ARTICLE IN PRESS
GLOBAL-01496; No of Pages 13
Global and Planetary Change xxx (2009) xxx–xxx
Contents lists available at ScienceDirect
Global and Planetary Change
journal homepage: www.elsevier.com/locate/gloplacha

Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~1970), Landsat (~2000), and ALOS (~2007) satellite data

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ARTICLE INFO

Article history:
Received 6 March 2008
Accepted 19 August 2009
Available online xxxx

Keywords:
glacier area changes
regional differences
water shortages
glacier hazards
ALOS
Landsat
Corona
Tien Shan Mountains
Central Asia

ABSTRACT

Geographic variability of the recent changes of glacier coverage in the Tien Shan Mountains, Central Asia, is assessed using Corona KH-4B satellite photographs for 1968–1971, Landsat 7 ETM+data for 1999–2002, and ALOS/PRISM and AVNIR data for 2006–2008. The four mountain regions investigated (Pskem, Ili-Kungöy, At-Bashy, and SE-Fergana) cover several distributed glacierized areas in the Tien Shan Mountain system, a region that is affected by highly variable local precipitation regimes. Over the 30 years investigated between ~1970 and ~2000, glacier area decreased by 19% in the Pskem region, 12% in the Ili-Kungöy region, 12% in the At-Bashy region, and 9% in the SE-Fergana region. In the last 7 years (~2000 to ~2007), glacier area shrank by 5% in the Pskem region, 4% in the Ili-Kungöy region, 4% in the At-Bashy region, and 0% in the SE-Fergana region. Glacier behavior has varied markedly in these regions. The most dramatic glacier shrinkage has occurred in the outer ranges of the Tien Shan Mountains. Recent glacier area loss has resulted from rising summer temperatures. Regional differences of glacier-area changes related to local climate conditions, to the altitudinal distribution of glacier areas, and to the relative proportion of glaciers in different size classes. The observed accelerated glacier shrinkage is expected to have two impacts on the more populated outer ranges: 1) water shortages during summer and 2) increased threat from glacier hazards such as glacier lake outburst floods (GLOFs) and ice avalanches.

1. Introduction

The population of arid and semi-arid lowland areas (oases and irrigated agricultural areas) in Central Asia depend largely on fluvial water originating from mountain areas. Mountain glaciers contribute part of this important water resource. Glaciers collect solid precipitation in winter and release this precipitation as meltwater in summer (Hagg et al., 2007; UNEP, 2007), providing an important reliable water supply during drought years when other water sources are depleted. Decrease of glacier area is expected to lead to a decline of river discharge during the summer dry season (Hagg et al., 2007). Recent studies about glacier cover in the Tien Shan Mountains, based on remotely sensed data (Aizen et al., 2006; Liu et al., 2006; Narama et al., 2006; Shangguan et al., 2006; Bolch, 2007; Li et al., 2007; Niederer et al., 2007), have reported significant glacier shrinkage. Temperature increases by 2100 (IPCC, 2001) are also expected to lead to 43 to 81% decreases in glacier coverage in parts of the Pamirs and Himalayas (Böhner and Lehmkuhl, 2005). In the context of water resources, changes in glacier coverage in the Central Asian mountains should be monitored as recent climate change continues.

Previous studies of glacier change in the Tien Shan Mountains have used various types of remotely sensed data and examined different time periods, which has hindered comparison of their conclusions. Climatically, the Tien Shan Mountains are characterized by interactions between Westerlies and the Siberian High over complex mountain topography (Aizen et al., 1995), producing significant regional differences in seasonal and annual precipitation (Fig. 1). As atmospheric warming continues, this spatial variability in precipitation may lead to significant regional differences in the degree of glacier change. This study uses Corona KH-4B, Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Advanced Land Observing Satellite (ALOS) / Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) and Advanced Visible and Near Infrared Radiometer (AVNIR) data to understand regional differences in glacier area changes for similar time-spans in four mountain regions. This paper reports on the current state of glaciers and on potential problems related to the observed glacier shrinkage in the Tien Shan Mountains.

2. Study area

Four study regions in the Tien Shan Mountains were selected for analysis: the Pskem, Ili-Kungöy, At-Bashy, and SE-Fergana regions (Fig. 1). The Pskem region includes the Ugam, Maidantal, and Pskem

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doi:10.1016/j.gloplacha.2009.08.002

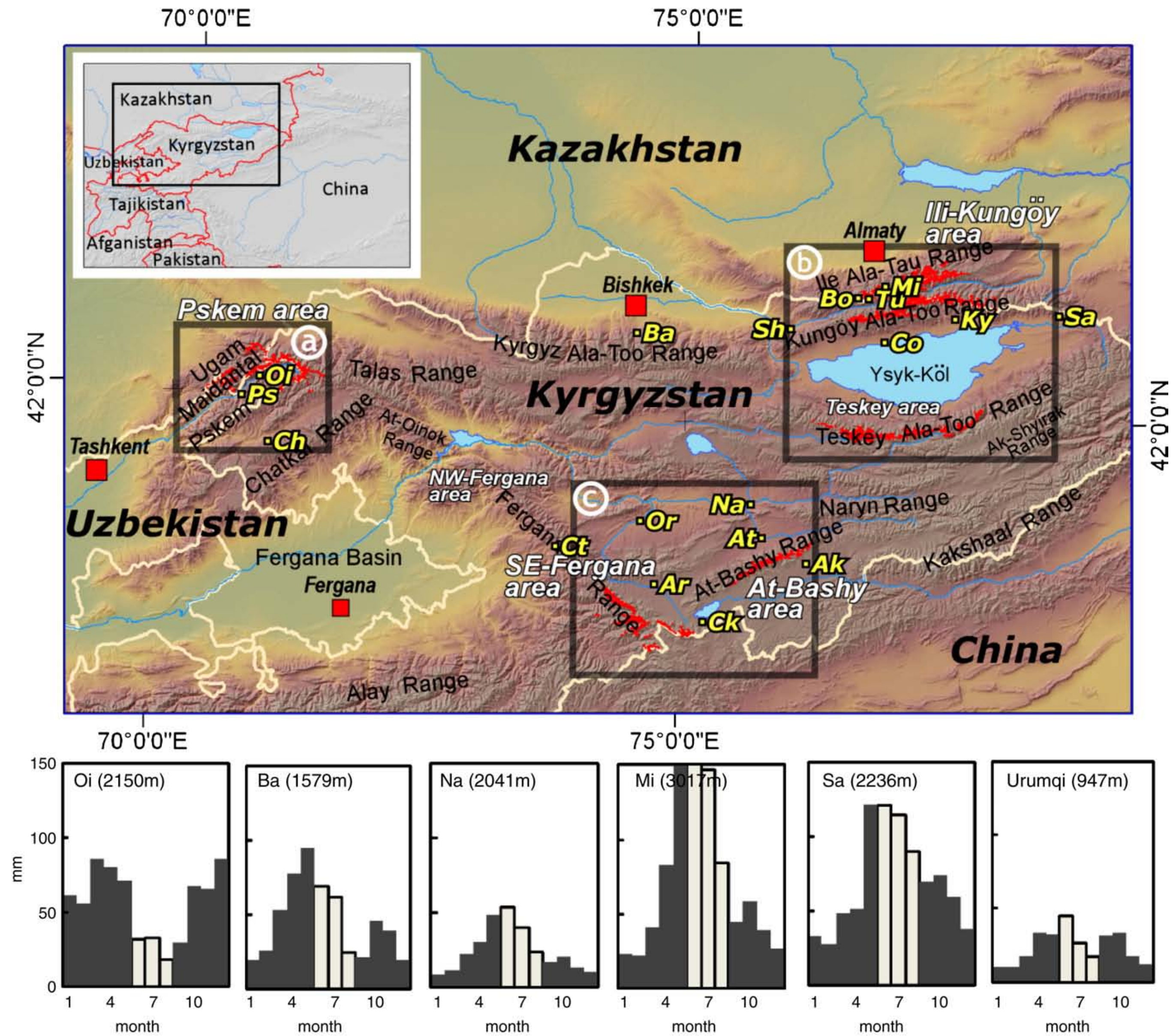

Fig. 1. Studied mountain regions in the Tien Shan. Black rectangles (a, b, c) indicate the areas enlarged in Fig. 2. Red areas indicate the glacier areas produced and investigated in this study. Yellow two-letter abbreviations and dots show the locations of the 18 meteorological stations used (Table 1). Figures at the bottom show the seasonal variation in monthly precipitation for 1981–1990 for selected stations (white bar: JJA).

ranges, and the western part of the Talas range (Fig. 2). The Ili-Kungöy region includes the Ili Ala-Too (Kazakh: Ile Ala-Tau) and Kungöy Ala-Too (Kazakh: Kungey Ala-Tau) ranges. The At-Bashy region encompasses the At-Bashy range, where comparably large glaciers (>1 km^2) are concentrated in the central part of the range. The southeastern (SE) Fergana region includes the southeastern part of the Fergana range, which extends approximately 200 km from northwest to southeast through the Kyrgyz Republic (Kyrgyzstan). The highest concentration of glaciers is in the SE-Fergana region. The four regions chosen are particularly suitable for spatial comparison of glacier area changes in the Tien Shan Mountain system because they are affected by various precipitation regimes and include small alpine glaciers with clean-ice surfaces at similar elevation ranges (4000–5000 m asl). Such small, debris-free glaciers are expected to react to and thus indicate climatic changes comparably direct and unfiltered due to their shorter response times and lack of insulating supraglacial debris. The Pskem and Ili-Kungöy regions contain some debris-covered glaciers. Pan-sharpening of the applied multispectral satellite data using the Landsat 7 ETM+pan-chromatic channel (15 m resolution) and ALOS PRISM data (2.5 m) was used to support manual mapping of such glacier boundaries (see Methods).

To analyze recent climate changes, 18 meteorological stations at high elevations were selected around the four mountain regions (Fig. 1). Seasonal and annual precipitation vary significantly throughout the Tien Shan Mountains (Table 1; Fig. 1). The Pskem region receives most of its precipitation from winter to spring. In contrast, in the Ili-Kungöy, At-Bashy, and SE-Fergana regions, maximum precipitation occurs when the weakened Siberian High allows moisture to

Fig. 2. Location of glaciers investigated in four mountain regions, enlarged from Fig. 1. (a) Pskem region, (b) Ili-Kungöy and Teskey regions, (c) At-Bashy and SE-Fergana regions. The Teskey region was documented by Narama et al. (2006). The study presented here examined 2014 glaciers, including 269 glaciers of the Teskey region. Yellow symbols indicate the locations of meteorological stations (Table 1).

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71°0'0"E
Kazakhstan
525 glaciers
a
Talas range
Ugam range
Maidantal
Oi
Ps
Uzbekistan
Pskem range
Kyrgyzstan
Chatkal
0
30
60
km
Ch
42°0'0"N
77°0'0"E
78°0'0"E
Kazakhstan
P2
Ili Ala-Too range
Mi
Bo
Tu
735 glaciers
43°0'0"N
Kungöy Ala-Too range
Ky
Sh
Co
Kyrgyzstan
Ysyk-Köl
269 glaciers
Teskey Ala-Too range
b
0
50
100
km
42°0'0"N
75°0'0"E
76°0'0"E
0
40
80
km
c
Na
Kyrgyzstan
Or
At
Ak
41°0'0"N
Fergana range
Ar
At-Bashy range
192 glaciers
Ck
306 glaciers
China

Table 1
The 18 meteorological stations and climate data used in this study. Seasonal precipitation shows the proportion of precipitation in each of the four seasons. The trends of summer temperature and seasonal precipitation show a linear relationship.

Mountain region	Meteorological station	Symbol (Figs. 1 and 2)	Elevation (m asl)	Ann. ave. temp (°C) in 1981–1990	Ann. precip. (mm) in 1981–1990	Seasonal precip. (%) DJF	MAM	JJA	SON	JJA temp.ternd (°C) In 1961–2000	Seasonal precip.ternd (mm) In 1961–2000	
Pskem	Pskem	Ps	1260	9.5	799.3	**33**	**35**	7	25	0.01	DJFMAM	1.58
	Oikaing	Oi	2150	2.9	684.4	**29**	**35**	12	24	0.01	DJFMAM	0.62
	Chatkal	Ch	1937	2.8	328.9	**30**	**36**	13	21	–	DJFMAM	–
Kyrygz	Baityk	Ba	1579	6.6	598.2	12	**40**	**29**	19	0	MAMJJA	−1.25
Ili-Kungöy	Shabdan	Sh	1520	4.9	454.9	10	**41**	**32**	17	0.01	MAMJJA	0.04
	Tuyuksu	Tu	3450	−4.0	993.0	8	**30**	**43**	19	–	MAMJJA	–
	Bolshoe Almatinkoe Lake	Bo	2516	1.4	844.3	10	**36**	**37**	17	0.01	MAMJJA	−1.15
	Minzylky	Mi	3017	−1.5	882.9	8	**32**	**44**	16	0.03	MAMJJA	−0.15
	Cholpn-Ata	Co	1645	8.1	306.5	10	**28**	**38**	24	0.02	MAMJJA	1.07
	Kyrchyn	Ky	2100	2.7	624.7	11	**31**	**38**	20	–	MAMJJA	–
	San-Tash	Sa	2236	2.5	850.4	12	**26**	**38**	24	0.02	MAMJJA	2.92
At-Bashy	Naryn	Na	2039	3.5	298.2	10	**34**	**39**	17	0.02	MAMJJA	0.78
	At-Bashy	At	2025	1.9	288.4	13	**34**	**39**	14	0.02	MAMJJA	−0.37
	Ak-Say	Ak	3135	−7.4	268.5	7	**31**	**47**	15	0.02	MAMJJA	−1.27
SE-Fergana	Arpa	Ar	3000	−4.8	251.7	14	**34**	**35**	17	0.01	MAMJJA	−0.17
	Orto-Syrt	Or	2806	−2.7	329.7	8	**29**	**49**	14	0.01	MAMJJA	−0.57
	Chatyr-Köl	Ck	3540	−5.2	224.7	5	**31**	**50**	14	–	MAMJJA	–
NW-Fergana	Chaal-Tash	Ct	2748	1.8	1125.5	17	**41**	18	24	–	MAM	–

Bold: high precipitation season, Trend: liner regression.

Table 2
Corona KH-4B, Landsat 7 ETM+, and ALOS (PRISM and AVNIR) data used in this study.

Study area	Corona date	Corona	Landsat date	Landsat (ETM+)	ALOS date	ALOS PRISM/AVNIR-2
Pskem	1968-08-18	DS1101-2169DA074	1999-08-20		2006-08-19	PRISM
		DS1101-2169DA075	**2000-09-23**	**LE7153031000125350**	2007-09-08	AVNIR-2
		DS1101-2169DA076	2001-09-10		2008-09-22	PRISM
		DS1101-2169DA077			2008-08-07	AVNIR-2
Ili-Kungoy	1971-09-17	DS1115-2201DA001	**1999-08-08**	**LE71490301999220**	2006-08-16	PRISM/AVNIR-2
		DS1115-2201DA002	2001-06-26	LE71490302001177	2007-09-17	PRISM/AVNIR-2
		DS1115-2201DA003				
	1971-09-23	DS1115-1104DA124				
		DS1115-1104DA125				
		DS1115-1104DA126				
	1973-08-03 (Hexagon)	DZB1206-500080L013001				
At-Bashy	1968-08-19	DS1104-2185DA070	1999-09-16	LE71500311999259	2007-08-21	ASTERL3A
		DS1104-2185DA071	**2000-09-02**	**LE71500312000246**	2008-09-07	PRISM
SE-Fergana	1968-08-19	DS1104-2185DA071	**2000-09-02**	**LE71500322000246**	2006-09-07	AVNIR-2
		DS1104-2185DA072	2001-08-20	LE71500322001232	2007-09-10	PRISM
		DS1104-2185DA073	2002-09-24	LE71500322002267	2008-07-11	PRISM/AVNIR-2
		DS1104-2185DA074				
		DS1104-2185DA075				

Bold: the reference images for glacier polygon in ~2000.

arrive from the west in spring and from the north in summer (Aizen et al., 1995; Yatagai and Yasunari, 1998; Böhner, 2006). The outer mountain ranges block moisture carried by the Westerlies, causing larger annual precipitation in the Pskem and Ili-Kungöy regions of the outer ranges, as compared to precipitation in the At-Bashy and SE-Fergana regions in the interior. In the NW-Fergana region, annual precipitation resulting from southwest cyclonic circulation of the Westerlies (Aizen et al., 1995) at the Chaal-Tash meteorological station is >1000 mm (Fig. 1; Table 1). In contrast, the SE-Fergana region, located east of the Fergana-Alay ranges, is the driest of the four study regions with 224.7 mm annual precipitation in Chatyr-Köl .

In this paper, local Kyrgyzstan geographic names are used according to Barataliev (2004) and Barataliev et al. (2004), with Roman orthography based on Komatsu et al. (2005).

3. Methods

3.1. Satellite data and processing

To compare recent changes in glacier area over similar time intervals (~1970, ~2000, ~2007) in four regions of the Tien Shan Mountains, this study analyzed 17 Corona photographs taken during 1968–1971, 10 Landsat Enhanced Thematic Mapper Plus (ETM+) images taken during 1999–2002, and 13 ALOS PRISM and AVNIR satellite data sets during 2006–2008 (Table 2). The Corona photographs used are from the Corona KH-4B satellite (a surveillance satellite) and have approximately 1.8 m resolution at a scale of approximately 1:247,500. Within our study region, the Corona KH-4B program took several continuous acquisitions over an area of about 14×188 km in the former USSR. In snow-covered areas of

Fig. 3. Example for a comparison of glacier outlines from (a) ALOS/pan-sharpened (PRISM: 2.5 m/AVNIR: 10 m), (b) Landsat 7 ETM+/pan-sharpened (bands 5, 4, 3: 30 m/band 8: 15 m), and (c) Corona KH-4B (1.8 m) images of the Kungöy Ala-Too range. Red glacier outlines of 2007, yellow outlines of 1999, and blue outlines of 1971.

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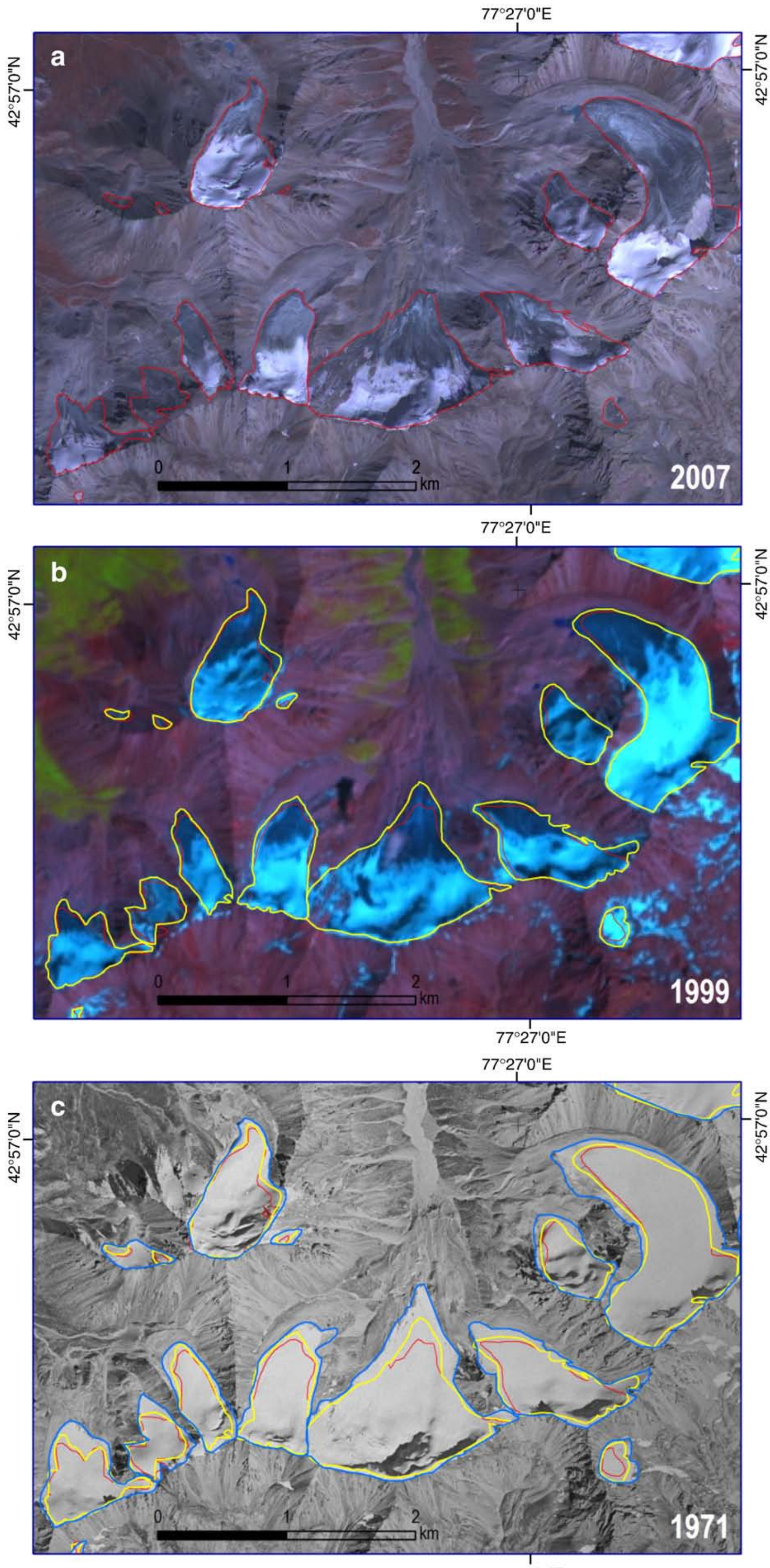

the Pskem region, a Hexagon KH-9 image from 1973 was used for validation. The Hexagon KH-9 satellite image covers an area of about 161 × 241 km with approximately 6–9 m spatial resolution. In the At-Bashy region, ASTER data (L3A orthorectified image product by ERSDAC) were used to interpret glacier outline visually in support of ~2007 mapping.

The Landsat 7 ETM+images have spatial resolutions of 30 m (multispectral) and 15 m (band 8; pan-chromatic) over an area of 180 × 180 km. The ALOS/PRISM sensor includes a nadir, forward, and backward sensor, generating a stereoscopic image data set of 35 × 35 km (triplet mode) and 70 × 35 km (nadir only) with a spatial resolution of 2.5 m. ALOS/AVNIR (70 × 70 km) provides four bands from a visible to near-infrared radiometer with a spatial resolution of 10 m (JAXA, 2009). A topographic map (1:50,000) produced in the 1980 s by the USSR, and a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM3) were used for orthoprojection of the Corona KH-4B, Landsat 7 ETM+, and ALOS data using the PCI Geomatica Orthoengine version 10.1 software. The Corona data (four scenes scanned at 3600 dpi) were oriented based on ~50 to 100 ground control points (GCPs) from the topographic maps (1:50,000) and pan-sharpened Landsat 7 ETM+images (15 m resolution) using a camera model and bundle adjustment (Narama et al., 2006). For the Landsat and ALOS data, more than 20 GCPs were used per scene, and all images were orthorectified with the SRTM DEM. For the Corona, Landsat, and ALOS data, the orientation resulted in a root mean square error (RMSE) of less than 30 m. The orthorectified Landsat (bands 3, 4, 5, and band 8: pan-chromatic) and ALOS (AVNIR bands 2, 3, 4, and PRISM pan-chromatic) images were fused and the pan-sharpened images by IHS model were used for retrieving a large number of GCPs for orientation of the Corona KH-4B and Hexagon KH-9 photographs (Fig. 3).

3.2. Glacier outline extraction

To produce accurate glacier outlines, the first step was to extract current (~2007) glacier areas manually as polygon data, using pan-sharpened ALOS (PRISM, AVNIR) images (2006–2008) at high resolution (2.5 m; Fig. 3).

In a second step, pan-sharpened Landsat 7 ETM+images (1999–2002; 15 m resolution) and ratio images of bands 4/5 of Landsat 7 ETM+ (Paul et al., 2002; Kääb, 2005) were used to retrieve glacier outlines manually around the year 2000. Images from 1999 or 2000 formed the main source for glacier outlines for ~2000 (Table 2). However, for those

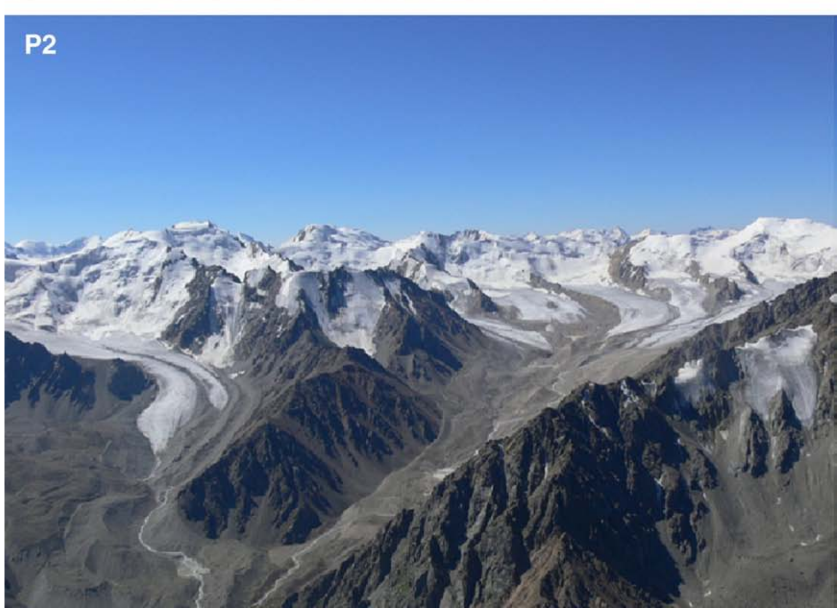

Fig. 4. (P1) Photographs of typical mountain glaciers in the Maidantal Range by D. Kobayashi (29 Aug 1999), (P2) the Talgar valley in northern flank of the Ili Ala-Too Range by V.N. Vinokhodov (22 Aug 2006; Fig. 2).

Table 3
Derived glacier parameters (~2007) for the four study areas.

Study area		Pskem	Ili-Kungöy	At-Bashy	SE-Fergana
Elevation min. (m)		3002	3306	3526	3521
Elevation max. (m)		4426	4939	4740	4980
Elevation ave. (m)		3716	3909	4159	4241
Elevation range ave. (m)		300	365	363	398
Area (%)	0.01–0.1(km^2)	3	1	2	2
	0.1–0.5 (km^2)	29	12	19	19
	0.5–1(km^2)	26	11	13	19
	1--5 (km^2)	41	50	60	55
	5– (km^2)	0	26	5	6
Slope (degree)		24	23	25	24
Aspect (%)	N	0.5	1	4	0
	NE	16	11	17	12
	E	26	18	12	14
	SE	16	13	18	16
	S	13	15	16	17
	SW	12	15	15	19
	W	11	21	10	13
	NW	6	7	8	9
Number of glaciers measured		525	735	192	306
Glacier area in Corona (km^2)		219.8	672.2	113.6	190.1
Glacier area in Landsat (km^2)		177.0	590.3	99.9	172.6
Glacier area in ALOS (km^2)		168.7	564.2	95.7	171.7

images and sections containing clouds or fresh snow cover, glacier polygons were improved using two or three different pan-sharpened Landsat 7 ETM+images for different years (1999–2002).

In a third step, glacier cover for ~1970 was digitized manually using the Corona orthorectified images (1968–1971). Because the northern part of the Pskem region was snow-covered in these images, the estimated glacier outlines were validated using an orthorectified Hexagon KH-9 image from 1973.

The areas of the extracted glacier polygons were computed using ArcGIS 9.2. Glacier areas smaller than 0.01 km^2 were omitted, resulting in a total sample size of 525 glaciers in the Pskem region, 735 in the Ili-Kungöy region, 192 in the At-Bashy region, and 306 in the SE-Fergana region (Fig. 2). Finally, 2014 glaciers, including some obtained in another study in the Teskey region (Narama et al., 2006), were compared in this study. In addition, some of the glaciers were visited in fieldworks from 1999 to 2008, to better understand the glacier distribution and settings of the four study regions (Fig. 4). Due to the lack of according data, we do not consider differences between polythermal and temperate glaciers in this study.

4. Results

4.1. Characteristics of glacier distribution

We investigated the characteristics of glacier distribution in the study region by analyzing statistically the relations between topographic parameters (mean, min., max. elevation, slope, area size class, hypsography, slope, aspect; Table 3) and the glaciers using the extracted glacier polygon data from ~2007. Some parameters show clearly regional characteristics of glacier distribution. For example, the relationship between glacier area and aspect shows that many large glaciers tend to concentrate in southern aspects in the four regions. The relationship of glacier area and slope shows that large glaciers tend to have a lower average slope. These above statistical trends for glacier distribution are similar in all four mountain regions. The largest differences in the four regions are the distribution of glacier-area size classes and the distribution of glacier area with elevation (hypsography).

Fig. 5 shows the distribution of glacier coverage in the four mountain regions from approximately 1970–2000, according to the glacier size class (0.01–0.1 km^2, 0.1–0.5 km^2, 0.5–1 km^2, 1–5 km^2, >5 km^2). In the Pskem region (Fig. 4), small glaciers with areas less than 1 km^2 occupy 59% of the total glacier area, and no glaciers are larger than 5 km^2. In the other three regions, the distribution of each glacier size class is roughly similar: glaciers with areas of less than 1 km^2 occupy 25% of the Ili-Kungöy region, 35% of the At-Bashy region, and 40% of the SE-Fergana region (Table 3). The Ili-Kungöy region has large glaciers (26% of the >5 km^2 class, lowest proportion of <1 km^2 small glaciers) and the largest total glacier area (~671 km^2 in ~1970) of the four mountain regions (Fig. 5).

Fig. 6 shows the hypsography of glacierized areas in glacier-area size class for ~2007, by 25-m elevation intervals based on the glacier polygons and the SRTM DEM. The glaciers range in elevation from 3000 to 5000 m asl. The peak of maximum glacier-area differs in the four mountain regions. The present equilibrium line altitudes (ELAs; Kunakhovitch and Sokalskaya, 1997; Dyurgerov et al., 1995) are close to coincident with the elevation of the total maximum glacier area. The present-day glacier areas in the Pskem and Ili-Kungöy regions, in the outer ranges, are at lower elevations than those in the At-Bashy and SE-

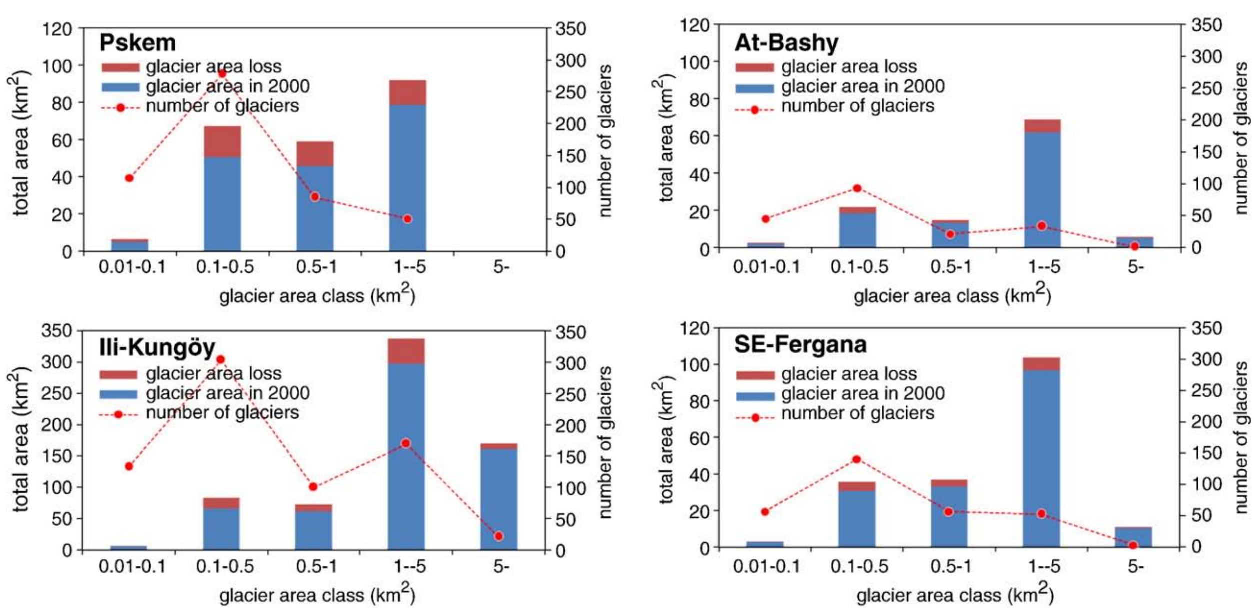

Fig. 5. Glacier area and area loss by glacier size class for ~1970–2000. The proportion of small glaciers (<1 km^2) is highest in the Pskem region. The Ili-Kungöy region has the largest glacier coverage among the four study regions.

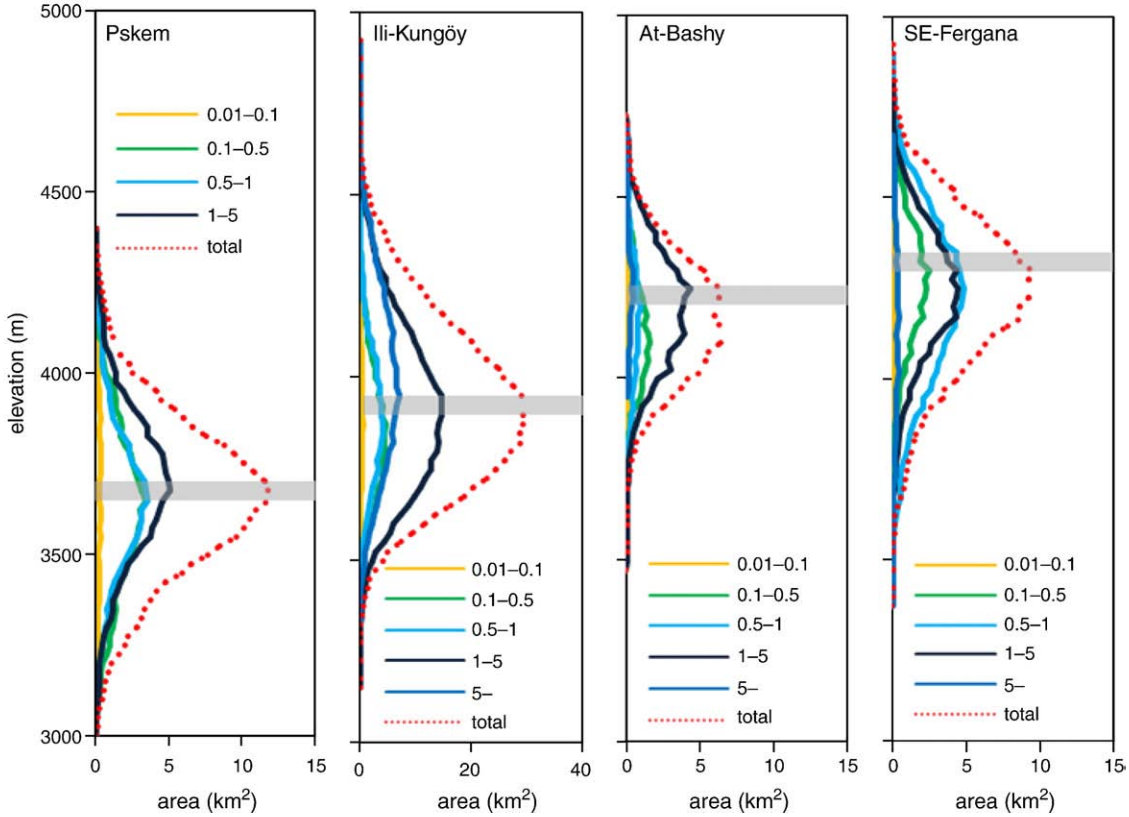

Fig. 6. Hypsography (~2007) of glacier area (0.01–0.1 km^2, 0.1–0.5 km^2, 0.5–1 km^2, 1–5 km^2, >5 km^2, and total) distribution by 25-m elevation intervals, as derived from glacier polygons and the SRTM DEM. Gray zones show the present equilibrium line altitudes (ELAs) reported by Dyurgerov et al. (1995).

Fergana regions, in the interior mountain ranges (Table 3). This indicates that differences in climatic conditions in elevation affect glacier response, and that glacier melting in the Pskem and Ili-Kungöy regions is promoted by higher temperature at the lower elevations. The relationship between glacier area and minimum glacier elevations in the Ili-Kungöy, At-Bashy, and SE-Fergana regions shows, unsurprisingly, that the termini of the large glaciers are located at lower elevations. However, the glacier terminus altitudes of small glaciers are scattered over a wide elevation range (Fig. 6). In particular in the Pskem region which many small glaciers (<1 km^2) the altitudinal distribution shows no correlation with glacier size. This suggests that the mass loss of small glaciers in this region might not largely differ from the mass loss of the larger glaciers.

4.2. Changes in glacier area from ~1970–2000 and ~2000–2007

Changes in glacier area extracted from repeat satellite data show that glacier behavior has differed markedly within the Tien Shan Mountains since ~1970. In the period from approximately 1970–2000 (Corona and Landsat data), the glacier area decreased by 19% in the Pskem region, 12% in the Ili-Kungöy region, 12% in the At-Bashy region, and 9% in the SE-Fergana region (Fig. 7a). From approximately 2000–2007 (Landsat and ALOS data), glacier coverage shrank by 5% in the Pskem region, 4% in the Ili-Kungöy region, 4% in the At-Bashy region, and 0% in the SE-Fergana region (Fig. 7b). Including the 8% decrease in the Teskey region from Narama et al. (2006), the greatest decrease in areal extent of that glaciers studied was in the Pskem region (19% and 5%), followed by the Ili-Kungöy and At-Bashy regions (12% and 4%). In contrast, only small decreases in glacier area were found for the SE-Fergana region (9% and 0%). Glaciers in the SE-Fergana region exhibited in total no decrease (0%) during ~2000–2007. Recent glacier shrinkage (2000–2007) took place with a slightly higher rate than during 1970–2000, except in the SE-Fergana region (9% and 0%).

Fig. 8 shows the relationship between glacier area and glacier change (%) from approximately 1970–2000 in the Pskem and Ili-Kungöy regions. Small glaciers (<1 km^2) had a large range of change from −80% to +3%. In contrast, the relative shrinkage of large glaciers (>1 km^2) for each glacier was small, although large glaciers lost

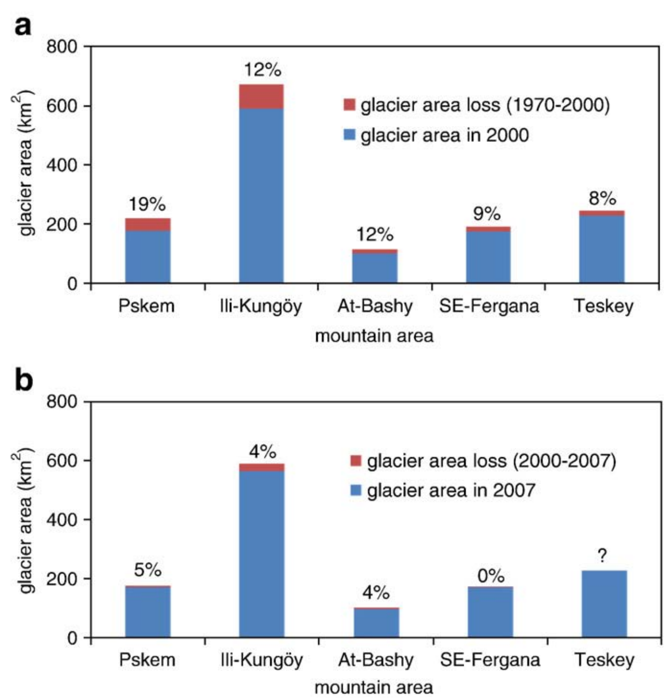

Fig. 7. Changes in total glacier area in five mountain regions for (a) ~1970–2000 and (b) ~2000–2007.

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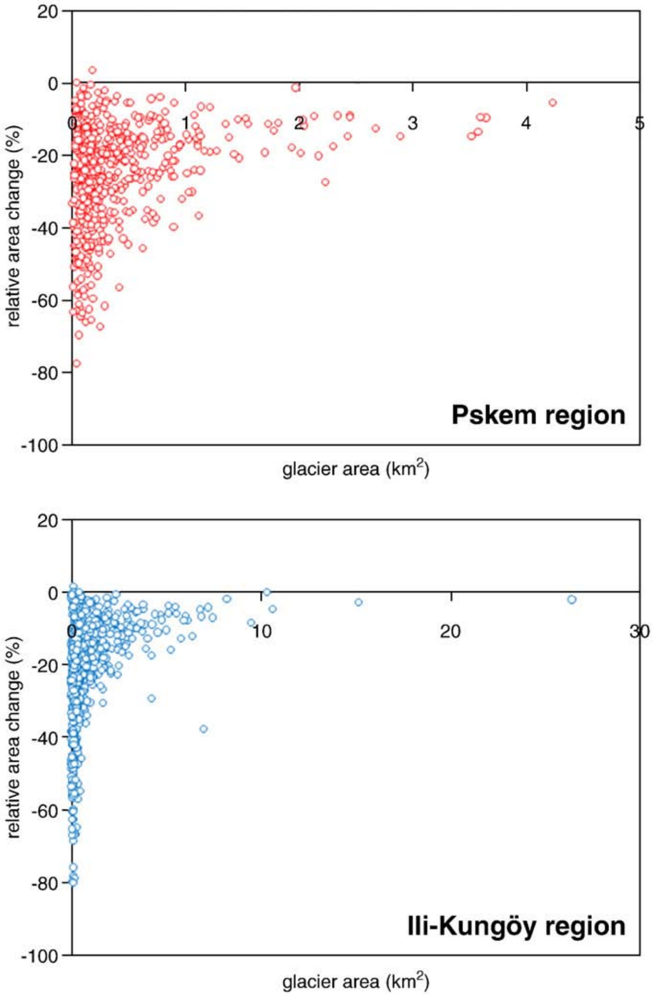

Fig. 8. Relationship between glacier area and relative glacier-area change (%) for ~1970–2000 in the Pskem and Ili-Kungöy regions.

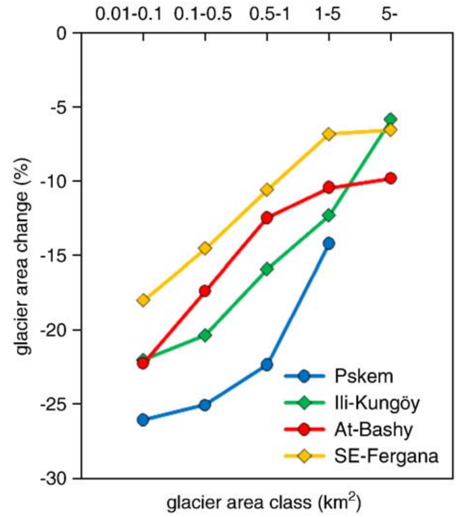

Fig. 9. Glacier area loss for ~1970–2000 by glacier-area size class (0.01–0.1 km^2, 0.1–0.5 km^2, 0.5–1 km^2, 1–5 km^2, and >5 km^2).

comparatively large areas at lower elevations. The termini of small glaciers are particularly sensitive to climatic changes (Jóhannesson et al., 1989; Knight, 1998; Nesje and Dahl, 2000), and small glaciers are distributed over a wide elevation range (Fig. 6), resulting both in larger overall area loss and larger variability of area changes compared to larger glaciers. Thus, small glaciers contribute disproportionately to the overall glacier shrinkage. In addition to the importance of microclimatic and local glaciological factors (Kuhn, 1995), a group of small glaciers of a given total area will have a much longer total outline length than a group of larger glaciers with the same total area, so that the same mass loss leads to a larger percentage of area loss for the group of smaller glaciers.

Thus, the relative abundance of glaciers in the different size classes strongly affects on the total percentage glacier area loss (Fig. 8). In fact, comparing glacier size classes and glacier shrinkage, the Pskem region in the outer range, with its many small glaciers (<1 km^2) experienced large glacier shrinkage (19%). In contrast, the Ili-Kungöy region in the outer range has many large glaciers (>5 km^2) and glacier shrinkage was smaller (12%). To evaluate the effect of regional differences in climatic conditions on glacier shrinkage in the four mountain regions, glacier shrinkage was compared in five glacier size classes (0.01–0.1 km^2, 0.1–0.5 km^2, 0.5–1 km^2, 1–5 km^2, and >5 km^2; Fig. 9). Glacier shrinkage in all glacier size classes was greatest in the Pskem region, followed by the Ili-Kungöy region, both of which are outer ranges of the Tien Shan. In contrast, the At-Bashy and SE-Fergana regions, in the interior ranges, exhibited comparatively small reductions. Percentage glacier area loss in the dry SE-Fergana region was small. The region where climatic conditions and glacier hypsography most strongly affect glacier shrinkage are the Pskem region, followed by the Ili-Kungöy region. In addition, the Pskem region experienced the largest glacier shrinkage (19%) because the highest proportion (59%) of small glaciers. In all four mountain regions, the glacier shrinkage trend with size class was similar (Fig. 9).

4.3. Glacier advances in the SE-Fergana region since ~2000

Although most mountain regions experienced glacier retreat over the last 7 years (~2000–2007), glacier coverage in the SE-Fergana region exhibited no change (0%). In this area, 16 of the 306 glaciers measured advanced dramatically over the 7-year interval, by as much as 1400 m. These enlarged glaciers exhibit characteristics of glacier surging, such as many crevasses on the glacier surface and steep convex snouts. These surge-type events for large glaciers (>1 km^2) took place simultaneously during the period from ~2000–2007. Although many glacier surges were documented in the central Pamirs (e.g. Kotlyakov et al., 1996; Knizhnikov et al., 1998; Konovalov and Desinov, 2007), these events were infrequent. In contrast, most small glaciers have been shrinking. Excluding the glaciers with clear signs for surging, glaciers in the SE-Fergana region decreased by −3% in areal extent during ~2000–2007.

5. Discussion

5.1. Recent glacier shrinkage related to local climate changes

Glacier area has been decreasing recently in five mountain regions, including the Teskey region. Fig. 10 shows summer temperature anomalies (June–August; JJA) and precipitation during the accumulation season from 1961–2000 for the four study regions. Table 1 presents climate trends from 18 meteorological stations in high elevation around the four study regions, analyzed using non-parametric Mann–Kendall rank statistics (e.g., Press et al., 1989). Precipitation data for the accumulation season in each region were used for the trend analysis (Pskem region: winter/spring, Ili-Kungöy region: spring/summer, At-Bashy region: spring/summer, SE-Fergana region: spring/summer; Table 1). Although trends were not statistically significant at the 5% level, the trends show that most summer temperature series for the study regions showed increases; increasing summer temperature was significant in the Ili-Kungöy and At-Bashy regions. In contrast, precipitation in accumulation season decreased during 1961–2000, except in the Pskem region and parts of the Ili-Kungöy region.

In the Pskem region, glacier accumulation takes place in winter/spring (Table 1). Snow accumulation during this time is very

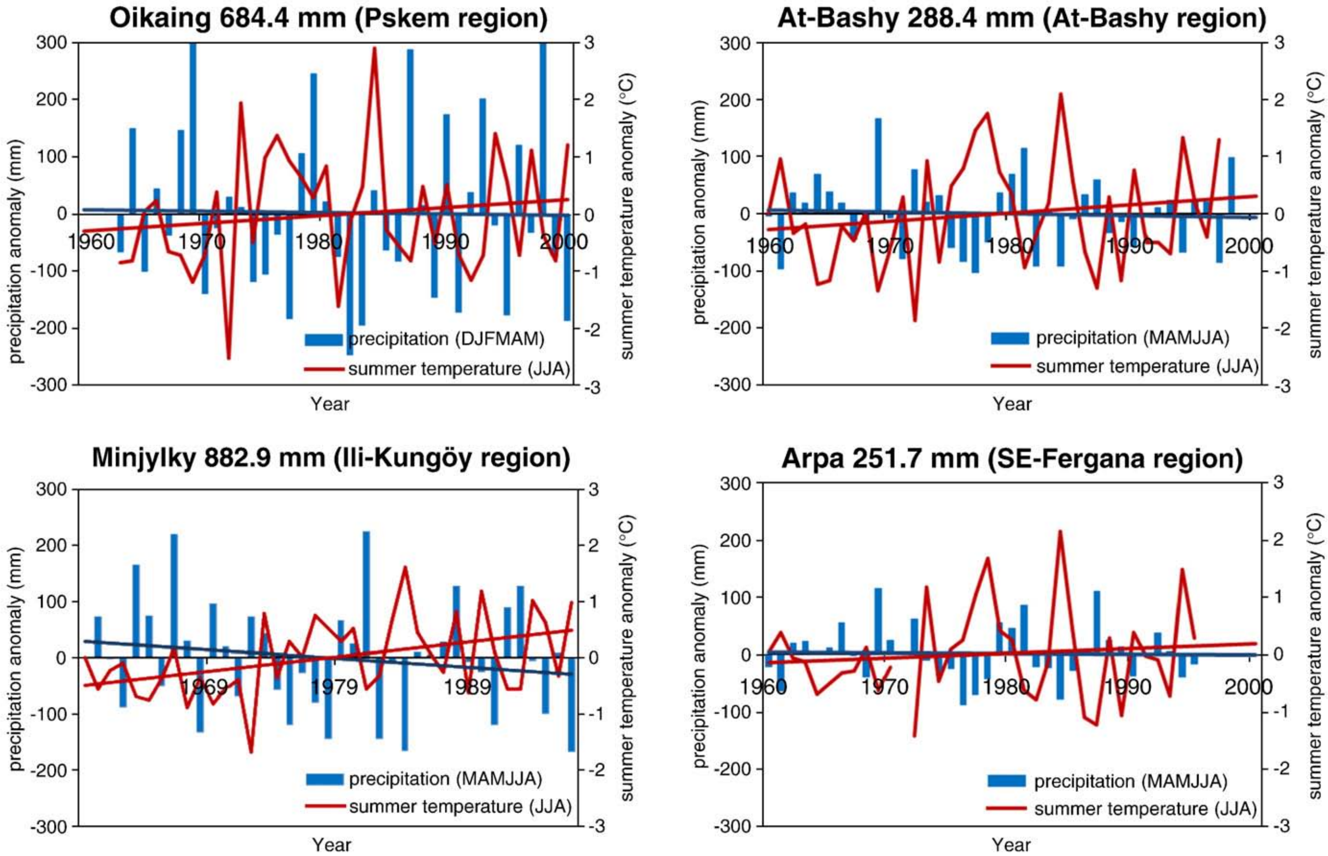

Fig. 10. Summer temperatures (June to August) and precipitation during the accumulation season for 1961–2000 in four meteorological stations in each region.

important in delaying ice-melting because snow cover on glacier surfaces maintains a high albedo. Although the winter/spring precipitation increased slightly or remained stable from 1961 to 2000 (Table 1), generally increasing summer temperature led to significant glacier-ice melt, which exceeded obviously snow accumulation. In the Ili-Kungöy, At-Bashy, and SE-Fergana regions, glacier accumulation occurs in spring/summer (Table 1), meaning that the seasons of highest accumulation and ablation are close or even coeval. This is characteristic for the "summer-accumulation glacier type" in the Himalayas (Ageta and Higuchi, 1984), in which air temperature strongly controls both snow fall and melting. Increasing summer temperature leads to 1) an increased amount energy available for ice and snow melt, 2) decreased snow accumulation (and increased proportion of liquid precipitation), and 3) lower albedo of the glacier surface (Ageta and Kadota, 1992; Fujita and Ageta, 2000; Dikich and Hagg, 2004; Hagg and Braun, 2005). Spring/summer precipitation recorded at meteorological stations in these regions decreased or showed no change, except for the Cholpon-Ata, San-Tash, and Naryn meteorological stations. Regardless of the difference in accumulation season, the Pskem region experienced the greatest glacier shrinkage of the four study regions. Regionally, climate change during 1961–2000 caused increased summer temperature, which seems to be the most significant factor for recent glacier shrinkage in the Tien Shan.

5.2. Regional differences in glacier area changes

Although glaciers have generally shrunk recently under increasing summer temperatures, changes in glacier area have significantly differed among the study regions. Several factors contribute to these differences:

1) Glaciers in the outer ranges receive the highest annual precipitation (Table 1). Ice-mass turnover is assumed to be particularly large in the outer ranges where the accumulation-to-ablation ratio is high leading to larger mass flux between accumulation and ablation zones. Especially when the precipitation in the accumulation season decreased or showed no change during 1961–2000 while at the same time the summer temperatures where increasing, the potential for glacier mass loss was strongest in the Pskem and Ili-Kungöy regions. Previous studies also show significant glacier area reduction; 12% (1977–2003; Aizen et al., 2006) and 28% (1963–2000; Niederer et al., 2007) in Kyrgyz region; 16–32% (1955–1999) in Ili-Kungöy regions (Bolch, 2007). In contrast, glacier area loss is much less significant in the interior ranges (At-Bashy and SE-Fergana), where cold/dry conditions prevail and cause a lower glacier mass turnover. In the dry/cold western Kunlun Mountains, where evaporation represents 30% of the total ablation, glaciers shrank by only 0.4% from 1970–2001 (Shangguan et al., 2007). In the north-western part (NW-Fergana) of the Fergana range (Fig. 1), sparse and small glaciers are present on mountain tops. This region, which receives abundant moisture from southwestern cyclonic circulation in spring (Aizen et al., 1995), receives most precipitation among the Tien Shan mountains (Fig.1, Table 1; Chaal-Tash meteorological station). The above results show that the glaciers in the outer Tien Shan Mountains that receive highest precipitation volumes are particularly sensitive to climatic changes due to their large mass-turnover rates.
2) The average elevations of glacier termini in the outer mountains (3700–3900 m asl) are lower than those in interior areas (4150–4250 m asl). Glaciers in the outer ranges experience more significant ice melting because air temperatures are higher than in interior mountain areas at higher elevation (Fig. 6). This effect is especially clear in the Pskem area, where glacier shrinkage has been most pronounced. In addition, the average elevation range (~300 m) of glaciers in the Pskem region is smaller than that of the other regions (~365–400 m; Table 3). The Pskem region may in the

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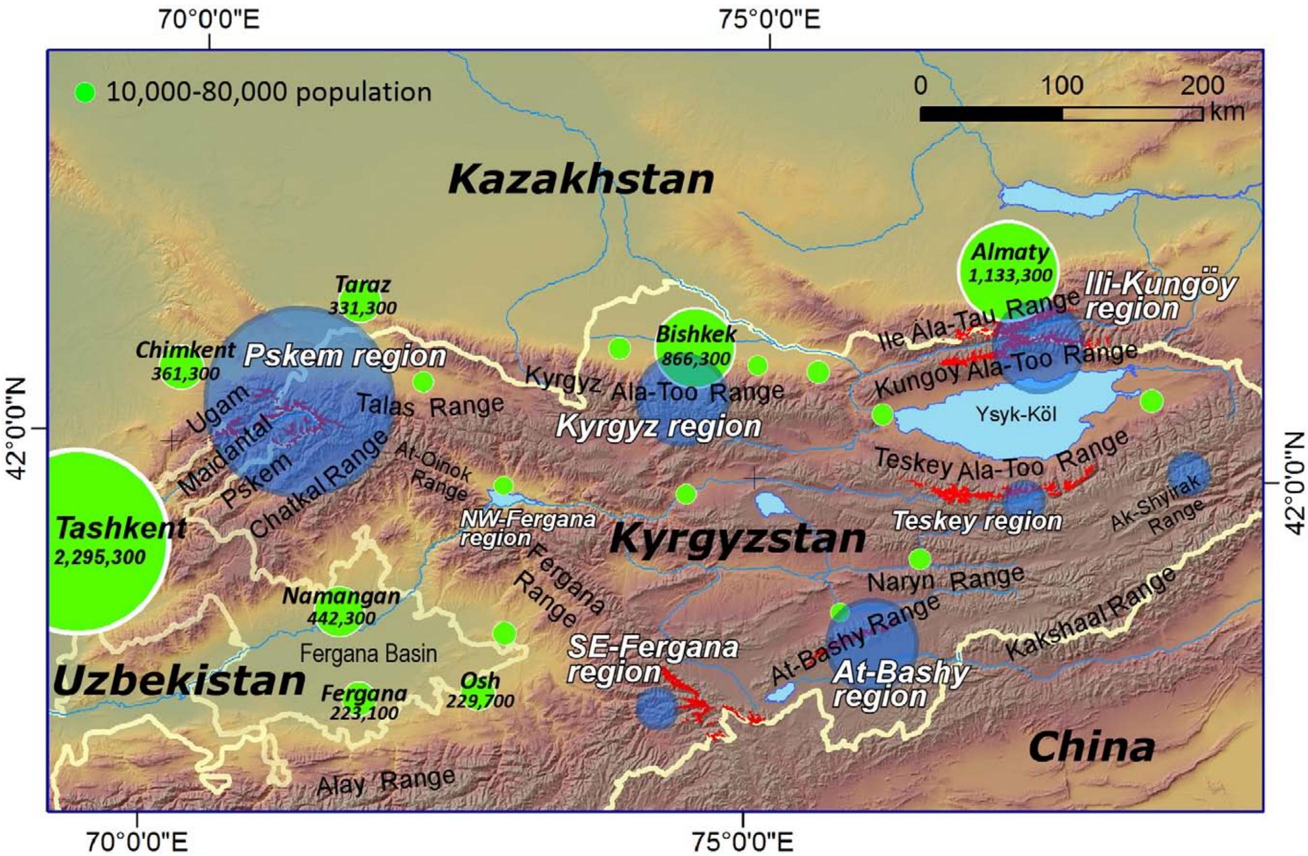

Fig. 11. Blue circles: glacier shrinkage (Pskem, Ili-Kungöy, At-Bashy, SE-Fergana and Teskey regions: ~1970–2007; Kyrgyz and Ak-Shiyrak regions from Aizen et al., 2006: 1977–2003). Green circles: population in cities around the Tien Shan.

near future even suffer more glacier ablation because glaciers that stretch over such a small elevation range are in risk that their entire area falls in the ablation zone through the ELA climbing above their maximum heights. The environmental conditions (mainly climatic conditions and hypsography) that produce the greatest glacier reduction are expressed in the outer ranges (Fig. 9), in the Pskem region, followed by the Ili-Kungöy region.

3) Taking into account the influence of the glacier size distribution in the four regions, the Pskem region, characterized by many small-scale glaciers (<1 km^2), has had the most significant glacier reduction (Fig. 5). The Ili-Kungöy region has not shown a large percentage glacier reduction because of the many large glaciers (>1 km^2) that dominate. However, the Ili-Kungöy region, with the largest glacier coverage (~671 km^2) of the four regions, may have the significant effect on discharge to lowland areas. As reported by Aizen et al. (2006) and Niederer et al. (2007), the Kyrgyz region of the same outer ranges will experience decreases in the glacier areas.

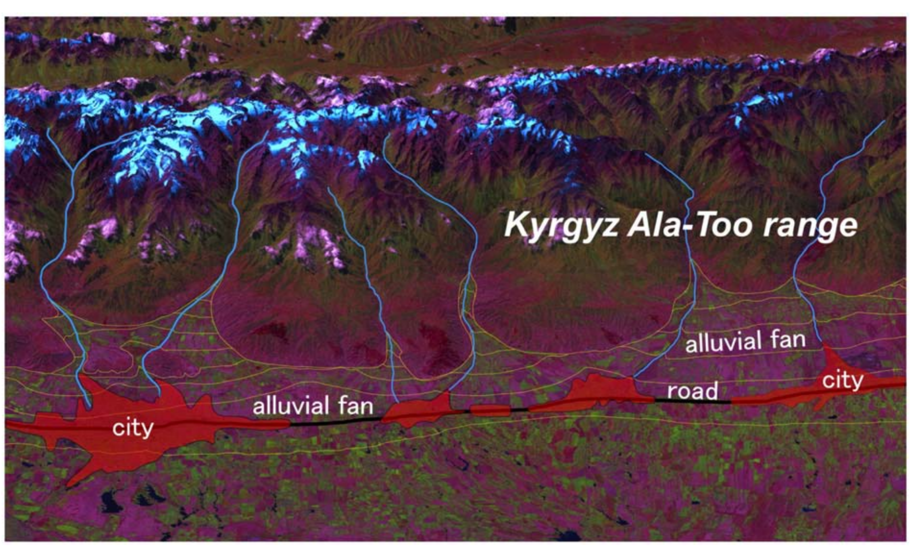

Fig. 12. Cities developed on alluvial fans along the outer ranges of the Tien Shan. Residences use ground water for drinking water. Background: oblique view on a Landsat image draped over the SRTM DEM.

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5.3. Potential effects of shrinking glaciers

It is important to determine where glacier shrinkage will have the greatest potential to affect lowland areas. Fig. 11 shows the glacier shrinkage from this study and Aizen et al. (2006), and population distribution for major cities in the Tien Shan Mountains. Densely populated, large cities (e.g., Tashkent, Bishkek, and Almaty) have developed along the outer ranges, where glacier shrinkage is greatest. Changes in seasonal runoff volume have been estimated for 50% glacier loss in the Tien Shan, using models based on meteorological data and assuming the $2\times CO_2$ scenario for 2050 to 2075 (Hagg et al., 2007). Decreased glacier coverage leads to decreased summer time glacier-melt discharge in July and August. In the Pskem region, where glaciers accumulate in the winter/spring and summers are dry, decreased summer runoff caused by glacier shrinkage may result in water shortages for residents of lowland areas (e.g. Tashkent, Chimkent) in the Pskem region. The following large shrinking glaciers in the Kyrgyz and Ili-Kungöy regions also may eventually not be able to supply the water needed for stable discharge during drought years. In addition, large cities (e.g., Bishkek, and Almaty) have developed on alluvial fans at the bases of outer ranges (Fig. 12). These urban centers rely on glacier meltwater for domestic water, irrigation, industry, and hydropower (Severskiy et al., 2006; UNEP, 2007). Many urban households use ground water, and while industrial development and population increase have remained small in recent years, water use has increased in both urban and rural areas of the outer range (Oosinova, 2001). As urban populations are foreseen to increase over the coming decades and declining water discharge leads to depleted groundwater reservoirs, cities along the outer ranges of the Tien Shan may experience enhanced problems for water supply.

Other problems associated with glacier shrinkage are glacier hazards such as glacier lake outburst floods (GLOFs). Glacier lakes have developed rapidly since the 1970 s in the outer ranges of the Tien Shan. Recently developed pro-glacier lakes have reached sizes similar to lakes found in the 1960 s–1970 s, when a number of catastrophic GLOFs occurred (e.g., Kubrushko and Staviskiy, 1978; Baimoldaev and Vinohodov, 2007; Narama et al., 2009). Lake outbursts may thus become an increasing threat in the Tien Shan. The above factors stress the need for research on sustainable water-use practices and monitoring of glacier change and glacier-related hazards.

6. Conclusions

Glaciers of the Tien Shan decreased significantly in area between ~1970 and ~2007, primarily due to increasing summer temperatures. Regional glacier shrinkage has varied greatly mainly as a function of the regional climate conditions, glacier area variation with elevation (hypsography), and the proportional of glacier-size distribution. Glacier shrinkage was more pronounced in the outer ranges of the Tien Shan than in interior regions. The largest glacier shrinkage during ~1970–2007 was in the Pskem region. Particularly many water users are concentrated in the outer ranges, and continuing glacier shrinkage is expected to present an increasing problem for water availability in the region. This threat is most likely to be realized during the summer dry season in the Pskem region, when decreased summer runoff resulting from reduced glacier areas may lead to water shortages for residents of lowland areas. In addition, glacier shrinkage enhances the probability for moraine lake development and increase, producing glacier hazards such as GLOFs. The recently observed extensive development of glacier lakes may thus enhance these threats to local residents.

Acknowledgments

Special thanks are due to B. Romstad, G. Moholdt, and R. Frauenfelder of the University of Oslo, Y. Ageta and K. Fujita of the Nagoya University, J. Kubota and M. Watanabe of RIHN, G. Glazirin of the Central Asian Research Hydro Meteorological Institute, I. Severskiy of the Institute of Geography, Kazakhstan, C. Ormukov of the Institute of Seismology, Kyrgyz Republic, R. R. Usubaliev of CAIAG, T. Kajiura of the Rissho University, M. Zaiki of Seikei University, V.N. Vinokhodov, D. Kobayashi, for their valuable scientific advice, provision of materials, and accommodation. We also thank K. McGuffie and three reviewers for valuable comments on the manuscript. This work was supported by the Ministry of Education, Culture, Sports, Science and Technology (JSPS Fellow 16-0508), Sasagawa Grants for Science Fellow (SGSF), and Ili Project of the Research Institute for Humanity and Nature (RIHN). The work of A. Kääb is supported by the European Space Agency GlobGlacier project. The presented study is connected to the Global Land Ice Measurements from Space (GLIMS) project.

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