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Glacier characteristics and changes in the Sary-Jaz River Basin (Central Tien Shan, Kyrgyzstan) – 1990–2010

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The water discharge from the heavily glacierized Sary-Jaz River Basin (Eastern Kyrgyzstan) is of high importance for the very arid Tarim Basin located in Xinjiang (north-western China). We investigated glacier changes in the entire Sary-Jaz River Basin, which covers a large part of the Central Tien Shan, for the period from 1990 to 2010 based on Landsat 'TM'/'ETM+'data. We found 1310 glaciers (>0.1 km^2), which covered 2055 ± 41.1 km^2 ($\sim$18% of the entire basin) in 1990. The glaciers shrank by 77.1 ± 57.1 km^2 (3.7 ± 2.7%) until 2010. This is considerably lower than in most other ranges of the Tien Shan. The lowest insignificant area loss (-1.5 ± 2.7%) was found in the eastern part of the basin where the largest glaciers and highest peaks are situated. Debris-covered glaciers shrank significantly less than clean-ice glaciers of comparable size. We also identified a few advancing glaciers which show surge characteristics. Climate data from the Tien Shan weather station (3614 m asl.) close to the study region showed no significant long-term trend.

1. Introduction

The mountain ranges of the Tien Shan are surrounded by densely populated arid lowlands with little summer precipitation, where glacier-fed rivers are the major source for freshwater (Sorg *et al.* 2012). Despite a dry climate, the Tien Shan holds one of the greatest concentrations of glacial ice in mid-latitude Eurasia (Kotlyakov *et al.* 2012), while Kyrgyzstan has the largest number of glaciers in the mountain range. Our study region, the Sary-Jaz River Basin ('SJRB'), is the main glacierized region of the Tien-Shan. Available studies estimate that 75% of the total discharge of the Tarim River, which is the principal source of freshwater in the Takla-Makan Basin, originates from 'SJRB'. About 40% of the overall discharge is possibly due to glacier melt water (Dikikh *et al.* 1991, Sorg *et al.* 2012). Despite their importance, our knowledge about the 'SJRB' glaciers has been limited until now. Some researchers investigated glacier

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area changes in few smaller sub-catchments (Aizen *et al.* 1997, 2006, Kutuzov and Shahgedanova 2009), but a comprehensive investigation of the entire 'SJRB' is still missing. The first information about the glacier coverage is available from the Soviet Glacier Inventory ('GI' USSR 1969–1978). However, these data are about 40 years old, and recent studies showed that the glacier area information given in the inventory is subject to inaccuracies (Narama *et al.* 2010, Sorg *et al.* 2012). Our aim is, therefore, to provide a detailed and up-to-date glacier inventory for the 'SJRB' and analyse the changes in all glaciers of this basin for the last 20-year period (1990–2010).

2. Study area

The 'SJRB' covers an area of ~11,000 km^2 and is situated in the Central Tien Shan between the Terskey Alatau Range and Kokshaal-Tau Range (highest peak: Peak Pobeda/Tomur Feng – 7439 m asl. and Khan Tengri 6695 m asl., figure 1). These mountain ranges receive most precipitation (~75%) from the Westerlies during summer. The highest amount of precipitation in the 'SJRB' can be expected in the eastern parts where the highest peaks are located, while the lower western and southern parts are likely drier (Dikikh *et al.* 1991, 'GI' USSR 1969–1978). The region receives considerably less precipitation during winter months, when the Siberian anticyclone arrives from the northeast and prevents the moist air from the west to reach the mountains. Consequently, glaciers in Central Tien Shan are mostly of summer-accumulation type. The mean annual temperature ('MAAT') is coldest in the eastern region and warmest in the western part of 'SJRB'. Long-term records of the Tien Shan weather station (3614 m asl.), located northwest of the study region, reveal the coldest temperatures in January (monthly average −21.8°C) and the warmest month is July (+4.3°C).

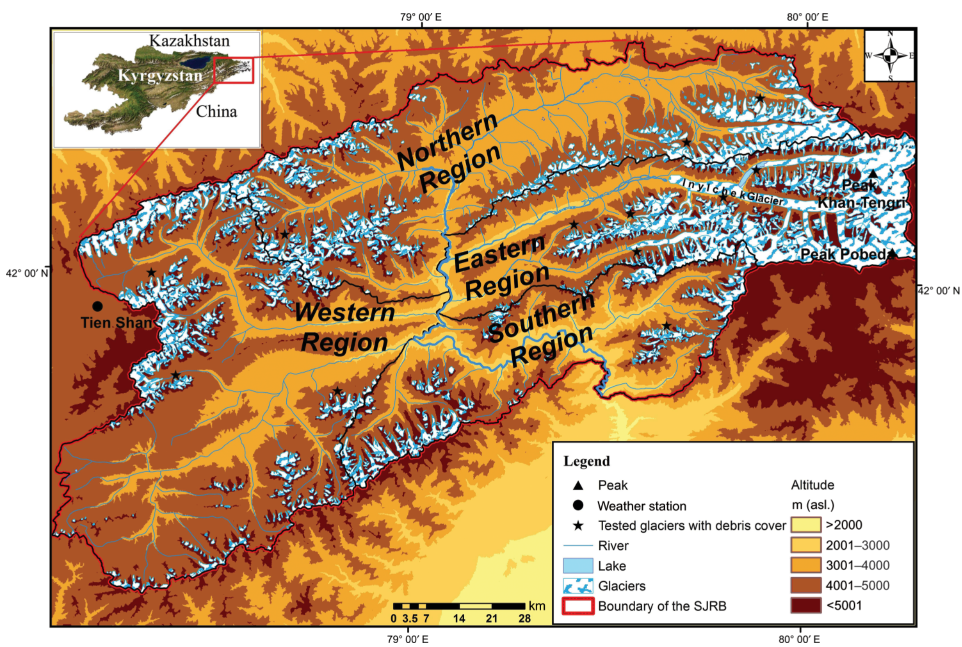

Figure 1. Location and topography of the Sary-Jaz River Basin.

Winter (December–February) is the driest period (measured precipitation ∼5.5 mm per month), while monthly precipitation is about 55 mm in summer (June–August).

3. Data and methods

The glaciers were delineated using Landsat for the last 20 years (table 1). The images were acquired during the ablation period with minimum snow and cloud cover. Unfortunately, there were no perfect scenes available for all periods; especially, seasonal snow hampered the correct identification of the glaciers in parts of some scenes. In these cases, we used the best available alternative images using data from previous years (table 1). Additional Landsat images from 1998 to 2009 were chosen for a more detailed investigation of rapidly advancing glaciers. We applied the well-established band ratio technique ('TM band 4/TM band 5') with a threshold of 2.0 for mapping of debris-free glaciers (Paul *et al.* 2002, Bolch 2007). Misclassified areas like lakes, cast shadow, seasonal snow and debris cover were manually edited. The major challenges were the correct mapping of smaller high-altitude glaciers, especially on the 1990 scene, and the identification of the debris-covered glaciers due to similar spectral signals of the surrounding debris. Here, multi-temporal scenes helped to identify the glacier margins as visible glacier movement is a sign of the presence of glacier ice underneath the debris. A direct assessment of the uncertainty is difficult with the remote-sensing-based investigations due to the lack of ground truth. Therefore, we estimated overall uncertainty based on visual checks and previous experiences (Paul *et al.* 2002) to be 2%. We distinguished four glacier size classes: small (< 0.5 km^2), medium (0.5–1.0 km^2), large (1.0–5.0 km^2) and largest (> 5.0 km^2). For more detailed analyses of the glaciers and their changes, we subdivided the 'SJRB' in four sub-regions (northern, eastern, southern and western) according to landscape and distribution of 15 river sub-basins, precipitation and temperatures (figure 1, table 2). In addition, we compared 12 debris-covered glaciers from different sub-regions with 12 clean-ice glaciers of the same size and used *t*-test paired sample analysis to test for the possible significance of behavioural differences. Climate data from the Tien-Shan weather station (3614 m asl., 41° 55′ N, 78° 17′ E) were obtained from the

Table 1. List of applied satellite images. (Image source: U.S.G.S.)

Satellite	Sensor	Path row	Image resolution (m)	Acquisition date	Remarks
Landsat5	(TM)	147*r*31	30	10 September 1990	Some seasonal snow
Landsat5	(TM)	148*r*31	30	31 July 1990	Good snow conditions
Landsat5	(TM)	147*r*31	30	16 August 2010	Few clouds and seasonal snow
Landsat7	(TM)	148*r*31	30	08 September 2010	Few clouds
Landsat5	(TM)	147*r*31	30	02 October 1998	Some seasonal snow
Landsat7	(TM)	147*r*31	30	18 August 2002	Few clouds and seasonal snow
Landsat7	(TM)	147*r*31	30	20 July 2003	Few clouds and seasonal snow
Landsat5	(TM)	147*r*31	30	08 August 2007	Some seasonal snow
Landsat7	Enhanced Thematic ETM+	148*r*31	30	11 July 2009	Some seasonal snow, SLCoff

Notes: *Basic data source; ** the alternative data source. TM = Thematic Mapper; ETM+ = Enhanced Tehmatic Mapper+

Table 2. Glacier area changes in the SJRB during 1990–2010.

Region	Area of region (km^2)	No. of glaciers	Glaciated area (km^2)		Change in glaciated area (1990–2010)	
			1990	2010	Absolute value (km^2)	Relative value (%)
North	2818.9	348	487.4 ± 9.7	455.8 ± 9.1	−31.6 ± 13.4	6.5 ± 2.7
East	2329.8	318	926.8 ± 18.5	912.8 ± 18.3	−14.0 ± 26.0	1.5 ± 2.7
South	1662.9	146	130.1 ± 2.6	124.1 ± 2.5	−6.0 ± 3.6	3.4 ± 2.7
West	4389.8	498	510.7 ± 10.2	485.2 ± 9.7	−25.5 ± 14.1	5.0 ± 2.7
Total	112,014	1310	2055 ± 41.1	1977.9 ± 39.6	−77.1 ± 57.0	3.7 ± 2.7

Kyrgyz hydro-meteorological State Department. The station was relocated in 1997 and reequipped without calibration, and we noted higher precipitation thereafter.

4. Results

We mapped 1310 glaciers in 'SJRB' with a total coverage of 1977.9 ± 39.6 km^2 in 2010. Small- and medium-sized glaciers are large in number but have limited total coverage, while the fewer large and largest glaciers represent the major part of the glacierized areas. These glaciers also had an uneven distribution between the sub-regions: the eastern region had maximal glacier coverage (43.5%), while the southern region had the least area with glaciers (9.7%), and the northern and western regions had intermediate glacier coverage (22.8% and 24.0%, respectively).

In total, the glacier-covered area in 'SJRB' decreased from 2055 ± 41.1 km^2 by 3.7 ± 2.7% during 1990–2010 (0.19 ± 0.14% per year), with the highest glacier shrinkage in the northern and western regions and the lowest in the eastern region (table 2; figures 2 and 3). During this period, small- and medium-sized glaciers

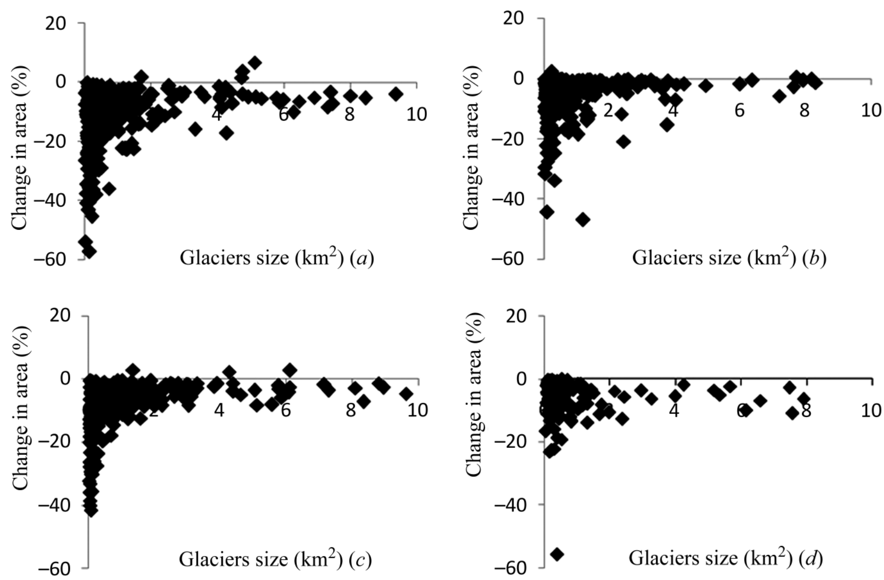

Figure 2. Relative change in glacier area (1990–2010) plotted against initial glacier area for the different regions: (*a*) northern; (*b*) eastern; (*c*) southern; (*d*) western.

were more sensitive to climate change, while large glaciers shrank considerably less. Furthermore, 8.6% of the large glaciers (1.0–5.0 km^2) disintegrated over the last two decades and transformed into medium-sized glaciers. Very few glaciers showed an area loss of more than 25% while the vast majority of the glaciers shrank less than 5%. Glaciers with large debris cover shrank significantly less than clean-ice glaciers ($4.54 \pm 0.65\%$ vs. $8.80 \pm 1.56\%$, $t = 4.00$, df $= 10$, $P < 0.003$). The largest glaciers, Inylchek and Kaindy, which also have considerable area of debris cover, decreased only by 1.4% and 2.3%, respectively.

We found 10 glaciers with an area increase up to 13.0% (3.9% on average) between 1990 and 2010. Advancing was observed primarily for large glaciers (area ~5 km^2), but also for three glaciers of medium size (area ~2 km^2, table 3). The area increase was significant for 6 of 10 glaciers; furthermore, all of them, except 1 (5 from 6), were situated in northern and western regions. Nine out of ten glaciers were found on slopes of northern or northwestern aspect (table 3). In the eastern region, glaciers demonstrated an insignificant area increase, while for 2 of 3 such glaciers in the northern and western regions, the area increase exceeded the uncertainty ($2.9–6.8 \pm 2.7\%$). The largest growth of about 0.8 km^2 (~13%) was demonstrated by Glacier No. 377 located in the southern region (table 3). A more detailed analysis revealed that this glacier was rather stable between 1990 and 1998 (area change ~ −0.5%), followed by an increase of ~15% (1999–2002) with an advance of ~850 m and a clear broadening in 2003. Thereafter, the length continued to increase but with a decreasing width; and since 2007, we observed a small shrinkage of ~1%. In total, this glacier grew by 13% and moved down for 3 km during the entire period (1990–2010). Hence, this glacier showed clear signs of a glacier surge. Advances were identified for some tributaries of Kaindy Glacier but were not further investigated as it is difficult to clearly distinguish them from the main glacier.

5. Discussion

5.1. *Glacier changes*

Glacier retreat has been described for many parts of the Tien Shan and neighbouring Dzhungarskiy Alatau (Vilesov and Morozova 2005, Kutuzov and Shahgedanova 2009, Narama *et al.* 2010, Sorg *et al.* 2012) but not for 'SJRB'.

Our results indicate that glacier area loss in 'SJRB' (~0.19% per year for 1990–2010) was one of the lowest reported in the Tien Shan for this period. This is in line with earlier studies which show that the highest glacier shrinkage occurred in the outer ranges of Tien Shan Mountains, or in peripheral, lower-elevation ranges near the densely populated forelands, while significantly smaller rates are reported for glaciers of inner ranges (Narama *et al.* 2010, Sorg *et al.* 2012). Typical published values for the outer ranges are loss rates of ~0.6–0.7% per year in Northern and Western Tien Shan during 2000–2007 (Narama *et al.* 2010), ~0.35% per year for Inner Tien Shan (Terskey Alatau, 1990–2003, Kutuzov and Shahgedanova 2009; Akshiirak, 1977–2003, Aizen *et al.* 2006) and 0.30–0.35% per year in Eastern Tien Shan (1963–2000, Li *et al*. 2006, Liu *et al.* 2006). A lower recession rate of 0.1% per year was found in the Aksu-River Basin in the Chinese part of the Central Tien Shan (1963–2000, Liu *et al.* 2006). Similarly, glaciers of the Akshiirak Range retreated by only 0.12% per year in an earlier period (1943–1977, Kuzmichenok 1989), while an acceleration of area loss was found during 1977–2003 (Aizen *et al.* 2006). Increasing rates of area loss were also found in other parts of the Tien Shan (e.g. Bolch and Marchenko 2009, Kutuzov and

Table 3. Advancing glaciers in Sary-Jaz River Basin 1990–2010 (Glacier inventory (GI.) of the USSR/V. Central Asia, ed. II Kirgizia **14,** 7–10).

ID number in GI.	Region of SJR	Type of glaciers	Aspect	Area, GI. (km^2)	Date of information	Source of data	Glaciated area (km^2) 1990	Glaciated area (km^2) 2010	Change in glaciated area % 1990–2010
99	North	Valley	North	4.2	1943/8	GI. Vol. 8	4.7	4.8	1.7 ± 2.7
98	North	Valley	North	4.2	1943/8	GI. Vol. 8	4.7	4.9	3.7 ± 2.7
95	North	Valley	North	5.0	1943/8	GI. Vol. 8	5.1	5.5	6.8 ± 2.7
137	East	Valley	North	2.1	1964/7	GI. Vol. 7	1.7	1.75	1.8 ± 2.7
324	East	Hanging-valley	North	3.7	1943/8	GI. Vol.10	7.7	7.8	0.4 ± 2.7
270	East	Valley	North-west	5.1	1970/8	GI. Vol.10	0.24	0.25	2.3 ± 2.7
253	West	Cirque-valley	South	1.7	1956	GI. Vol. 7	1.3	1.4	2.9 ± 2.7
238	West	Valley	North	4.8	1964/8	GI. Vol. 7	6.0	6.1	2.7 ± 2.7
331	West	Valley	North-west	5.9	1943/9	GI. Vol. 7	4.2	4.3	3.3 ± 2.7
377	South	Hanging-valley	North-west	2.8	1943/8	GI. Vol.10	5.8	6.6	13.0 ± 2.7

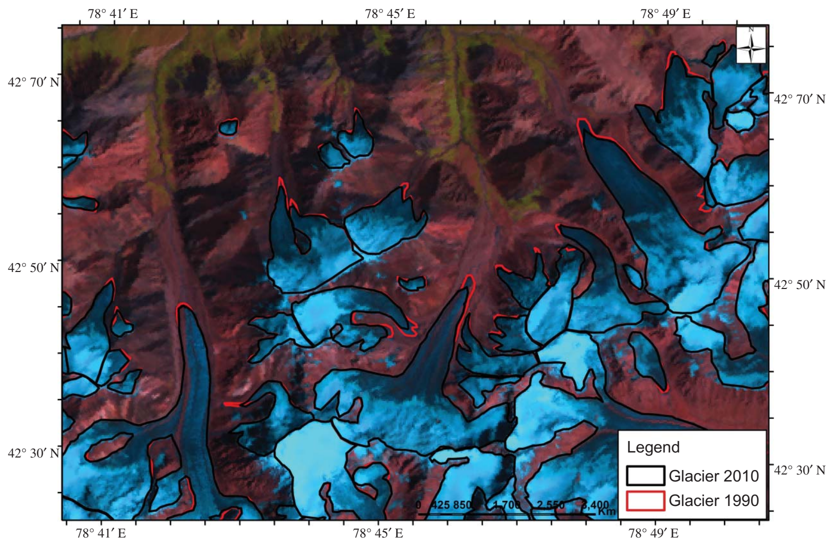

Figure 3. Glaciers' area changes in the northern region of our study area during 1990–2010 (the background is the Landsat TM scene of 31 July 1990).

Shahgedanova 2009, Narama *et al.* 2010, Hagg *et al.* 2012). The lower area loss in the Central Tien Shan can also be explained by the cold or polythermal nature with low mass-turnover rates and longer response times than of temperature glaciers. Hence, it is difficult to compare directly glacier area change rates, and also glacier sizes vary within the different investigated regions.

Our analyses demonstrated an inhomogeneous glacier shrinkage in the 'SJRB'. The eastern region with the highest elevations has the largest ice cover compared to other areas due to favourable topographic and climatic conditions, which resulted in the lowest glacier retreat (table 2). Three glaciers of different sizes were stable (table 3). Another reason for the lower area loss can be attributed to the more intensive debris coverage in this region. Our northern and western regions showed not only larger area loss (table 2, figure 3), especially in the case of small glaciers, but also some clearly advancing glaciers (table 3). This may be a result of the location, which is closer to Issyk-Kul Basin, where moist air masses originating from the large lake penetrate through the Terskey Alatau Range (Dikikh *et al.* 1991). The advancing and surging of glaciers has been described for the Karakorum (Copland *et al.* 2011) and the Pamir (Kotlyakov *et al.* 2008), as well as some Tien Shan ranges (Dolgushin and Osipova 1975, Narama *et al.* 2010, Pieczonka *et al.* 2013); and is now reported for the first time for the 'SJRB'. Surprisingly, the largest glacier, No. 377, located in the southern region, which is the lowest, driest and warmest among sub-regions, showed the most intensive and sudden advance compared to the other nine glaciers with an advancing trend. Furthermore, the area increase of this glacier was followed twice by an area decrease during the last 20 years. This phenomenon can be described as glacier pulsation (Dolgushin and Osipova 1982).

We found that debris-covered glaciers showed a significant lower area loss than clean-ice glaciers. This can be attributed to reduced ablation as a thick debris cover prevents the ice from melting as, for example, measured at Inylchek Glacier in the study region or at other debris-covered glacier tongues elsewhere (Hagg *et al*. 2008, Benn *et al.* 2012). However, it should be mentioned that heavily debris-covered glaciers in the Himalaya and south of Peak Pobeda close to our study region show clear mass loss despite a thick debris cover and low area loss (cf. Bolch *et al.* 2011, Pieczonka *et al.* 2013), which is likely due to enhanced melting at exposed ice cliffs and supra-glacial ponds that are common at debris-covered glaciers (Benn *et al.* 2012).

5.2. *Climatic considerations*

The observed general trend of glacier retreat in the Tien Shan is most likely a consequence of the observed general warming (Aizen *et al.* 2006, Bolch 2007, Narama *et al.* 2010). However, the air temperature during melting season (July–August) has increased only slightly over past decades, though a prolongation of the melting season has been detected for September throughout Central Asia. No significant trend was found for precipitation (Aizen *et al.* 1997, Bolch 2007, Sorg *et al.* 2012). Our analysis of the available climate data from the Tien Shan station indicates a slightly different behaviour. The period 1970–1996 was most unfavourable for the glacier mass budgets due to both increasing temperature and decreasing precipitation during the warm season (May–September, table 4. In the cold season, the temperature increased only slightly with even a decrease between 1970 and 1996. No clear trend exists for the precipitation in the colder months. Since 1997, the climate was the most favourable during measured period due to slight precipitation decrease only, but a temperature decrease during summer months (table 4). Hence, the glaciers might be currently close steady-state in this region, which was also found in a study about Gregoriev ice cap situated close to the Tien Shan station (Fujita *et al.* 2011). However, it has to be considered that glacier area changes as investigated in this study can not directly linked to the climate signal as the area shows a delayed signal to climate only; and the response time of the polythermal or even cold glaciers in this region is likely several decades. Therefore, more studies investigating mass changes both in situ and from remote sensing are recommended. The generated inventory is an important prerequisite therefore. In addition, the quality of Tien Shan station data is subject to inaccuracies, and further climate measurements are needed to further investigate the climate variability in the 'SJRB' and the representativeness of the Tien Shan station. Available gridded data sets from this region, such as the WATCH (http://www.eu-watch.org) or the ECMWF reanalysis data (www.ecmwf.int), can provide a hint about the representativeness, too, but these data sets also suffer from the lack of high-elevation climate measurements for validation.

Table 4. Changes of average air temperature and precipitation during three periods: 1930–1969, 1970–1996 and 1998–2009 at the Tien Shan weather station (3614 m asl., see figure 1).

Month	1930–1969	1970–1996	1998–2009
	Air temperature		
May–September	+0.08 K/10a	+0.20 K/10a	−0.58 K/10a
October-April	+0.10 K/10a	−0.23 K/10a	+0.15 K/10a
	Precipitation		
May-September	+3.1 mm/10a	−61.1 mm/10a	−5.1 mm/10a
October-April	+6.9 mm/10a	− 4.0 mm/10a	−6.0 mm/10a

6. Conclusions

We found 1310 glaciers in the 'SJRB' which covered 2055 ± 41.1 km^2 (~18% of the entire basin) in 1990 that shrank by 77.1 ± 57.1 km^2 (0.19 ± 0.14% per year) by 2010; however, the glaciers shrank with lower rates compared to other Tien Shan Ranges. This may be attributed not only to the more internal regional location within the Tien Shan with more favourable climatic conditions than in the outer ranges, but also to the comparatively large glacier sizes and extensive debris cover. We found that debris-covered glaciers shrank significantly less than clean-ice glaciers of comparable size. The lowest insignificant area loss (−1.5 ± 2.7%) between 1990 and 2010 was found in the eastern part of the basin where the largest glaciers and highest peaks are situated. The most intensive loss was found in the northern and western parts (−6.5 ± 2.7 % and −5.0 ± 2.7%, respectively). However, rapid advancing was also observed and primarily found for large glaciers. The advances were more often at a northern aspect (9 out of 10 cases).

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