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Glacier retreat and climatic variability in the eastern Terskey–Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century

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ABSTRACT

Changes in the extent of glaciers and rates of glacier termini retreat in the eastern Terskey–Alatoo Range, the Tien Shan Mountains, Central Asia have been evaluated using the remote sensing techniques. Changes in the extent of 335 glaciers between the end of the Little Ice Age (LIA; mid-19th century), 1990 and 2003 have been estimated through the delineation of glacier outlines and the LIA moraine positions on the Landsat TM and ASTER imagery for 1990 and 2003 respectively. By 2003, the glacier surface area had decreased by 19% of the LIA value, which constitutes a 76 km^2 reduction in glacier surface area. Mapping of 109 glaciers using the 1965 1:25,000 maps revealed that glacier surface area decreased by 12.6% of the 1965 value between 1965 and 2003. Detailed mapping of 10 glaciers using historical maps and aerial photographs from the 1943–1977 period, has enabled glacier extent variations over the 20th century to be identified with a higher temporal resolution. Glacial retreat was slow in the early 20th century but increased considerably between 1943 and 1956 and then again after 1977. The post-1990 period has been marked by the most rapid glacier retreat since the end of the LIA. The observed changes in the extent of glaciers are in line with the observed climatic warming. The regional weather stations have revealed a strong climatic warming during the ablation season since the 1950s at a rate of 0.02–0.03 °C a^{-1}. At the higher elevations in the study area represented by the Tien Shan meteorological station, the summer warming was accompanied by negative anomalies in annual precipitation in the 1990s enhancing glacier retreat. However, trends in precipitation in the post-1997 period cannot be evaluated due to the change in observational practices at this station. Neither station in the study area exhibits significant long-term trends in precipitation.

1. Introduction

Changes in the extent of glaciers are among the best natural indicators of climatic change (Haeberli, 2005; Kääb et al., 2007; Solomon et al., 2007). The historical records of such changes go further back in time than those of the other indicators of glacier response to climate change, e.g. mass balance and ice volume measurements. While mass balance measurements encompass about the last 70–50 years, the historical maps of glaciers and positions of glacier tongues date back to the mid-19th century allowing one to place the currently observed change into a more extensive historical context. Changes in position of glacier termini and surface area are often (although not always as in the case of debris-covered glaciers) relatively well defined and can be measured using remote sensing techniques (Kääb et al., 2002; Paul et al., 2002). Recent assessments have shown that glaciers are retreating in most regions, from polar to tropical, and that the observed retreat is accelerating (Barry, 2006). However, the majority of these assessments focus on the European Alps, Scandinavia, and North America (Barry, 2006) while other regions are discussed in a less detail.

The Tien Shan Mountains (approximately 40°–45° N; 67°–95° E) are among the main glaciated regions of Eurasia. According to the Catalogue of Glaciers of the USSR and the Glacier Inventory of China, compiled using data from the 1950s–1970s, there were just under 16,000 glaciers in the Tien Shan occupying about 15,400 km^2 at the time (Katalog Lednikov SSSR, 1967–1982; Glacier Inventory of China, 1987). The foothills are densely populated and with mean annual precipitation of 200–600 mm, local, predominantly agricultural economies rely on the glacier-fed rivers for irrigation. In the foothills, glacier nourishment contributes at least 30% to the total river discharge (Dikich, 1982) and an accurate estimation of glacier retreat is important in terms of water resources prediction and planning (e.g. Hagg et al., 2007). In spite of the importance of the state of glaciers for regional economies, regular glacier mass balance and other ground-based glaciological measurements were discontinued both in the Tien Shan and the neighbouring Pamir Mountains in the 1990s. This has encouraged assessments using remote sensing techniques. Two points emerge from the previous studies: (i) glaciers in the Tien Shan and Pamir are retreating and (ii) the rates of retreat vary between regions and time periods as illustrated by Table 1. The largest retreat rates have been observed in the northern Tien Shan

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Table 1
Results of assessments of glacier recession in Central Asia.

Region	Period	Number/area of investigated glaciers	Surface area reduction (%)	Reference
Northern Tien Shan				
Ala Archa	1963–2003	48/36.31 km^2 in 2003	15.2	Aizen et al. (2006)
	1963–1981	48/36.31 km^2 in 2003	5.2	
	1981–2003	48/36.31 km^2 in 2003	10.6	
Ili river basin	1955–2004	−/170.04 km^2 in 2004	38	Vilesov et al. (2006)
Malaja Almatinka	1955–1999	12/9.1 km^2 in 1955	37.6	Bolch (2007)
Bolshaja Almatinka	1955–1999	29/25.2 km^2 in 1955	34.5	
Levyj Talgar	1955–1999	42/72.3 km^2 in 1955	33.1	
Turgen	1955–1999	30/35.6 km^2 in 1955	36.5	
Upper Chon-Kemin	1955–1999	31/38.5 km^2 in 1955	16.4	
Chon-Aksu	1955–1999	48/62.8 km^2 in 1955	38.2	
Northern slopes of Zailiysky Alatau	1955–1990	307/287.3 km^2 in 1955	29.2	Vilesov and Uvarov (2001)
Tuyksu glaciers	1958–1998	7/7.74 km^2 in 1998	20.2	Hagg et al. (2005)
Sokoluk basin	1963–2000	77/31.7 km^2 in 1963	28	Niederer et al. (2007)
Central and Inner Tien Shan				
Akshiirak	1943–1977	178/317.6 km^2 in 2003	4.2	Kuzmichenok, 1989; Aizen et al., 2006
	1977–2003	178/317.6 km^2 in 2003	8.7	
Western Terskey Ala-Too	1971–2002	269/226 km^2 in 2002	8	Narama et al. (2006)
Eastern Terskey Ala-Too	LIA-2003	335/ 328 km^2 in 2003	19	This study
	1965–2003	109/120 km^2 in 1965	12.6	
	1990–2003	335/328 km^2 in 2003	4	
Eastern Tian Shan				
No. 1 Glacier (China)	1962–2003	1/1.72 km^2 in 2003	11.8	Jing et al. (2006)
Middle Chinese Tien Shan	1963–2000	70/48 km^2 in 2000	13	Li et al. (2006)
Pamir				
Gissaro-Alay	1957–1980	4287/2183 km^2 in 1957	15.6	Shchetinnikov (1998)
Pamir	1957–1980	7071/7361 km^2 in 1957	10.5	
Pamiro-Alay	1957–1980	11358/9545 km^2 1957	12.5	
The Saukdara and Zulumart Ranges	1978–1990	5/33.7 km^2 in 2001	7.8	Khromova et al. (2006)
(eastern part of the Pamir)	1990–2001	5/33.7 km^2 in 2001	11.6	
Muztag Ata and Konggur mountains of the eastern Pamir plateau	1962/66–1999	302/835 km^2 in 1962/66	7.9	Shangguan et al. (2006)
Muksu river basin	1980–2000	−/468.4 km^2 in 1980	7.4	Desinov and Konovalov (2007)
Djungarsky Alatau				
South Dzhungaria	1956–1990	440/218.8 km^2 in 1956	40	Vilesov and Morozova (2005)

where glaciated area has declined by 30–40% during the second half of the 20th century (Table 1). The rates of deglaciation were slower further east and south, however, acceleration of glacier retreat has been noted in the eastern Pamir by Khromova et al. (2006) from 7.8% to 11.6% over the 1978–1990 and 1990–2001 periods respectively.

The importance of glaciers for regional water resources and the lack of homogeneity in the rates of glacier retreat necessitate further assessments of glacier behavior in the mountains of Central Asia. This study presents the most comprehensive assessment of fluctuations in the extent of glaciers over the past 150 years in the eastern Terskey–Alatoo Range and the neighbouring glaciated massifs in the inner Tien Shan (Figs. 1 and 2). Changes in the extent of 335 glaciers (Fig. 2) have been assessed using the remote sensing techniques and related to the observed changes in regional climate. The study addresses the following research questions:

(i) How has the glaciated area changed since the end of the Little Ice Age (LIA) and more recently in the 20th–21st centuries?
(ii) How have glaciers of different size, type, and aspect changed?
(iii) How has climate of the area changed during the period of instrumental records?
(iv) How are the observed climatic and glacier changes linked?

2. Research area

The study area is located mainly (~80%) in the eastern Terskey–Alatoo and also in the neighbouring Djetimbel and Suek Ridges and in the western part of the Koilu Ridge (Figs. 1 and 2). The Terskey–Alatoo extends from west to east for 380 km along the southern shore of Lake Issyk–Kul and in addition to providing water for irrigation, runoff from these glaciers is important for maintaining the Issyk–Kul water level and quality. The elevations in the area range mainly between 3300 and 4800 m above sea level (a.s.l.). The northern slope of the Terskey–Alatoo has a dissected relief with deeply cut valleys while the southern slope is less steep and accommodates elevated plateaus termed *syrt*. In the 1960s, there were 1375 glaciers with an area of approximately 1135 km^2 in the mountain range of Terskey–Alatoo (Katalog Lednikov SSSR, 1967–1982). Glacier areas range between 0.01 km^2 and 24.9 km^2 with an average of 1 km^2 in 2003. Glaciers with an area below 1 km^2 and of 1–2 km^2 accounted for 75% and 12% respectively in 2003. Six types, recognised by the World Glacier Inventory (WGI) classification (http://nsidc.org/) are distinguished including valley glaciers with compound basin (101.2 km^2 in 2003), valley glaciers with simple basin (126.1 km^2), mountain glaciers with simple basin (26.9 km^2), flat-summit glaciers or ice caps (22.9 km^2), niche (22.7 km^2) and cirque glaciers (28.1 km^2). The steep and deeply dissected northern slope accommodates smaller valley and mountain glaciers with simple basins, cirque and niche glaciers. The less steep southern slope accommodates larger valley glaciers with compound basins and flat-summit glaciers. The Kolpakovsky (compound-valley) Glacier, the largest in the Terskey–Alatoo with a maximum length of 12 km and a total surface area of about 24 km^2 (as in 2003) is located on the southern slope (Fig. 2). There are 48 flat-summit glaciers in the study area and the largest is Gregoriev Glacier (Fig. 2) with a surface area of 8 km^2 (as in 2003).

The climate of the Terskey–Alatoo is characterized by strong seasonal variations in precipitation and low air temperature that are

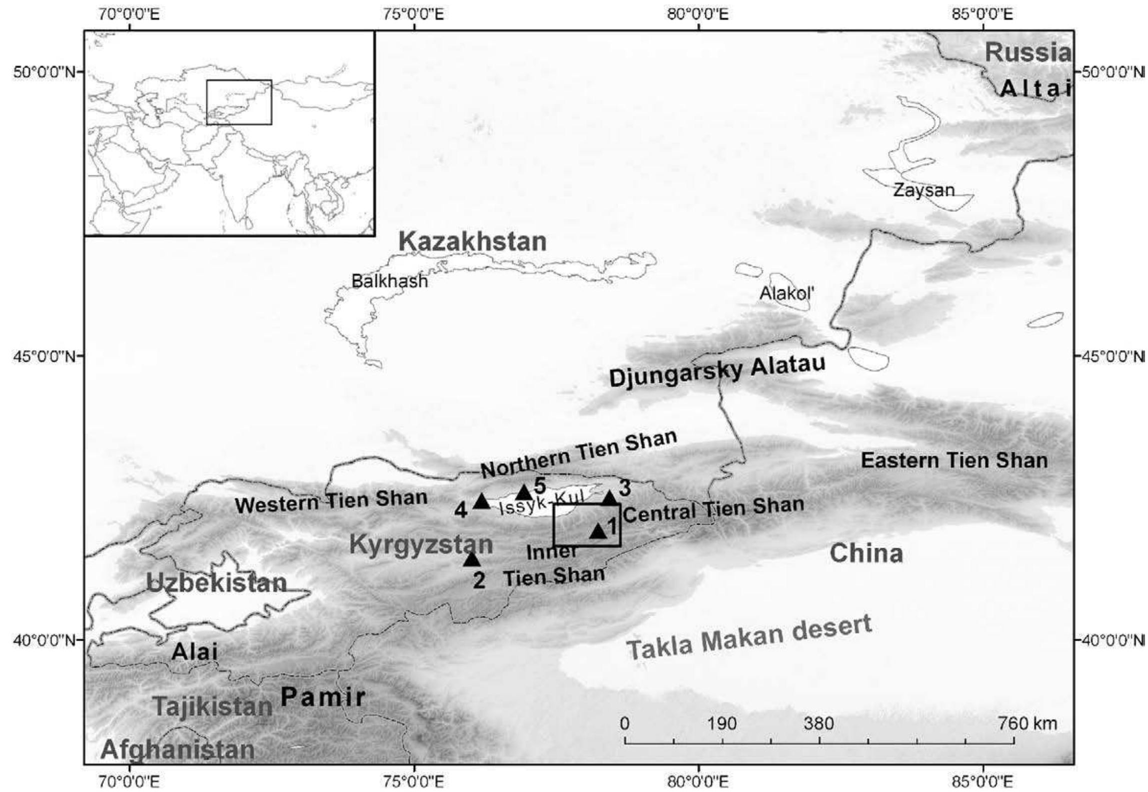

Fig. 1. Study area. The black rectangle on the main figure shows the area depicted in Fig. 2. Triangles show locations of the weather stations: (1) Tien Shan; (2) Naryn; (3) Karakol; (4) Balykchi; (5) Cholpon-Ata. Characteristics of the stations are given in Table 2.

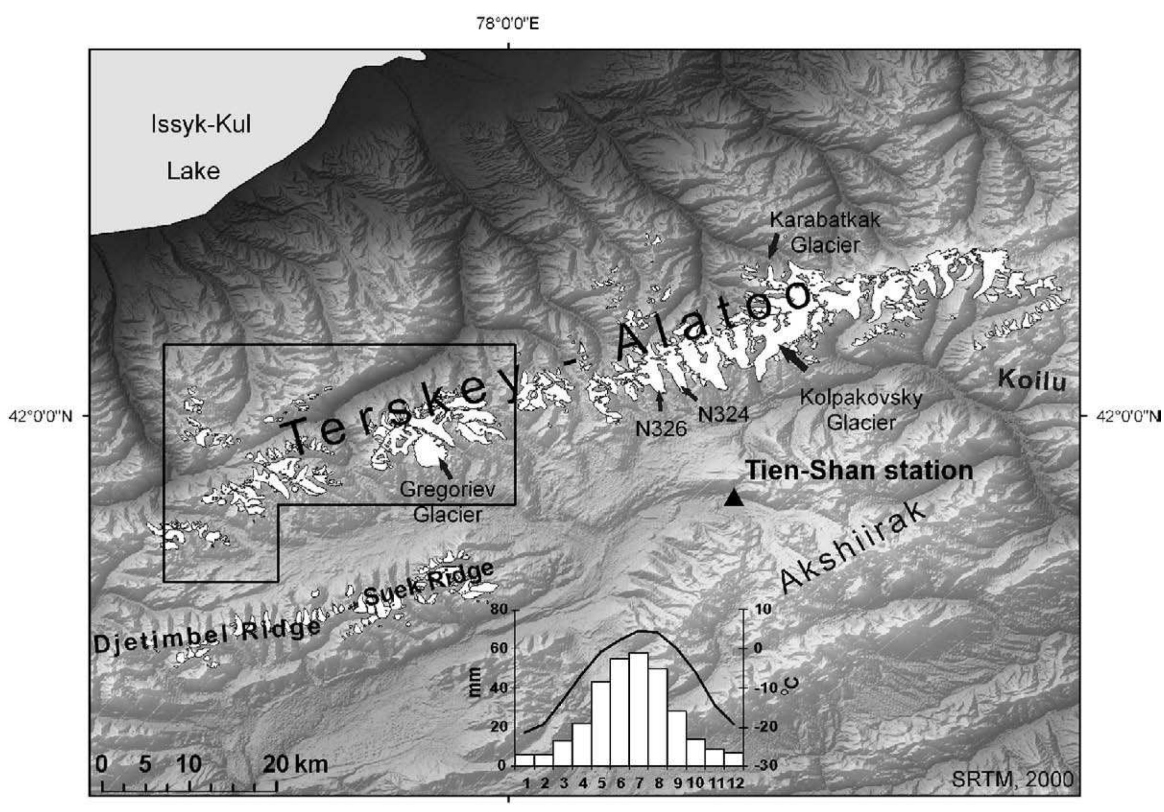

Fig. 2. The outlines of the studied glaciers derived from the 2003 ASTER imagery. The 1930–1996 monthly precipitation totals (mm) and temperature averages (°C) for the Tien Shan meteorological station (3614 m a.s.l.) are shown. The area enclosed by the bold line shows the region for which the 1965 maps, used to analyse changes in extent of 109 glaciers, are available. The Shuttle Radar Topography Mission (SRTM) data were used to construct a background map.

observed throughout the year due to high altitudes (Voloshyna, 1988; Aizen et al., 1997). At the Tien Shan station (Fig. 2), the 1930–1996 average July temperature was 4.4 °C declining to −21.8 °C in January. Precipitation peaks between May and September when it accounts for 76% of the annual total (Fig. 2). The warm-season precipitation maximum is associated with the westerly flow and position of the Polar front over the Tien Shan (Lydolf, 1977). The westerly flow is blocked by the area of high pressure extending from southern Siberia into the planes of Central Asia and the lower mountains (up to ~2 km) of the Tien Shan in winter. The upper mountains are dominated by the westerlies throughout the year but in winter, the Polar front migrates south of the Tien Shan resulting in low winter precipitation (Lydolf, 1977). The spatial distribution of precipitation is controlled by altitude and by orientation of the ridges and valleys and varies from 200 to 300 mm a^{-1} in the valleys to 400–600 mm a^{-1} at the highest elevations decreasing from north-west to south-east (Voloshyna, 1988). The combination of low temperatures and summer precipitation maximum predetermines the simultaneous occurrence of accumulation and ablation in summer. On Karabatkak Glacier (Fig. 2), the average annual accumulation and ablation were 762 and 1160 mm of water equivalent (mm w. e.) respectively in 1957–1997 resulting in an average negative mass balance of 438 mm w. e. (Dyurgerov, 2002; Section 5 of this paper). Glaciers of the Terskey–Alatoo repeatedly advanced and retreated throughout the Holocene and the latest period of advance was dated by Savoskul and Solomina (1996), Solomina (2000), and Solomina et al. (2004) to 1730–1910 with the majority of terminal and side moraines forming in the middle of the 19th century.

3. Data and methods

3.1. Mapping changes in glacier surface area

The outlines and termini positions of 335 glaciers (Fig. 2) were mapped using (i) a Landsat Thematic Mapper (TM) scene from 31/07/1990 (resolution 30 m) and two Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes from the 10/09/2003 (resolution 15 m). All images were obtained for the [nearly] cloud-free conditions and for the ablation period when the extent of snow cover was minimal to reduce potential uncertainty in glacier boundary delineation due to snow cover. Changes in the extent of glaciers were assessed with regard to two periods, (i) between the middle of 19th century and 1990 and (ii) between 1990 and 2003 and analyzed with regard to the type, surface area, and aspect of glaciers. Where a glacier had split into several fragments, the net area change in a studied period was based on the total area of the individual fragments. The information on type and aspect was obtained from the Catalogue of Glaciers of the USSR (Katalog Lednikov SSSR, 1967–1982). These results are presented in Section 4.1.

Most assessments of glacier change in Central Asia (Table 1) refer to the period between the middle and the end of the 20th century. Changes in the extent of 109 glaciers (Fig. 2) between 1965 and 2003 were measured using the 1:25,000 scale topographic maps based on aerial photographs obtained in 1965, the 1990 Landsat, and 2003 ASTER images to enable a comparison with the results obtained for other regions in Central Asia. The maps were not available for the whole of the study area and the difference between two samples (335 and 109 glaciers) necessitates a separate assessment. These results are presented in Section 4.2. In addition, changes in surface area of 10 glaciers were estimated with a smaller time step using topographic maps from 1965, aerial photographs from 1943, 1956, 1977, and an ASTER image from 16/07/2006 (Figs. 2 and 3). The 2006 ASTER image was not used for a larger area because of the cloud cover. These results are presented in Section 4.3.

All images and maps were re-projected into 1984 WGS UTM zone N44 projection. The Landsat image was geocorrected and co-registered using ERDAS Imagine 9.0 software with a re-sampled pixel size of 30 m. The ASTER images were provided in the framework of Global Land Ice Measurements from Space (GLIMS) project. The ASTER images were orthorectified using methodologies described by Toutin (2002) and Kääb (2004) and PCI Geomatica 9.1 Orthoengine software. The ASTER images were co-registered to the Landsat TM

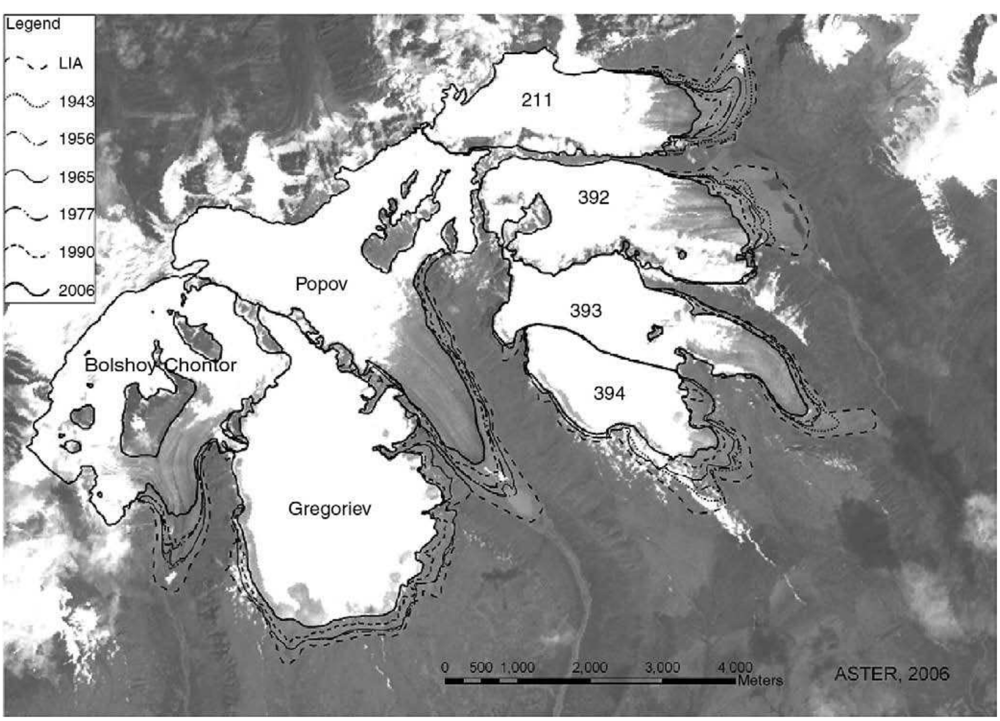

Fig. 3. Outlines of seven out of ten glaciers for the LIA, 1943, 1956, 1965, 1977, 1990, and 2006. The location of the remaining three glaciers (N 324, 326, and Kolpakovsky) is shown in Fig. 2. Glaciers are named and numbered as in the Word Glacier Inventory (http://nsidc.org/data/glacier_inventory/). Note that the flat-summit glaciers (e.g. Gregoriev and No 394) retreat along all their margins thereby losing a larger proportion of surface area.

(1990) image to eliminate a horizontal shift of ~200 m between the two images remaining after the orthorectification. This was carried out using interactive ground control points (GCP) of the image geometric correction tool available in ERDAS Imagine 9.0. The clearly distinguishable terrain features were used to determine the locations of the GCPs. Thirty GCPs have been collected with the root mean square error (RMSE) value of 18 m. The paper prints of the aerial photographs were digitized 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). The paper prints of the aerial photographs were orthorectified and co-registered to the ASTER images using the same procedure in ERDAS Imagine 9.0. On average, 50–60 GCPs were used for each pair of images to obtain satisfactory RMSE values (10 m). The nominal horizontal accuracy of the 1965 maps was 5 m and maps of the same series were used by Aizen et al. (2006) for assessment of glacier change in Aksiirak.

The high resolution of sensors (Landasat TM, ASTER) enabled accurate mapping of even small (<1 km^2) glaciers as demonstrated earlier by Paul et al. (2002). The glacier outlines and surrounding moraines were mapped manually using false-colour composite TM bands 5, 4, and 3 on the Landsat imagery (30 m resolution) and 3 bands in visible and near-infrared (VNIR) with 15 m resolution on ASTER images using ERDAS Imagine 9.0 and GLIMS View software (www.GLIMS.org). Earlier assessments conducted within the GLIMS framework have confirmed that human interpretation remains the best tool for extracting detailed information from satellite imagery for glaciers (Raup et al., 2007) particularly when mapping is conducted by the same person using a combination of different types of imagery (e.g. aerial photographs and ASTER) (Paul et al., 2002). Supra-glacial debris cover is a factor reducing the accuracy of mapping as it contributes to the overall accuracy of the glacier outline. However, in this particular case the debris cover of the glaciers is not extensive. The repeated mapping of a sample of glaciers with the surface area greater than 0.1 km^2 using different types of imagery has shown that the error of estimation of individual glacier area was below 5%. An assessment by Paul (2003) shows that this accuracy allows one to achieve an error of less than 3% for a large (over 100) sample of glaciers.

The terminal and lateral moraines were identified for all the glaciers under investigation in order to evaluate glacier size at the end of the LIA and glacier recession since the end of the LIA. Moraines are well defined in the area. Most are distinguishable on the satellite images by the absence of vegetation and for 36 glaciers, location of the moraines was known from the earlier field surveys by Solomina (2000) and GPS surveys conducted in 2003. Aerial and ground-based photographs were used in addition to satellite imagery to enhance the accuracy of determination of moraine locations (e.g. Fig. 4). Most of the moraines formed during the 1830s–1880s period (Savoskul and Solomina, 1996; Solomina, 2000; Solomina et al., 2004). To simplify statistical analysis, 1860 was taken as an average date of the formation of the latest LIA moraines.

3.2. Climatic data

Monthly air temperature and precipitation data from five high-altitude meteorological stations with a long period of observations were used (Table 2; Fig. 1). Four out of five stations are standard synoptic stations taking measurements every 3 h and supplying information to the National Hydrometeorological Service of Kyrgyzstan (NHSK) who is responsible for station maintenance and quality control of the data. Three out of these stations remained in the same place throughout the period of observation and their surroundings remained unaltered (e.g. neither station is affected by strong urbanization). The Karakol station was transferred by 200 m in 1953. In 1950, precipitation gauges were changed from Nipher to Tretyakov type, however, there was a period of cross-measurements and corrections for the change in the gauge type were made by the USSR Hydrometeorological Service at all stations. The Tien Shan meteorological station was functioning as a synoptic station until 1997 at an elevation of 3614 m a.s.l. In 1997, a Campbell Scientific automatic weather station (AWS) which collects data every 5 s recording hourly

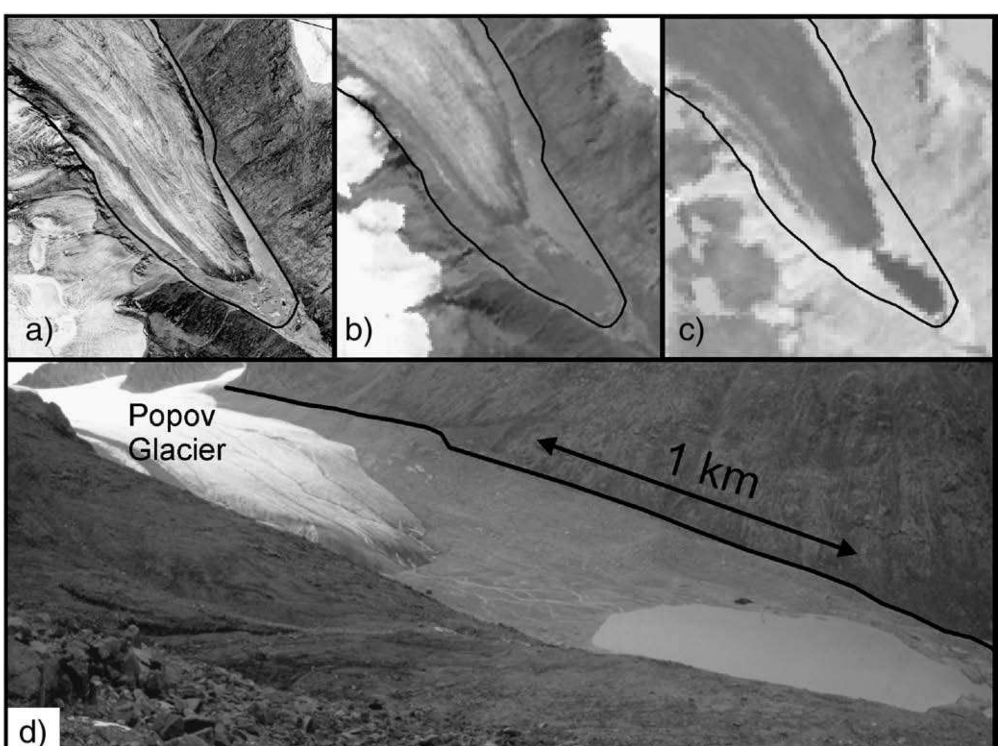

Fig. 4. Position of the end of the LIA moraine (bold line) of Popov Glacier on (a) 1956 aerial photograph, (b) 2003 ASTER image, (c) 1990 Landsat TM image, and (d) 2002 ground-based photograph (courtesy of Dr. V. Mikhalenko).

Table 2
Meteorological stations used in this study (locations are shown in Fig. 1).

Meteorological station	Lat (N)	Lon (E)	Altitude (m)	Observation period
Naryn	41° 26′	76° 01′	2049	1882–2005
Karakol (Prjeval'sk)	42° 30′	78° 26′	1716	1879–1997
Tien Shan	41° 55′	78° 14′	3614/3660	1930–2006
Cholpon-Ata	42° 36′	76° 56′	1645	1929–2004
Balykchie (Rybachiy)	42° 27′	76° 11′	1621	1931–2004

averages was installed. The AWS was positioned close to the previous location at an elevation of 3660 m. A cross-measurement period in 1997 has shown a close agreement between the air temperature measurements, however, there was a notable discrepancy between the precipitation records. Therefore, in this study the Tien Shan precipitation data collected after 1997, when the AWS replaced the standard station, were not used.

There is a strong correlation between May and September mean air temperature variations recorded at the five stations with correlation coefficients exceeding 0.74 (significant at 0.01 confidence level; Table 3). Similarly, Voloshyna and Sianchen (1995) reported a close correlation (0.72–0.93) between temperature records of eleven high-altitude stations located in different regions of the Tien Shan. The spatial distribution of precipitation is more varied: not all correlation coefficients between the annual precipitation totals are significant at 0.05 confidence level and the significant ones do not exceed 0.47 for annual precipitation (Table 3) and 0.57 for May–September precipitation.

Prior to analysis, all temperature and precipitation records were standardized by subtracting the mean and dividing by the standard deviation of the time series to ensure comparability of the records (Wilks, 1995).

4. Results

4.1. Glacier area loss and terminus retreat between LIA, 1990, and 2003: 335-glacier sample

Between the end of the LIA and 2003, the total surface area of the 335 studied glaciers has decreased by 19% of the LIA value from 404 km^2 to 328 km^2. The average terminus retreat was 438 m with a standard deviation (σ) of 308 m. The total number of glaciers has increased since the middle of 19th century when there were 297 glaciers in the study region. In particular, the number of simple-basin valley glaciers has increased from 47 at the end of the LIA to 71 in 2003 due to the fragmentation of the compound-basin valley glaciers. At least 16 glaciers, which were present on the aerial photographs of 1943, 1956, and on the maps of 1965, had disappeared completely by 2003.

Between the end of the LIA and 1990, 330 glaciers have retreated and no change has been detected in areas of 5 glaciers. The total glaciated area has decreased by 63 km^2 or 16% of the mid-19th century value. The average decrease rate was 0.5 $km^2\ a^{-1}$ or 0.1% a^{-1} of the LIA area. The majority of glaciers (200) have lost between 5% and 25% of their LIA area (Fig. 5). 41 glaciers have lost more than 40% of their LIA area. Average terminus retreat was 366 m (σ=264 m). The 5 glaciers, which remained unchanged, were smaller than 0.5 km^2 and located on the lee side of the ridges. Accumulation on such glaciers depends primarily on snow drift and their behavior is determined by local conditions rather than climatic variations. The overriding importance of local conditions for the behavior of small glaciers has also been noted by Surazakov et al. (2007) for the Altai.

The glacier recession intensified between 1990 and 2003: the total glacier surface area in the studied region has decreased by 3.8% of the 1990 value (13 km^2 of ice). Between 1860 and 1990, the glacier area reduced each year by 0.12%, while in the period 1990–2003 the annual area decrease was already 0.23% per year, based on the area of 1860. On average, glacier termini retreated by 72 m (σ=66 m) and the majority (65%) of the glaciers have retreated by 10–100 m (Fig. 6). The average annual retreat rate was 5.5 m a^{-1}, which is almost twice the average annual retreat rate observed between the end of the LIA and 1990 (3 m a^{-1}).

The rate of recession varied between glaciers of different type, size, and aspect. The pattern of relative changes in glacier area between the mid-19th century and 2003 is illustrated by Fig. 7. Glaciers with areas larger than 10 km^2 have lost on average 10% of their area. Glaciers smaller than 1 km^2 lost on average 34% of their area with a median value of 28% exhibiting, however, a large range of variability. Occupying 23% of the glaciated area at the end of the LIA, they accounted for 33% of the total loss between the mid-19th century and 2003.

The highest relative recession (% of glacier area) characterized the flat-summit glaciers, which were losing on average 0.6% of their surface area per year between 1990 and 2003. The largest absolute reduction in surface area was characteristic of the compound-valley glaciers, which were losing 0.015 $km^2\ a^{-1}$ per glacier (Fig. 8). The combined loss of surface area was highest for the glaciers with southern, south-eastern, eastern, and northern aspects (Fig. 9a). The northern slope accommodates the largest number of glaciers (87), which explains a high combined loss. The individual glaciers, however, retreated slower than the south- and east-facing glaciers (Fig. 9b), which are characterized by larger areas and smaller elevation span. The relationship between the loss of glacier surface area and its aspect is not uniform across the mountains of Central Asia and in the Pamir–Alai the south-facing glaciers tend to retreat slower due to their higher elevation and stronger compensating role of precipitation (Glazyrin, 2003).

4.2. Glacier area loss between LIA, 1965, and 2003: 109-glacier sample

The selected 109 glaciers have lost 9.6% of their LIA area between the end of the LIA and 1965 (0.1% a^{-1}) and 11.4% (0.3% a^{-1}) in the 1965–2003 period based on the area of 1860 (Table 4). The total loss of glacier surface area was 28 km^2 between the mid-19th century and 2003 or 21% of the LIA value. The relative reduction is slightly larger than that in the 335-glacier sample (19%) because the large compound-valley glaciers, whose relative area loss was moderate (Fig. 8), are not represented in the 109-glacier sample (Fig. 2) while the large flat-summit glaciers (e.g. Gregoriev Glacier), whose relative area loss was the highest, are well represented. Among these 109 glaciers, 69 were smaller than 1 km^2 in 1965 occupying 19% of the glaciated area. The loss of glaciated area by these glaciers accounted for 27% of the total loss. This is a smaller contribution than that observed in the Swiss Alps, where small glaciers accounted for 44% of the total loss between 1973 and 1999 occupying 18% of the glaciated area (Paul et al., 2004).

4.3. Glacier changes between LIA and 2003: 10-glacier sample

The analysis of 10 glaciers located on the southern slope of the Terskey–Alatoo, using historical maps, aerial photographs, and ASTER

Table 3
Correlation coefficients between the May–September (MJJAS) temperature and annual precipitation (bold) time series from the regional meteorological stations. Only those coefficients that are significant at 0.05 confidence level are shown.

	Tien Shan	Naryn	Karakol	Cholpon-Ata	Balykchi
Tien Shan	1	0.80	0.85	0.74	0.84
Naryn	**0.40**	1	0.77	0.74	0.82
Karakol	**0.40**	**0.47**	1	0.77	0.86
Cholpon-Ata	**0.29**		**0.43**	1	0.75
Balykchi			**0.27**	**0.39**	1

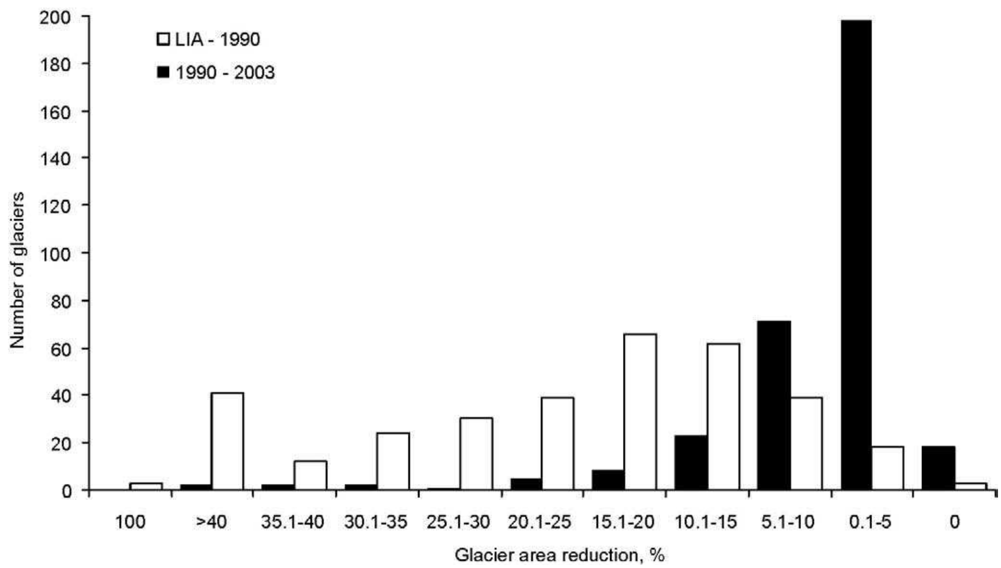

Fig. 5. Frequency distribution of reduction in glaciated area for 335 glaciers for the LIA — 1990 (% of LIA area) and 1990–2003 (% of 1990 area).

imagery (Table 5), has enabled glacier extent variations over the 20th century to be characterized with a higher temporal resolution. In 2006, the surface area of these glaciers varied from 2.4 km^2 through 8 km^2 (the largest flat-summit Gregoriev Glacier) to 24.8 km^2 (Kolpakovsky Glacier). The retreat rate of the selected glaciers was higher than the average of the 335 glaciers sample, however, their retreat rate was typical of the glaciers of these size class. The selected glaciers are considerably larger than average (78% of all Terskey–Alatoo glaciers were smaller than 2 km^2 in 2003; Section 2) and large glaciers exhibit greater absolute loss. The flat-summit glaciers (e.g. Gregoriev; N 394) are also among the most rapidly retreating glaciers (Fig. 8). The detailed pattern of glacier change is illustrated by Figs. 3 and 10. Glaciers retreated relatively slowly in the decades following the end of the LIA at an average rate of 3.9 m a^{-1} between the end of the LIA and 1943. This conclusion is supported by the historical surveys conducted between 1875 and 1947 in the study area (Prinz, 1909; Kassin, 1915; Korzhenevsky, 1930; Kalesnik, 1935; Avsuk, 1950). The average rate of retreat increased in the 1943–1956 period reaching 16 m a^{-1} but decreased in the 1956–1977 period to 9.5 m a^{-1}. From 1977, the rate of deglaciation increased rapidly and between 1990 and 2006 the average terminus retreat rate reached 19 m a^{-1}. The Kolpakovsky Glacier exhibited the highest rate of retreat reaching 32 m a^{-1} between 1990 and 2006 (Table 5; Fig. 10).

The retreat of glaciers has been accompanied by the formation of glacial lakes especially after the 1950s when more than 30 lakes were formed in the study region. The formation of the ice-contact lakes is known to intensify glacier recession significantly. A lake formed at the terminus of Popov Glacier in the 1950s (Fig. 3). Between 1956 and 1965, the central section of the glacier tongue which terminated into the lake retreated by 190 m while sections terminating on the dry land retreated by about 70 m. Similarly, sections of the South Ashu-Tor Glacier (also termed No 326) tongue terminating into a lake retreated by 80 m further than those terminating on the dry land in the 1977–2006 period.

4.4. Climate variations

The glaciers of the Teskey–Alatoo gain and lose mass predominantly in the boreal summer (Voloshyna, 1988) and, therefore, air temperatures observed between May and September (MJJAS) and annual precipitation are the main factors controlling glacier mass balance. The records from the regional meteorological stations (Table 2; Fig. 1) show that MJJAS air temperatures have been increasing since the 1950s (Fig. 11). At the Tien Shan station, the closest to the study area (15–25 km), the last two decades were the warmest on record since 1930 (Fig. 11a). In 1997 and 2006, MJJAS average air temperatures exceeded two standard deviations from the record average. Temperature records from two other stations, Naryn and Karakol (Fig. 11b, c) dating back to the 1880s show that similarly warm summers were observed in the first two decades of the 20th century. At the Naryn station, five out of 10 warmest summer

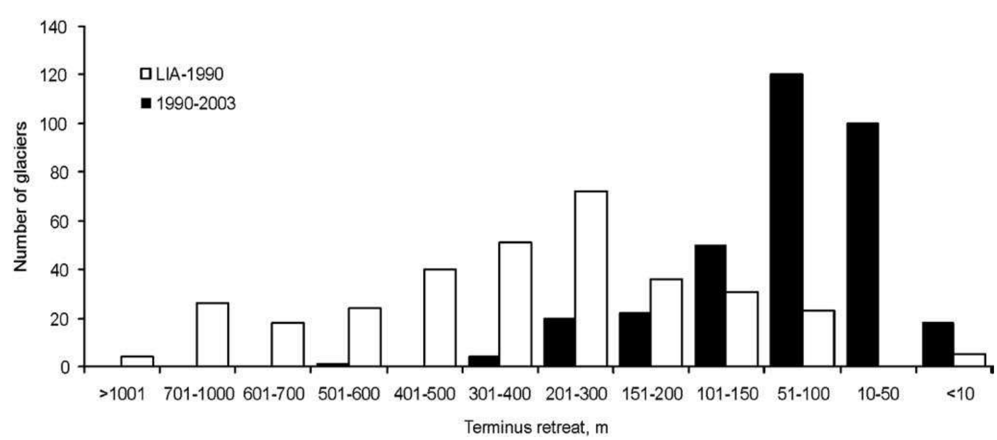

Fig. 6. Frequency distribution of terminus retreat (m) for 335 glaciers for the LIA — 1990 and 1990–2003.

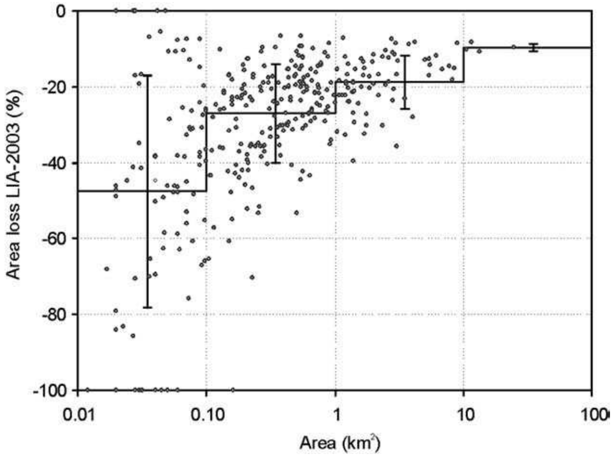

Fig. 7. Scatterplot showing relative change in glacier size from the mid-19th century to 2003 versus glacier size (as in 2003). Mean values of glacier area change (horizontal bold line) together with standard deviation (vertical bars) are given for four area classes (in km^2: <0.1, 0.1–1, 1–10, >10).

seasons occurred in the last 30 years. Although three warmest years were 1900, 1917 and 1978 (with a positive anomaly of 2.0–2.1 °C), the early 20th century was characterized by much stronger interannual variability in air temperatures whereby the summer seasons with strong positive and negative temperature anomalies intermingled. No strong negative anomalies (exceeding one standard deviation) have been observed in the region since the 1960s. At the Balykchi, Cholpon-Ata (not shown) and Tien Shan (Fig. 11a) stations, nine out of ten warmest MJJAS seasons occurred in the last 30 years and six in the 1997–2007 period. Between 1956 (chosen a starting point because of the availability of aerial photographs) and 2007, positive linear trends explain between 15% and 35% of the total variance in the time series and all are significant at 0.01 confidence level. During this period, at the Tien Shan station MJJAS air temperatures have been increasing a rate of 0.03 °C a^{-1} and at the Naryn and Karakol stations at a rate of 0.02 °C a^{-1} although the onset of the warming was delayed at higher elevations. Similar trends have been reported by Bolch (2007) and Aizen et al. (2006, 2007) in the neighbouring regions of the northern Tien Shan, Akshiirak, and Ala Archa. Although the recently observed warming extends over a large range of elevations from 1600 m to 3600 m (Table 2), all the stations are located at least 300 m below the glacier termini. The area-averaged time series of air temperature at the 500 mb geopotential surface derived from the ERA-40 (Uppala et al., 2005) and NCEP/NCAR (Kalnay et al., 1996) reanalyses have not revealed any long-term trends. However, there is no statistically significant correlation between the station data and the spatially-averaged data from both reanalyses at lower elevations and, therefore, the absence of warming at the 500 mb geopotential height shown by the reanalyses data should be interpreted with caution.

While temperature trends are consistent across the region, trends in precipitation are less homogeneous (Fig. 11). Typically, there is a negative correlation between MJJAS temperatures and annual precipitation which is explained by a simple fact that the drier summers, dominated by anticyclonic weather, are also warmer ones. This correlation is best seen in the Karakol station record whereby the warm periods in the 1920s and 1940s were accompanied by strong negative anomalies in precipitation (Fig. 11c). This counter-phase behavior characterized the current warming at the Tien Shan station until 1997. Annual precipitation has been declining at the Tien Shan station between the 1960s and 1990s (Fig. 11a) at an average rate of 4.6 mm a^{-1}. The linear trend explained 45% of total variance in the time series (significant at 0.01 confidence level). The lowest on record precipitation was observed in 1996 and 1997 (also the warmest year). There are no reliable post-1997 data for the Tien Shan station and due to the weak cross-station correlation in precipitation (Table 3) precipitation measured elsewhere cannot serve as a reliable indicator of change at the Tien Shan station. At the other stations, an increase in both MJJAS and annual precipitation accompanied the recent warming (Fig. 11), however, no significant long-term trends have been observed in these and neighbouring regions (e.g. Aizen et al., 2007).

5. Discussion

The majority of glaciers in the inner Tien Shan were not in equilibrium since the end of the LIA. The observed reduction in glacier surface area intensified in the second half of the 20th century in line with a strong positive trend in regional air temperature (Fig. 11). An increase in air temperature during the melting season (May–September) at a rate of 0.02–0.03 °C a^{-1} has been observed at all five regional meteorological stations and in the neighbouring regions (Aizen et al., 2006, 2007; Bolch, 2007). A strong negative correlation (−0.67 to −0.76) between the Karabatkak Glacier mass balance time series for the 1957–1997 period (Fig. 12) and the June–July–August (JJA) air temperature time series from the Tien Shan, Naryn, and Karakol stations (Fig. 11) confirms the importance of the ablation season warming for glacier change in the Terskey–Alatoo. Correlation between Karabatkak mass balance and annual precipitation totals at the Tien Shan station is lower (0.60). Stronger sensitivity of glacier mass balance to the ablation season temperatures has also been

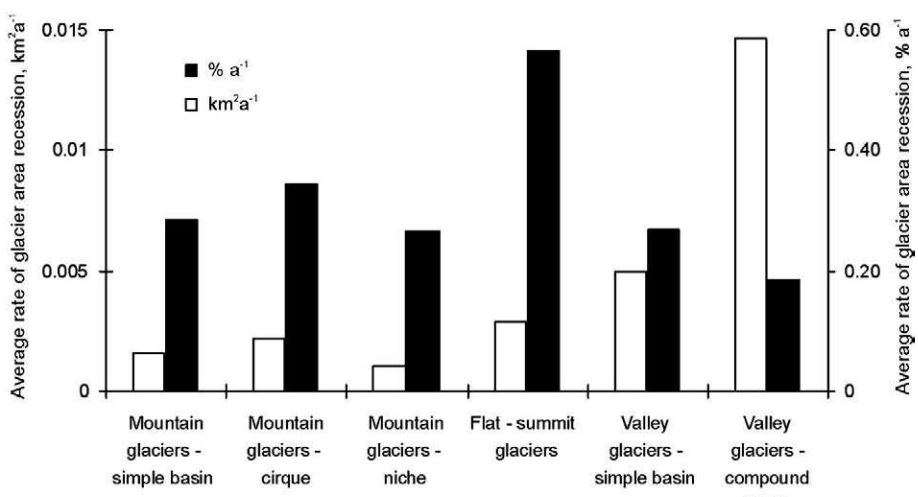

Fig. 8. Average rate of recession for different types of glaciers between 1990 and 2003 in km^2 a^{-1} and in percent of the 1990 area per year.

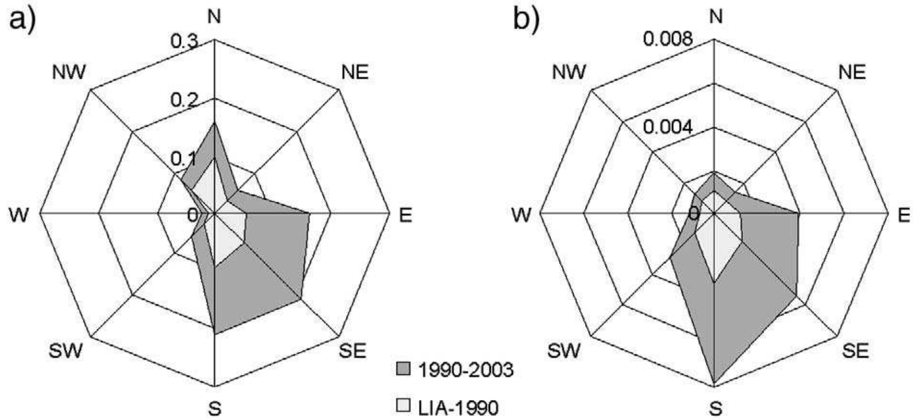

Fig. 9. The combined (a) and average (b) rate of area loss by glaciers with different aspects for the two periods, LIA — 1990 and 1990–2003 ($km^2\ a^{-1}$). In 2003, 87 glaciers faced north; 40 — north-east; 42 — east; 39 — south-east; 27 — south; 20 — south-west; 18 — west; and 62 — north-west.

confirmed by Jing et al. (2006) for Glacier No 1 in the eastern Tien Shan. However, it is a combination of climatic warming and a negative anomaly in precipitation observed in the 1990s (Fig. 11) that has created unfavourable conditions for the glaciers enhancing their retreat. Braithwaite et al. (2002) has estimated that a 10% increase in precipitation is required to offset the effects of a 1 °C warming on glacier mass balance and subsequent retreat. Oerlemans (2005) provides a higher value of 25%. In the Terskey–Alatoo, no compensating change in precipitation was observed. By contrast, at the Tien Shan station in the 1990–2007 period, MJJAS temperature exceeded the record (1930–1997) average by 1 °C while annual precipitation in the 1990–1997 period was 169 mm that is 44% lower than the record average of 305 mm (Fig. 11a). An increase in precipitation was observed in the neighbouring regions (Aizen et al., 2006, 2007), however, it has not compensated for the current warming as glaciers in these areas continue to retreat too (Table 1; Aizen et al., 2006, 2007; Bolch, 2007). This observation agrees with the conclusion by Oerlemans (2005) that the sensitivity of glaciers to precipitation change is lower in comparison to their sensitivity to temperature change.

The compound-valley glaciers exhibited the largest absolute loss of surface area but it is the flat-summit glaciers that have lost the largest proportion of their area (Fig. 7). In contrast to glaciers of other types, the flat-summit glaciers do not have well-pronounced termini but are characterized by the large marginal areas enabling retreat around the whole glacier margin. A rapid retreat of these glaciers has occurred despite a high accumulation area ratio (AAR) of approximately 0.75 which was characteristic of these glaciers in the 1960s–1970s (Bakov and Chen, 1995) and which should make them less vulnerable to climatic warming (Dyurgerov, 2003). However, Dyurgerov (2003) has shown that the AAR of most glaciers worldwide, including those in the Tien Shan, has been declining since the 1960s (with a particularly significant reduction in the 1980s–1990s) as a result of an increase of the equilibrium line altitude (ELA). Observations at Karabatkak Glacier confirm that AAR has declined significantly from 0.7 in the 1970s to 0.54 in the 1990s with a negative linear trend explaining 60% of the total variance in the time series (Fig. 12). Due to the specific morphology of the flat-summit glaciers (gentle slopes, small difference between the lowest and highest point), even a small increase of ELA leads to a significant decrease in AAR and this may have also contributed to their rapid response to climatic warming despite their high absolute elevations. For example, a flat-summit Gregoriev Glacier located between 4200 and 4600 m a.s.l. (higher than average for the Terskey–Alatoo), has lost 7% of its area between 1990 and 2006 which is twice the average loss. Paul et al. (2007) provide a detailed review of estimations of ELA sensitivity to temperature rise in the European Alps evaluating it as 120–170 m per 1 °C. Observations at Karabatkak Glacier in the eastern Terskey–Alatoo confirm that the average ELA has risen from an average value of 3725 m a.s.l. for the 1957–1977 period to 3855 m a.s.l. in the 1977–1997 period (Fig. 12). The May–September air temperature records from the regional weather stations indicate that temperatures have increased by 0.5 °C (Tien Shan, Balykchi)–0.7 °C (Cholpon-Ata) in 1977–1997 in comparison with 1957–1977. This yields a rise of ELA of 130 m per 0.5–0.7 °C or [after interpolation], a rise of 180–260 m per 1 °C warming indicating a stronger sensitivity of ELA on the Karabatkak Glacier in comparison to the European Alps. Glazyrin et al. (2002) estimated that in the Pamir-Alai, a 20% decrease in annual precipitation leads to a 120–140 m rise of ELA. It can be suggested that a strong increase in ELA at Karabatkak Glacier reflects a combined impact of increasing air temperature and a negative precipitation anomaly observed in the 1980s as indicated by the Tien Shan station record.

Few studies have analyzed changes in extent of glaciers from the LIA. Solomina et al. (2004) assessed terminus retreat of 47 mostly compound-valley glaciers, which retreat faster than others, in the same region between the LIA and the late 1980s and obtained an average retreat value of 870 m. Our results for 335 glaciers have shown that the average rate is considerably lower at 370 m. However, Solomina et al. (2004) results are characteristics of glaciers of this type and the average terminus retreat of the compound-valley glaciers assessed in this study between the LIA and 2003 was 820 m.

Most studies compare glacier retreat between the middle and the end of the 20th century (Table 1). Our results for a sample of 109 glaciers show that they have lost 12.6% of their 1965 area between 1965 and 2003 or 0.33% a^{-1}. This is in close agreement with the

Table 4
Number of glaciers and changes in glacier surface reduction of 109 glaciers between the mid 19th century and 2003 for four area classes.

Class	Number of glaciers				Area in km^2				Area reduction in %				
km^2	LIA	1965	1990	2003	LIA	1965	1990	2003	LIA/1965	1965/1990	1990/2003	1965/2003	LIA/2003
<1	71	69	66	66	26.3	22.9	19.8	18.4	12.7	13.8	7.1	19.9	30.1
1–3	28	28	28	28	45.3	40.3	37.0	35.4	11.1	8.1	4.3	12.0	21.8
3–5	8	8	8	8	30.0	27.4	25.6	24.5	8.7	6.7	4.1	10.6	18.4
5–10	4	4	4	4	31.2	29.4	27.7	26.6	5.8	5.7	4.0	9.5	14.7
Total	111	109	106	106	132.8	120.0	110.1	104.9	9.6	8.3	4.7	12.6	21.0

Table 5
The surface area (km^2) and terminus retreat (m) of the selected 10 glaciers between the mid-19th century and 2006. Glacier types are abbreviated as follows: cdv — compound-valley, v — valley, fls — flat-summit glacier.

Name and type	LIA	1943	1956	1965	1977	1990	2006
Bolshoy Chontor cdv	6.9	–	6.6/320	6.5/390	6.4/540	6.3/670	6/980
Popov cdv	9.1	–	8.6/450	8.5/490	8.4/630	8/860	7.7/1075
Gregoriev fls	10	–	9.4/230	9.3/250	–	8.6/400	8/600
211 v	4.8	4.6/190	4.4/430	4.2/570	4.0/730	3.9/990	3.7/1290
392 v	5.7	5.0/480	4.9/560	4.85/600	4.8/660	4.6/760	4.4/890
393 v	4.5	4.2/130	4.1/180	4.0/230	–	3.9/360	3.7/460
394 fls	3.9	3.4/520	3.3/800	3.2/820	–	2.8/840	2.4/980
Kolpakovsky cvd	27.5	26.8/600	26.2/1030	–	25.9/1300	25.5/1520	24.8/2030
324 v	6.3	6.1/80	5.9/240	–	5.8/400	5.5/540	5.3/770
Ashu-Tor south (326) v	6.5	6.3/270	6.0/490	–	5.9/560	5.7/720	5.3/1090

eastern Tien Shan where glaciers lost 11–13% of their area between 1962 and 2003 or 0.27–0.32% a^{-1} (Jing et al., 2006; Li et al., 2006). The assessments by Aizen et al. (2006) for the neighbouring region of Akshiirak and by Narama et al. (2006) for the western Terskey–Alatoo for 1977–2003 and 1971–2002 respectively indicate the area loss of 8–9% or 0.26–0.34% a^{-1} which is close to our results. In the peripheral regions of the northern Tien Shan glaciers were retreating considerably faster (Table 1; Vilesov et al., 2006; Aizen et al., 2006; Bolch, 2007).

A comparison with other regions has shown that glaciers of the Altai, which develop under similar annual precipitation and winter temperature conditions and slightly lower summer temperatures, retreat at a higher rate. Thus Khromova (pers. com.) obtained an average reduction of 19% for the North and South Chuya Ridges of the Russian Altai for the 1952–2004 period. The glaciers located further into the continental interiors and at higher altitudes, e.g. in the eastern Pamir (Shangguan et al., 2006; Table 1), have shown the slower rates of retreat. By contrast, glaciers of the Dzhungarsky Alatau (Vilesov and Morozova, 2005; Table 1) have lost remarkable 40% between 1956 and 1990 probably due to the prevailing southern aspect and lower elevations.

6. Conclusions

Glaciers in the eastern Terskey–Alatoo have been retreating since the end of the LIA and 19% of ice surface area has been lost between the LIA and 2003. The retreat has accelerated since the 1960s when 12.6% of glacier surface area had been lost by 2003. The wastage rates for small (<1 km^2) glaciers where even higher at 19% area loss between 1965 and 2003. The recent decades have been characterized by a strong warming during the melt season and by negative precipitation anomalies in the 1990–1997 period providing a link between climatic variations and glacier shrinkage. Although glacier retreat in the inner Tien Shan has been less rapid than in the western parts of the Eurasian continent, e.g. in the Alps (Paul et al., 2004, 2007) and in the Caucausus (Stokes et al., 2006) or even in the northern Tien Shan (Bolch, 2007), it has already affected regional hydrology through

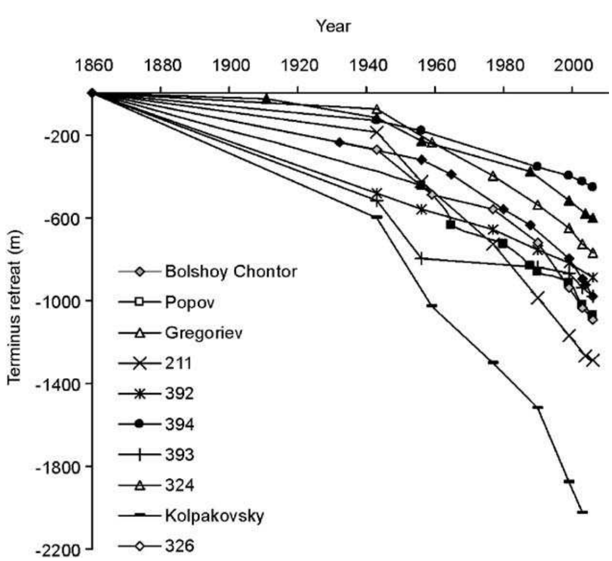

Fig. 10. Terminus retreat (m) of the 10 selected glaciers.

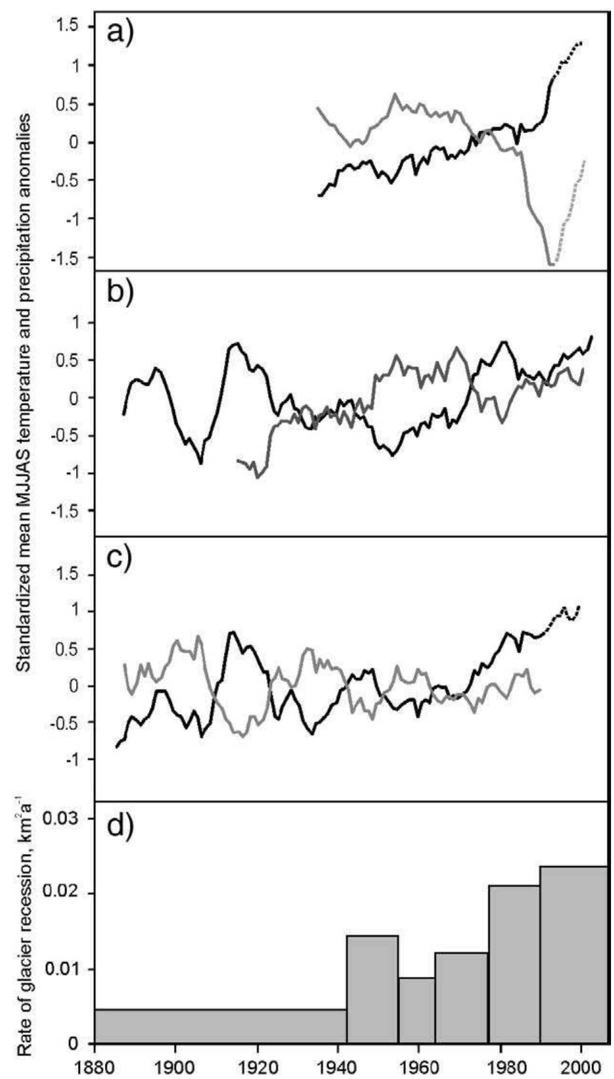

Fig. 11. Standardized anomalies of May–September mean monthly temperature (black line) and annual precipitation (grey line) for (a) Tien Shan (b) Naryn and (c) Karakol stations. The Balykchi station data were used for the extension the Karakol station time series in the post-1991 period using correlation method (dashed line). The AWS data are shown for the Tien Shan station in the post-1997 period (dashed line). The average rate of surface area reduction (km^2 a^{-1}) for the selected 10 glaciers is shown (d).

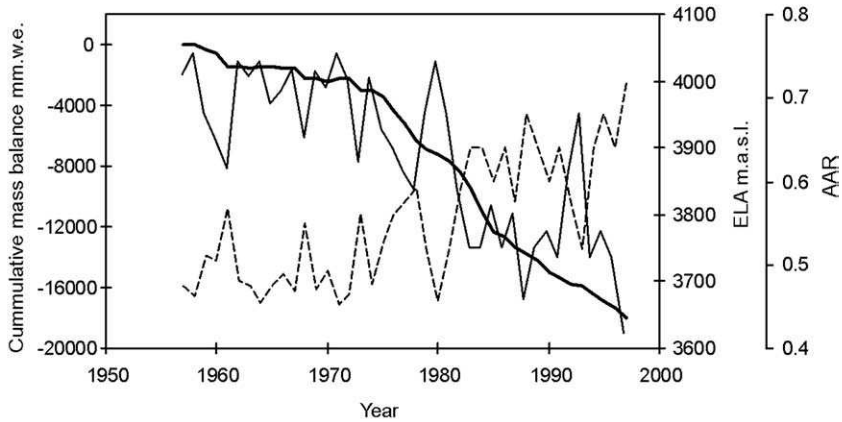

Fig. 12. Cumulative mass balance (bold line), accumulation area ratio (AAR; thin line), and equilibrium line altitude (ELA; dashed line) of Karabatkak Glacier between 1957 and 1997.

the formation of proglacial lakes which intensify glacier wastage further and present a potential hazard to local communities. Should the trends in glacier retreat continue with glaciers losing about 0.3% of their area per year as in 1990–2003, about 30% of glaciated area in Terskey–Alatoo will be lost by the end of the 21st century. Projections of future runoff based on doubling of CO_2 and a 50% reduction in glaciation in Tien Shan (Hagg et al., 2007) suggest higher risks of floods in summer turning into a runoff deficiency after a higher degree of deglaciation is reached. Assessment of changes in the volume of ice presents another way of evaluation of potential impacts of glacier wastage on water resources. The historical maps and aerial photographs used in this study can be used for this purpose in combination with DEM derived from high-resolution contemporary satellite imagery. This presents a direction for further development of this research.

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