. Golubina glacier surface elevation (1963–2000) and terminus position (1861–2003) changes determined from aerial photographs, 2003 ASTER image and 2000 SRTM data.

Our results, showing a decrease of 8.6% in the Akshiirak glacier area from 1977 to 2003, are in accordance with Liu and others (2006) and Narama and others (2006) who estimated the glacier recession in the northern and eastern Tien Shan between 1970 and 2004. However, our results do not correspond with the –23% estimate by Khromova and others (2003), particularly for the Akshiirak glacier area for the same period. We suppose that several methodological issues may contribute to the discrepancy in the results: (1) Khromova and others (2003) used a map developed by Kuzmichenok (1990a, b) to estimate glacier area changes from 1977 to 2001. However, the 1990 map (Kuzmichenok, 1990a, b) cannot be used for such analysis due to restrictions on large-scale thematic maps published for civilian use in the former USSR: there is no coordinate information on the map, and accurate georegistration is not possible. Also, during compilation of the 1 : 50 000 map from original 1 : 10 000 maps, significant non-systematic horizontal errors were introduced across the map. (2) Manual delineation of glaciers is subject to personal judgment as mentioned by Khromova and others (2003) concerning 'thin ice and snow patches'. To minimize this type of error, in our study the same person, one of the authors, interpreted the 1943, 1977 and 2003 data. (3) In the ASTER image used in Khromova and others' (2003) estimation, glaciers are almost completely covered by fresh snow, which complicates glacier boundary identification. (4) There was no assessment of the glacier area covered by debris. The six large Akshiirak glaciers have significant debris cover (around 1 km^2 in total) that we identified on large-scale aerial photographs of 1943 and 1977, and by stereo viewing of 3N and 3B bands of the ASTER image of 2003.

Table 4. Changes of the terminus position of Golubina glacier. dT and dP are warm-season air-temperature and annual precipitation deviations for the considered period from long-term mean ($T_{1913-2000} = 15°C$; $P_{1913-2000} = 549$ mm) at the Baitik station (1580 m)

Period	Length change Total	Annual	Notes	dT	dP
	m	m a^{-1}		°C	mm
1861–1913	–620	–12	On central axial line		
1913–49	–280	–8	On central axial line	0.1	–30
1949–58	–180	–20	On central axial line	–0.2	8
1958–59	+2.6	+1.3	On central axial line	–0.8	96
1959–63	–24.9	–6.2	On central axial line	0	1
1963–76	+80.4	+6.2	On central axial line with drift to left part	0	30
1976–78	–36.4	–18.2	On central axial line with drift to left part	0.9	–23
1978–81	+2.7	+0.9	On central axial line with drift to left part	–0.1	–13
1981–2003	–260	–11.8	On central axial line	0.1	1

6. CONCLUSION

By using ground measurements and remote-sensing data, we have determined that continuous glacial recession has occurred over the last 140 years in the Ala Archa and Akshiirak glacial regions of the Tien Shan. The glaciers retreated up to 3 km between the 1860s and 2003, the surface of their ablation areas lowered >100 m, and the glacier area shrank by 15.2% in the Ala Archa over the last 40 years. The Akshiirak glacierized massif lost about 10 km^3 of glacier ice between 1943 and 2000. However, the overall trend of glacier recession is variable. On a broader view, the fact that most of the Tien Shan glaciers have thinned over the study period does support the observation that, in general, glacial retreat accelerated from the mid-1970s to the present. The rate of glacier recession is about 3% higher in the northern peripheral Tien Shan ranges than in the central

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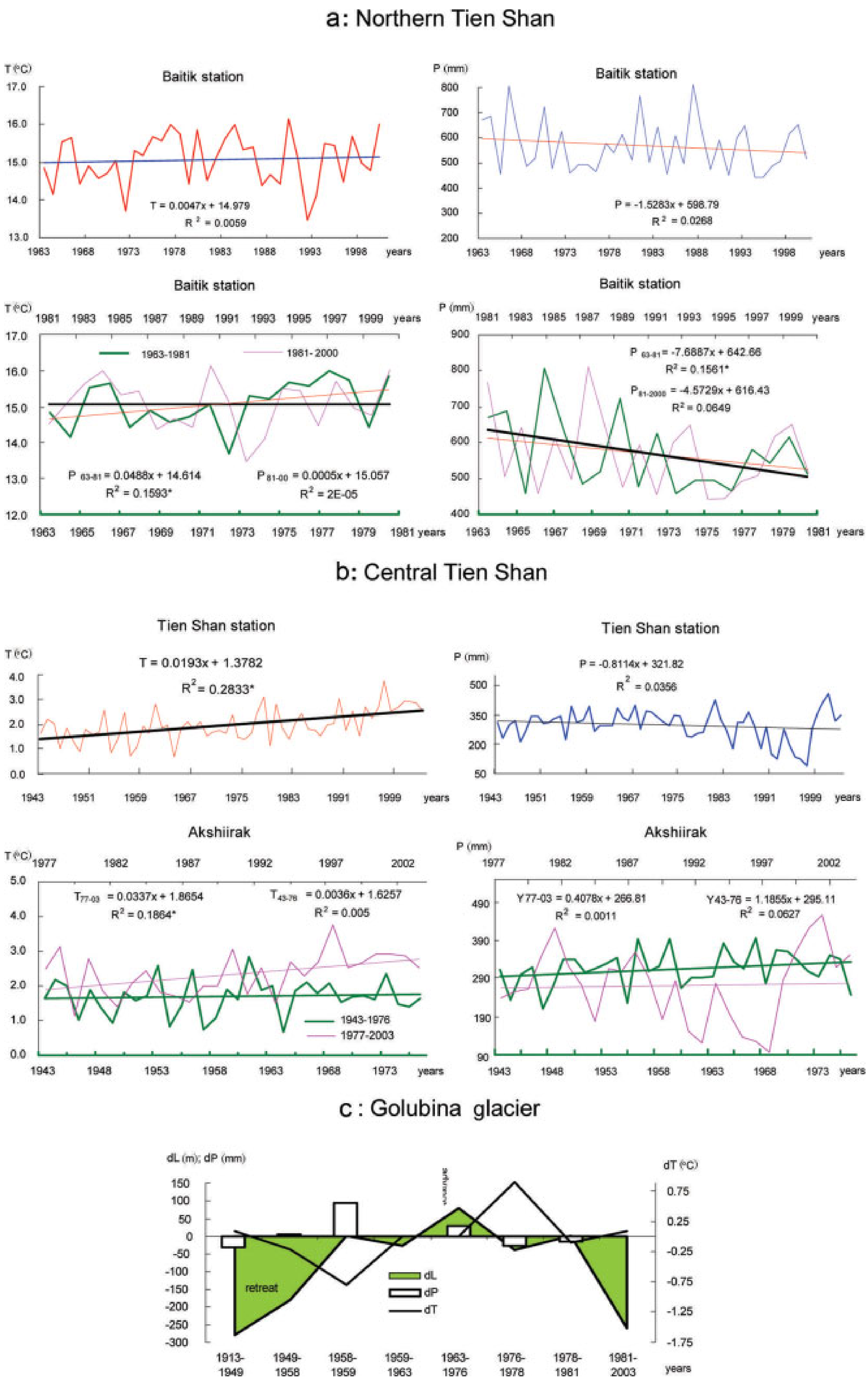

Fig. 8. (a, b) Annual precipitation amount (hydrological year: September–August) and mean warm-season air temperature (May–September) at the Tien Shan meteorological stations: (a) Baitik station (1580 m a.s.l.), Ala Archa basin; (b) Tien Shan station (3614 m a.s.l.), Akshiirak massif. (c) Changes of the terminus position of Golubina glacier (d*L* (m)) and warm-season air temperature (d*T* (°C)) and annual precipitation (d*P* (mm)) deviations for the considered period from long-term mean ($T_{1913–2000} = 15$°C; $P_{1913–2000} = 549$ mm) at the Baitik station.

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Tien Shan, which may be explained by severe continental climate and exclusively summer maximum precipitation in the central Tien Shan, while maximum precipitation in the northern Tien Shan is in spring and the first month of summer. Hence, continuous increase of warm-season air temperatures in the northern and central Tien Shan since the mid-1970s without increase of precipitation may further accelerate glacier recession and intensify desertification processes in central Asia and northwestern China.

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REFERENCES

Agrawala, S., M. Barlow, H. Cullen and B. Lyon. 2001. *The drought and humanitarian crisis in central and southwest Asia: a climate perspective*. Palisades, NY, Columbia University. International Research Institute for Climate Prediction. (IRI Special Report 01-11.)

Agricultural Report. 1915. *Selskohozyaistvennii obzor vodnih resursov Semerechenskoi oblasti na 1914 god [Agricultural survey of water resources of Semerechensk's county in 1914]*. Verniy, Vestnik of Irrigation No. 5), 96–198.

Aizen, V.B. 1984. Sovremennoe oledenenie baseina reki Ala Archi [The modern glaciation of the Ala-Archa river basin]. *Trudi Central'no-AsiatsKogo Regional'nogo Naucho-Issledovatel'skogo Instituta [Works of Central Asian Regional Institute of Science Investigations]*, **105**(186), 111–119.

Aizen, V.B. 1988a. Oledenenie iego evoluyciya na sevemoi peripherii Tien Shanya [Glaciation and its evolution at northern Tien Shan's peripheral ranges]. (PhD thesis, Russian Academy of Science.)

Aizen, V.B. 1988b. Reconstruktiya balansa massy lednika Golubina [Golubin glacier mass balance reconstruction]. *Mater. Glyatsiol. Issled.* 62, 119–126.

Aizen, V.B. 2003. Physical geography of central Asia. *In* Carpenter, C., *ed. The world and its peoples*. London, Brown Reference Group, 41–56.

Aizen, V.B. and G.V. Kalinichenko. 1979. Takheometricheskie izmereniya Ak-Sai, Adigine, Top Karagai, Tyuk, Golubima i Verchne Alarchinskogo lednikov (Basein Ala Archie, Kyrgyz Algtoo) *[Tacheometric measurements of the Ak-Sai, Adigine, Topkaragai, Tyuk, Golubina and Verhnie Ala Archinskie glaciers (Ala Archa Basin, Kyrgyz Alatoo)]*. Bishkek, Kyrgyz Hydrometeorological Agency.

Aizen, V.B., N.V. Maksimov and P.A. Solodov. 1983. Dynamiea lednika Grolubina za poslednie 20 let [Dynamic of the Golubina Glacier for the 20 last years]. *Trudi Central'no-Asiatskogo Regional'nogo Naucho-Issledovatel'skogo Instituta* [Works of Central Asian Regional Institute of Science Investigations, Tashkent], **91**(172).

Aizen, V.B., E.M. Aizen, J.M. Melack and J. Dozier. 1997. Climatic and hydrological change in the Tien Shan, central Asia. *J. Climate,* **10**(6), 1393–1404.

Aizen, V.B., E.M. Aizen, G.E. Glazirin and H.A. Loaiciga. 2000. Simulation of daily runoff in Central Asian alpine watersheds. *J. Hydrol.* **186**, 229–251.

Aizen, V.B., E.M. Aizen and V.A. Kuzmichenok. In press. Simulation and stochastic forecasting of water cycle components in Central Asian alpine basins. *J. Global Environ. Change.*

Avsyuk, G.A. 1953. Lednik Petrova [Petrova Glacier]. *Trudi Instituta Geographii AN SSSR: Raboti Tien Shanskoi phisiko-geographicheskoi stancii [Issues of Institute of Geography of USSR Academy of Science Works of Tien Shan physical-geographical station]* 2a, 103–131.

Beznosov, A. Iv. 1916. *O rezultatah rabot Semirechenskoi pochvenno-botanicheskoi ekspedicii [About the results of investigations from Semirechensk's soil-botanical expedition]*. St Petersburg, Russian Geographical Society. (Technical report No. 278.)

Bishop, M.P. *and 16 others*. 2004. Global land ice measurements from space (GLIMS): remote sensing and GIS investigations of the Earth's cryosphere. *Geocarto Int.,* **19**(2), 57–84.

Denisov, Y.M., N.A. Agaltseva and A.V. Pak. 2000. Avtomaticheskii metod dolgovremennogo prognoza gornogo rechnogo stoka v Srednei Azii *[Automated methods of long-term forecasting of mountain rivers run-off in Central Asia]*. Tashkent, Trudi Sredne-Asiatskoga Nauchno Issledovatel'skogo Instituta.

Freifeld, V.Y. 1952. Lednik Pastuhova v Kyrgyzskom Hrebte [Pastukhov Glacier at the Kyrgyz Range]. *In Pobejdennie vershini [The bitten peaks. Almanac of Soviet Alpinism]*. Moscow, Geographgiz, 52–60.

Glantz, M.H., *ed.* 1999. *Creeping environmental problems and sustainable development in the Aral Sea basin*. Cambridge, etc., Cambridge University Press.

Glazirin, G.E. 1996. The reaction of glaciers in western Tien Shan to climate change. *Z. Gletscherkd. Glazialgeol.,* **32**, 33–39.

Haeberli, W., J. Cihlar and R.G. Barry. 2000. Glacier monitoring within the Global Climate Observing System. *Ann. Glaciol.,* **31**, 241–246.

Il'in, I.A. 1954. Istochniki pitaniya I uslovii stoka stoka r. Ala Archa [Source of nourishments and regime of Ala Archa river runoff]. *Trudi Tashkentskoi geophizicheskoi observatorii,* **10**(11), 153–162.

Katalog Lednikov SSSR [Glacier Inventory of the USSR]. 1973. *Centralnaya Aziaya [Central Asia], Tom 14, Vol. 2, Kyrgyzstan, Part 2*. Leningrad, Hydrometeoizdat.

Kaulbars, A.V. 1875. Materiali po geographii Tien Shanya sobrannie vo vremya puteshestviya [Data on Tien Shan geography collected during the journey]. *Proc. Russ. Geogr. Soc.,* **5**, 253–539.

Khromova, T.E., M.B. Dyurgerov and R.G. Barry. 2003. Late-twentieth century changes in glacier extent in the Ak-shirak Range, Central Asia, determined from historical data and ASTER imagery. *Geophys. Res. Lett.,* **30**(16), 1863. (10.1029/2003GL017233.)

Korzjenewski, N.L. 1933. Nekotorie rezul'tati phisiko-geographischeskih nabludenii v srednei chasti Aleksandrovskogo hrebta [Results of physical geographical observation at the middle part of Aleksndrovskiy range]. *Materiali po gidrologii Uzbekistana,* **15**, 67–79.

Kuzmichenok, V.A. 1985. Opredelenie tochnosti sozdanija zifrovoi modeli vysokogornogo rel'efa stereofotogrametricheskim sposobom [Determination of accuracy of digital model for the high altitudinal relief via Stereophotogrammetry]. *In Sbornik nauchnih trudov NII prkladnoy geodezii [Scientific researches of the Applied Geodesy Institution]*, 52–57.

Kuzmichenok, V. A. 1990a. *Izmenenie lednikov hrebta Akshiirak c 1943 po 1977 godi [The Akshiirak glaciers changes from 1943 to 1977].* (Scale 1 : 50,000.) Moscow, Main Department of Geodesy and Cartography of the USSR.

Kuzmichenok, V.A. 1990b. Topographicheskaya s'emka rel'efa lozha lednikov radiolokacionnim metodom [Method of the glaciers surface and bedrock topography measuremnts by radio-echo sounding]. *Geodesiya i Kartogrphiya,* **11**, 18–23.

Kuzmichenok, V.A. 1991. Fluctuations of glaciers of the Ak-Shyirak ridge from 1943 to 1977. *IAHS Publ.* 208 (Symposium at St Petersburg 1990 – *Glaciers–Ocean–Atmosphere Interactions*), 507–513.

Kuzmichenok, V.A. 1996. O statisticheskoy ocenke ob'ema lednikov [Statisticla estimation of glacier volumes]. *Mater. Glyatsiol. Issled.* 80, 200–205.

Kuzmichenok, V.A. and D.R. Kasenov. 2002. *Izmeneiya nijnih granic lednikov v raione mestorojdeniya Kumtor po rezultatam instrumental'nih opredelenii v XIX, XX, XXI vekah* [Changes of the lowest glacier extensions in the Kumtor region based on instrumental measurements in XIX, XX and XXI centuries]. Bishkek, Kyrgyz National Academy of Science and 'Kumtop' Operating Company. Institute of Water Problem and Hydropower.

Langwagen, V.V. 1908. Ledniki hrebtov Aleksandrovskogo, Sailiiskogo i Kungei Alatau [Glaciers on the Alexandrovskiy, Sailiiskiy and Kumgei Alatau]. *Izv. Rus. Geograf. Obshch.,* **43**, 43–132.

Liu, S. *and 7 others*. 2006. Glacier retreat as a result of climate warming and increased precipitation in the Tarim river basin, northwest China. *Ann. Glaciol.,* **43** (see paper in this volume).

Marichek, B.R. 1950. V Kyrgyzskom Alatau [In Kyrgyz Alatau]. *In Pobejdennie vershini [Almanac of the Soviet Alpinism]*. Moscow, Geographgiz, 68–81.

Narama, C., Y. Shimamura, D. Nakayama and K. Abdrakhmatov. 2006. Recent changes of glacier coverage in the Terskey-Alatoo range, Kyrgyz Republic, using Corona and Landsat. *Ann. Glaciol.,* **43** (see paper in this volume).

Paul, F., A. Kääb, M. Maisch, T. Kellenberger and W. Haeberli. 2004. Rapid disintegration of Alpine glaciers observed with satellite data. *Geophys. Res. Lett.,* **31**(21), L21402. (10.1029/2004GL020816.)

Rabus, B., M. Eineder, A. Roth and R. Bamler. 2003. The shuttle radar topography mission: a new class of digital elevation models acquired by spaceborne radar. *ISPRS J. Photogramm. Rem. Sens.,* **57**(4), 241–262.

Rignot, E., K. Echelmeyer and W. Krabill. 2001. Penetration depth of interferometric synthetic-aperture radar signals in snow and ice. *Geophys. Res. Lett.,* **28**(18), 3501–3504.

Sarsembekov, T.T. 2000. Vodi and potoki: Kratkii obzor nekotorih problem vodnih resursov, navodnenii i irrigacii [Water and flood security: a brief review of some water problems of water resources, flood production and irrigation]. *In Integracionnoe vodnimi resursami* [An integrated management of water resources]. Tashkent, Tashkent Institute of Irrigation and Melioration.

Surazakov, A.B. and V.B. Aizen. In press. Estimating volume change of mountain glaciers using SRTM and topographic data. *ISPRS J. Photogramm. Rem. Sens.*

Venukov, M.I. 1861. Ocherki Zailiiskogo kraya i Prichuiskoi strain [Essays of Zailiiski region and Prichuiskii country]. *Izv. Russ. Geograf. Obshch., Rossiiskaya Akademiya Nauk,* **4**, 35–61.

Visnevski, Y.S. 1937. Lednik Golubina v Kyrgyzskom hrebte [Golubria Glacier in Kyrgiz range]. *Trudi Uzbekskoi GO,* **1**, 94–102.

Vorob'ev, S.P. 1935. Atlas lednikov Narino-Chantengrinskoi expedicii, Tien Shan, Verhov'e Bol'shogo Narina [Atlas of glaciers from the Nari-Chantihrinsk's expedition]. *Trudi lednikovih expedicii,* **2**, 187–188.

Zabirov, R.D. and U.F. Knijnikov. 1962. *Phototeodolitnaya s'emka lednikov Tien Shanya v period MGG [Photogrammetry survey of the Tien Shan glaciers during IGY].* Frunze, AN Kyrgyzskoi SSR Publisher.