Glacier change in the Karatal river basin, Zhetysu (Dzhungar) Alatau, Kazakhstan

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ABSTRACT. We investigated glacier changes in the Karatal river basin, the largest basin in Zhetysu (Dzhungar) Alatau, Kazakhstan, for the periods 1956–89, 1989–2001 and 2001–12, based on Landsat TM/ETM+ data analysis. In 1989, we found 243 glaciers with a total area of 142.8 km^2; by 2012 these had shrunk to 214 glaciers with a total area of 109.3 km^2, a decrease of 33.5 km^2 over 23 years (1.02% a^{-1}). This very high shrinkage rate is likely connected with a general trend of increasing temperatures, and small glaciers being situated at the relatively low altitude of the outer Zhetysu Alatau ranges. We also analyzed the shrinkage rate of glaciers based on their differences in size, altitude and aspect of slopes, as well as other topographic parameters, in four sub-basins where glacier shrinkage varied between 18% and 39%. Weather-station climate data showed a significant temperature increase and stable precipitation trends over the study period. We conclude that glacierized areas of the Karatal river basin are located in the most unfavorable conditions for glaciation, and as a result showed a higher shrinkage rate than other glacierized areas of the Tien Shan from 1956 to 2012.

KEYWORDS: climate change, glacier shrinkage, glacier mapping, mountain glaciers, remote sensing

1. INTRODUCTION

Glaciers play a crucial role in central Asia's hydrological cycle (Viviroli and others, 2003; Armstrong, 2010; Sorg and others, 2012). It has been demonstrated that even a basin whose glacier fraction is <5% can provide a significant contribution from ice melt to summer runoff (Hagg and others, 2007), when water is most needed for irrigation (Sorg and others, 2012). While the seasonal snowpack stores water mainly on an intra-annual timescale, glaciers store water for decades and centuries, thus partly compensating interannual fluctuations of precipitation and snowmelt contribution to river runoff (Unger-Shayesteh and others, 2013).

The Karatal river basin, Zhetysu (Dzhungar) Alatau, Kazakhstan, is surrounded by arid lowlands and deserts (Fig. 1), where irrigation during vegetation growth periods often depends on glacier melt (Kaser and others, 2010). The runoff formed in this basin is used for hydropower generation at four hydroelectric power stations, and further downstream for irrigation in southeastern Kazakhstan.

In spite of the glaciers' importance for regional economies, regular glacier mass balance and other ground-based glaciological measurements were discontinued in the Karatal river basin, as well as in the entire Zhetysu Alatau mountains, after the collapse of the USSR during the 1990s. The first detailed glacier inventory, the 'Catalogue of Glaciers' (Katalog Lednikov SSSR, 1980), was published in 1980, and was based on airborne imagery from 1956. Cherkasov (2004) compiled the second glacier inventory, using topographic maps on a 1 : 25 000 scale, based on aerial photographs taken in 1972, and two more limited glacier studies were conducted for the 1990s and 2000s. These inventories, however, remained as unpublished reports (Vilesov and others, 2013). Nevertheless, analyses of glacier changes for the entire Zhetysu Alatau were reported by several authors, who estimated the total decrease of the glacier area in the Karatal river basin was 34.8% during 1956–2000 (Severskiy and others, 2012; Vilesov and others, 2013). Thus, changes in glacier surface area in Zhetysu Alatau, including Karatal basin glaciers, are still poorly understood. This paper presents our detailed analyses of the glacier areas of the Karatal river basin for the periods 1956–89, 1989–2001 and 2001–12, using well-established semi-automatic methods based on band ratio techniques (Paul and others, 2013).

2. STUDY AREA

The Karatal river basin, the largest basin in Zhetysu Alatau, covers an area of 19 100 km^2; the total area of the four sub-basins studied here is 4370 km^2 (Kudekov, 2002). The Karatal river originates on the northwestern slopes of the Zhetysu Alatau central ridge. It is formed by the confluence of the Kora, Chizhin and Tekeli rivers (Vilesov and others, 2013), while further on the plain it meets with its largest tributary, the Koksu river (Katalog Lednikov SSSR, 1980).

The Karatal river basin is located in the outer western Zhetysu Alatau, where the elevations of the highest mountain crests range between 3800 and 3850 m a.s.l. (Katalog Lednikov SSSR, 1980). Most glaciers found here are small (<1 km^2) (Vilesov and others, 2013).

The climate of Zhetysu Alatau is formed by air masses from arctic and temperate areas. Arctic air masses flow from the north and northwest during winter, reducing air temperature in this region (Vilesov and others, 2013). Temperate air masses are formed over western Siberia, Kazakhstan and the Turanian plateau, as well as over the

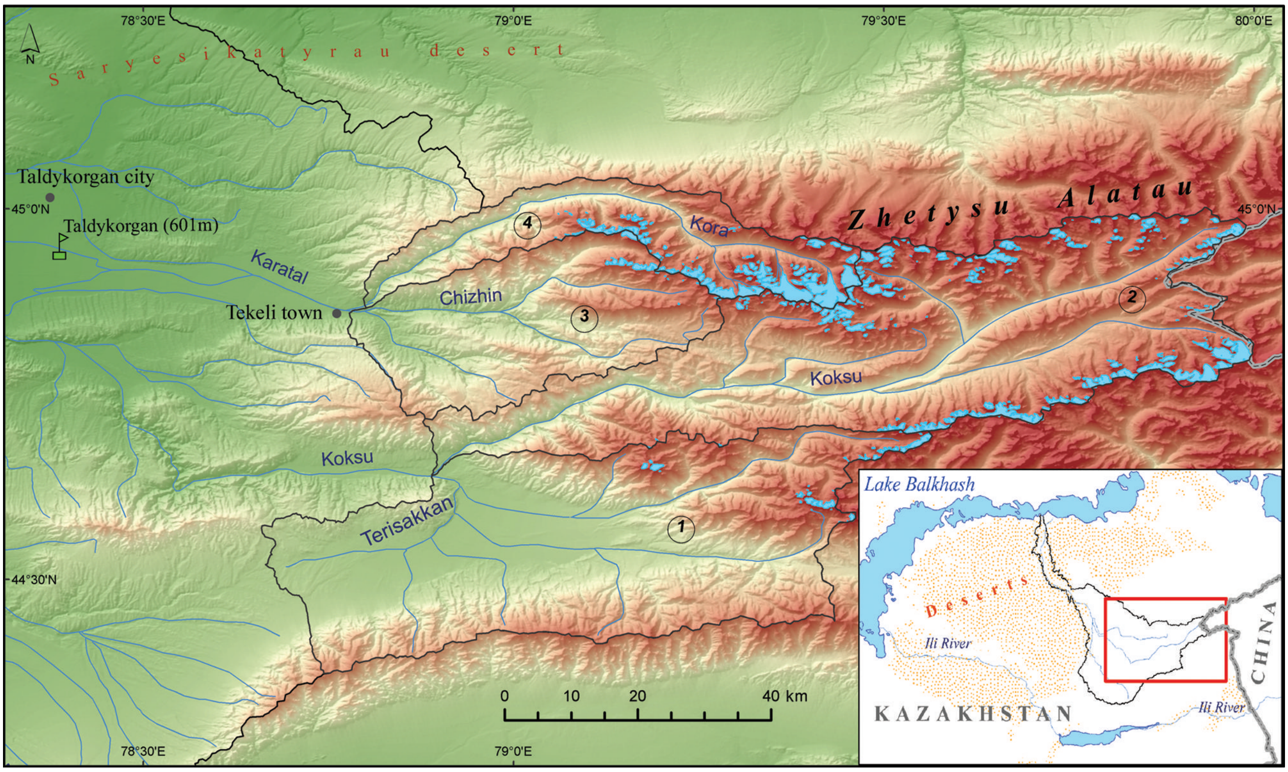

Fig. 1. Location of the study area. Map based on Shuttle Radar Topography Mission 3 (SRTM3) DEM. Sub-basins: 1. Terisakkan; 2. Koksu; 3. Chizhin; 4. Kora.

Atlantic Ocean, which has the greatest impact on the Zhetysu Alatau climate during the entire year. Hot air masses are formed over the intensely heated Turanian plateau; however, their incursions into the region during summer are very rare.

The mean annual air temperature is –5 to –7°C in the high-altitude zone of Zhetysu Alatau; January is the coldest month, at –13 to –14°C. The spatial distribution of precipitation is controlled by altitude and varies from 1000 to 1600 mm a^{-1}, with maximum amounts occurring at 1800–2200 m a.s.l. (Katalog Lednikov SSSR, 1980).

3. DATA AND METHODS

All of the selected Landsat Thematic Mapper (TM) and Enhanced TM Plus (ETM+) images were in good condition, and almost free of clouds and snow (Table 1). Nevertheless, several scenes for each year were also used due to different snow conditions and data gaps. Images provided by the US Geological Survey were processed to Standard Terrain Correction (Level 1T), achieving systematic radiometric and geometric accuracy. Landsat TM and ETM+ scenes were co-registered to the 2001 Landsat ETM+ scene, and root-mean-square error (RMSE) was within ±0.5 pixel.

Thresholding of ratio images is an efficient and time-effective approach compared to manual digitization, although the latter enables identification of snow and ice in shadows (Paul and others, 2003; Paul and Kääb, 2005; Bolch and Kamp, 2006). The advantages of thresholding are that it is simple to apply and the results are highly accurate for debris-free ice (Albert, 2002; Andreassen and others, 2008; Paul and Andreassen, 2009). Paul and others (2013) found an overall good agreement for clean ice, with sufficient contrast with the surrounding terrain (differences 5%). Based on these results, they concluded that automated mapping of clean ice is preferable to manual digitization and recommended using

Table 1. Satellite imagery used in this study

Date	Satellite and sensor	Path/row	Spatial resolution m	Suitability of scenes	Utilization
14 Sept 1989	Landsat TM	147/29	30/120	Some seasonal snow on the southeast part	Main source
9 Sept 1990	Landsat TM	148/29	30/120		Additional information
4 Sept 2000	Landsat ETM+	148/29	15/30/60	Some seasonal snow	Additional information
22 July 2001	Landsat ETM+	148/29	15/30/60		Main source
25 July 2002	Landsat ETM+	148/29	15/30/60	Some seasonal snow	Additional information
11 Sept 2011	Landsat TM	148/29	30/120		Additional information
20 July 2012	Landsat ETM+	148/29	15/30/60	Scan-line corrector off	Main source

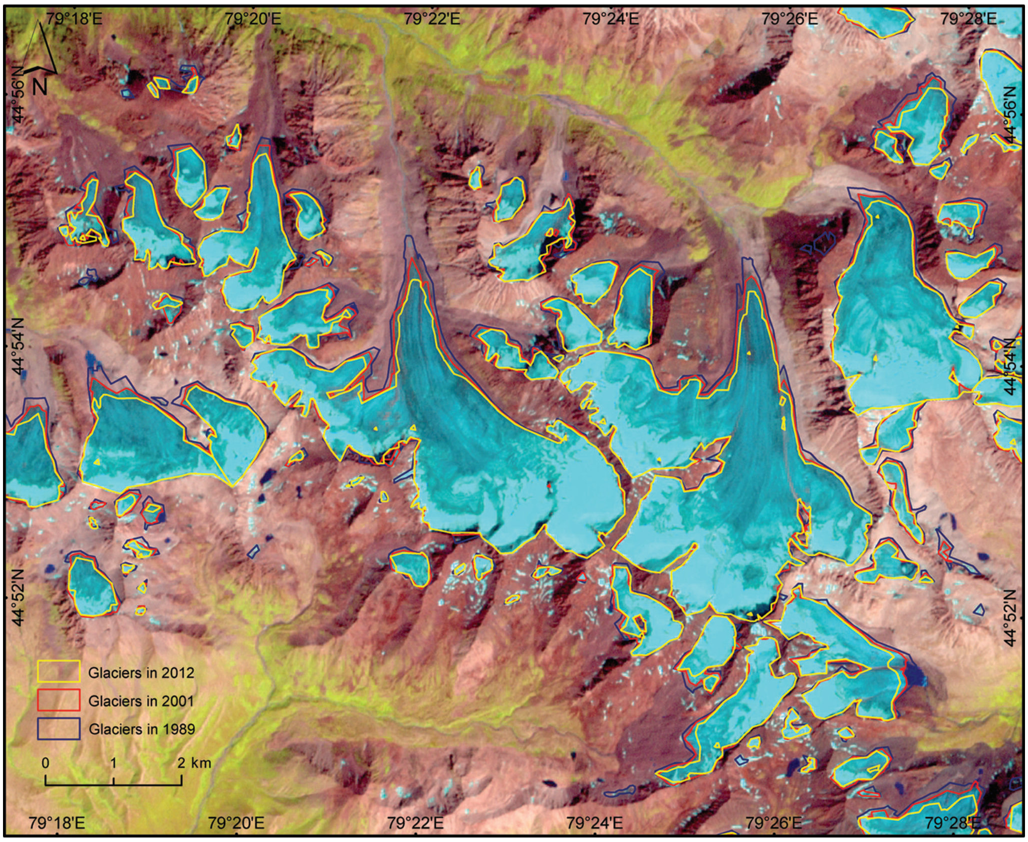

Fig. 2. Example of glacier changes in part of Kora sub-basin from 1989 to 2012. Background based on pansharpened Landsat ETM+ (22 August 2001).

the latter method only for required corrections of incorrectly mapped glacier parts (e.g. debris cover, shadows).

We applied a well-established semi-automated approach using the TM3/TM5 band ratio to produce glacier outlines. Misclassified areas (e.g. snowpatches, cast shadows and lakes) were corrected manually using false-color composite (TM bands 5, 4 and 3) on the Landsat imagery (Fig. 2). All of the images were obtained for cloud-free conditions and for the ablation period when the extent of snow cover was minimal, to reduce potential uncertainty in glacier boundary delineation. Changes in the extent of glaciers were assessed with regard to images from 1989, 2001 and 2012, and analyzed according to the surface area, aspect and elevation of glaciers.

Supraglacial debris cover is a factor reducing the accuracy of the glacier outline. However, in our study area, the glaciers were almost free of debris cover. Repeated mapping of glacier samples with different surface areas using different types of imagery has shown that the error in estimation of individual glacier area is <5% (Kutuzov and Shahgedanova, 2009). An assessment by Paul and others (2003) shows that this accuracy allows one to achieve an error of <3% for large (>100) samples of glaciers. We used the glacier area from the 1989 image as a mask to minimize misclassification due to certain factors (e.g. seasonal snow cover). When using this mask, we assumed that glaciers did not advance between 1989 and 2012. The mask also maintained consistency in the location of the upper glacier boundary and the margins of nunataks. This consistency is important in the case of seasonal snow that hampers correct identification of the upper glacier boundary (Bolch and others, 2010). We mapped only glaciers that were >0.01 km^2, as a smaller threshold would include many features that were likely to be snowpatches. 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 characteristic parameters (e.g. hypsography, median elevation and aspect) were calculated for each glacier for 1989, 2001 and 2012 based on the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) version 2. The DEM used matched the glacier outlines well. No DEM representing the 1989 conditions was available.

We estimated the uncertainty by the buffer method suggested by Granshaw and Fountain (2006) and Bolch and others (2010). The buffer size was chosen to be half of the estimated RMSE, i.e. 7.5 m to each side. The resulting accuracy was within ±5%.

For more detailed analyses of the glacier changes, we subdivided the Karatal river basin into four sub-basins (Terisakkan, Koksu, Chizhin and Kora) according to landscape differences. Results of glacier areas obtained for each sub-basin were compared with the same glacierized areas defined in the first glacier inventory for 1956. Information about the glacier characteristics from the first glacier inventory was available only as tables and schematic maps. Glaciers smaller than 0.1 km^2 were treated as bulk samples in the Catalogue of Glaciers, without information about their locations. We did not include these small glaciers in our calculation of the total glacierized area and showed them separately for all study regions.

In order to obtain information about climate trends for the Karatal river basin, we acquired data from Taldykorgan, the nearest available weather station to our study area. This

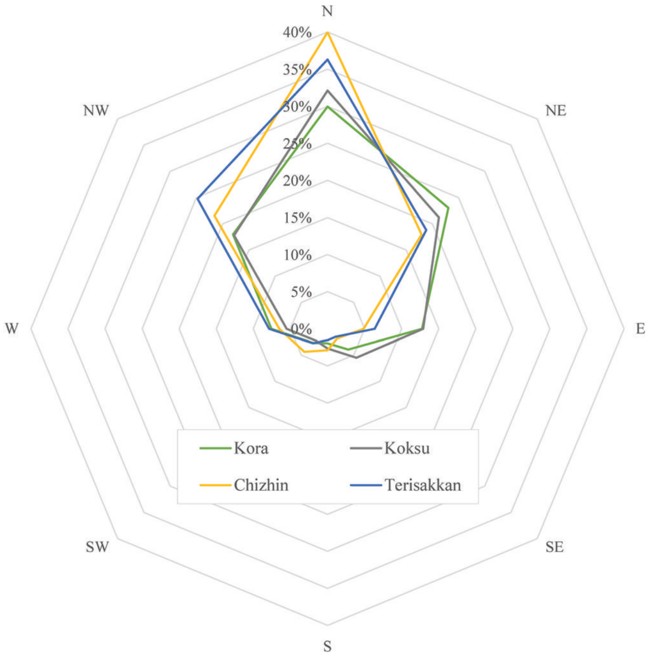

Fig. 3. Distribution of glacier areas according to aspect in different sub-basins during 1989–2012.

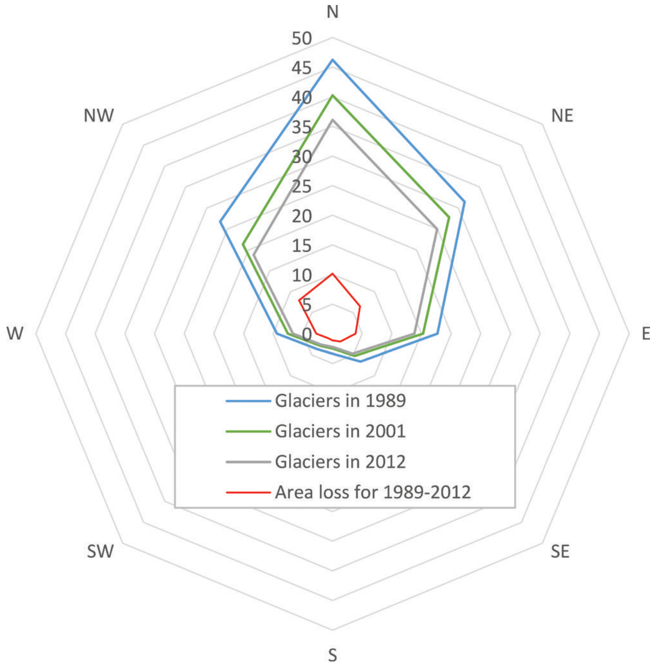

Fig. 4. Distribution of glacier areas and their changes according to aspect in the Karatal river basin during 1989–2012.

station is situated in the foothills (~600 m a.s.l.) and has provided long-term temperature and precipitation records since 1960.

4. RESULTS

4.1. Glacier characteristics

We identified and mapped 214 glaciers, with a total area of 109.3 km^2, in 2012. The vast majority (91%) were small glaciers (<1 km^2), which covered more than half of the total glacierized area. There were only four large glaciers, between 4 and 10 km^2 in size, but these contributed 23.5% of the total glacierized area in the study region.

The distribution of glacier aspect was determined using ASTER GDEM v2 and exhibited small differences between the regions. Most of the glaciers were north-facing (north, northwest and northeast) (Fig. 3) and situated between 3000 and 4000 m a.s.l. (Fig. 4). The largest area of glaciers was located between 3400 and 3600 m a.s.l., and the majority were concentrated in the Kora and Koksu sub-basins.

The median elevation of the glaciers, which is a suitable and widely used indicator of the long-term equilibrium-line altitude (ELA) based on topographic data (Braithwaite and Raper, 2010), is situated at ~3460 m a.s.l. Glaciers at lower elevations were located mostly in the northwestern corner of the study area (the Kora sub-basin), whereas glaciers at the highest elevations were situated in the southeastern part.

4.2. Glacier changes

We identified 243 glaciers in 1989, 226 in 2001 and 214 in 2012 which were listed in the Catalogue of Glaciers with total areas of 142.8, 122.2 and 109.3 km^2, respectively (Table 2). Thus, the summarized area change for the period 1956–89, based on our defined mountain regions, was –28%. Area change for 1989–2001 was –14%, and area change for 2001–12 was –11%; for the whole period, the total glacierized area decreased from 199.2 km^2 (285 glaciers) in 1956, to 109.3 km^2 (214 glaciers) in 2012, a shrinkage of 45% in 56 years. During our study period, 71 glaciers listed in the Catalogue of Glaciers and 39 unlisted small glaciers were not found. All of the glaciers

Table 2. Changes in glacier number and area

Region	Glacier area (number)				Area change (annual rate)					Mean size in 1989
	1956	1989	2001	2012	1956–89	1989–2001	2001–12	1956–2012	1989–2012	
	km^2	km^2	km^2	km^2	%	%	%	%	%	km^2
Terisakkan	14.1 (36)	8.4 (21)	6.5 (21)	5.1 (17)	–40 (–1.22)	–23 (–1.96)	–20 (–1.8)	–63 (–1.13)	–39 (–1.68)	0.403
Koksu	108.6 (167)	75.3 (149)	64.1 (140)	56.1 (135)	–31 (–0.93)	–15 (–1.24)	–13 (–1.14)	–48 (–0.86)	–26 (–1.11)	0.506
Chizhin	8.7 (19)	4.9 (11)	4.2 (10)	3.8 (10)	–44 (–1.32)	–15 (–1.24)	–9 (–0.79)	–56 (–1.0)	–22 (–0.97)	0.445
Kora	67.8 (66)	54.1 (62)	47.5 (55)	44.2 (52)	–28 (–0.61)	–14 (–1.03)	–7 (–0.63)	–35 (–0.62)	–18 (–0.80)	0.873
Total	199.2 (285)	142.8 (243)	122.2 (226)	109.3 (214)	–28 (–0.86)	–14 (–1.20)	–11 (–0.96)	–45 (–0.81)	–23 (–1.02)	0.588
Glaciers <0.1 km^2 in 1956	3.6 (73)	2.36 (77)	0.76 (39)	0.59 (34)	-34 (-1.04)	–68 (–5.63)	–22 (–1.99)	–83 (–1.49)	–75 (–3.25)	0.031

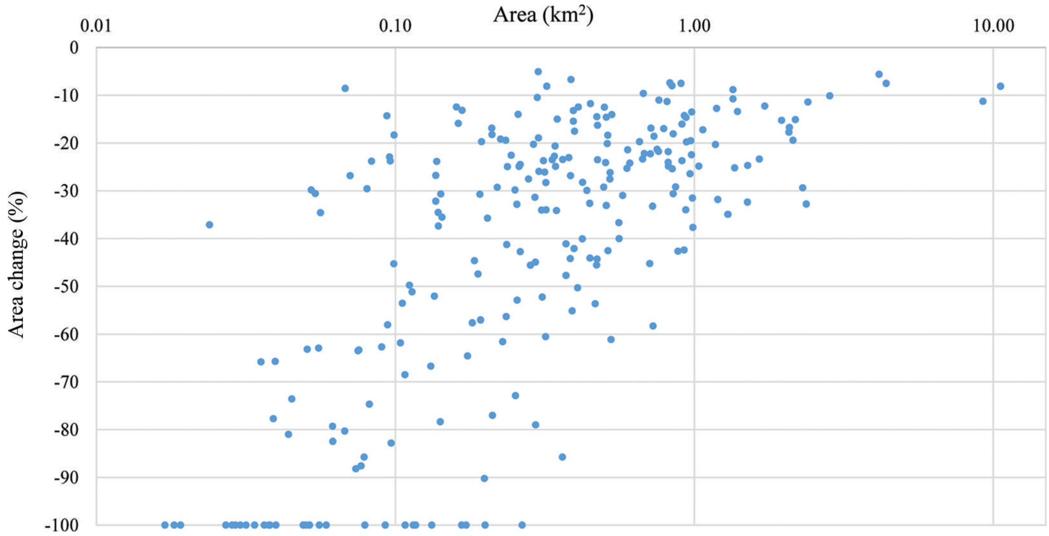

Fig. 5. Scatter plot of relative changes in glacier area vs initial glacier size for the 243 glaciers during 1989–2012.

shrank continuously throughout the study period. Our results indicate that glacier area loss in the Karatal river basin was 23% (1.02% a^{-1}) for 1989–2012. The Kora sub-basin had the largest glaciers, with a mean size of 0.873 km^2, while the Terisakkan sub-basin had the smallest, with a mean size of 0.403 km^2. Terisakkan had the highest shrinkage rate, 39% from 1989 to 2012. The rate of decrease in glacier numbers was significantly higher (more than 40%) for the Terisakkan and Chizhin glacierized areas during the study period.

Analysis of the relative area change against the initial glacier area indicates a greater relative loss for smaller glaciers (Fig. 5). However, there was a large scatter of loss, especially for smaller glaciers, while in all size classes there were glaciers that had shrunk only slightly. Absolute area loss was higher for larger glaciers (Fig. 6), and glacier median elevation increased by 40 m, while the average minimum elevation of the glaciers rose ~47 m, from 3288 up to 3335 m a.s.l., for 1989–2012.

All elevations showed a reduction in glacier area during 1989–2012 (Fig. 7). The glaciers of the west and northwest aspects decreased by up to 30%, while northern and northeastern aspects decreased by only ~20%.

5. DISCUSSION

The area changes of the investigated glaciers confirmed an expected and widely published trend of glacier shrinkage (Sorg and others, 2012; Unger-Shayesteh and others, 2013). However, with a shrinkage rate of about 0.8–1% a^{-1} for the periods 1956–89 and 1989–2012, our results for the Karatal river basin study area showed a comparatively higher shrinkage rate than some other glacierized areas of the Tien Shan (Aizen and others, 2007; Bolch, 2007; Kutuzov and Shahgedanova, 2009; Kriegel and others, 2013). Results of previous studies showed large variations in different parts of the Tien Shan: –0.76% a^{-1} (mid-1970s to mid-2000s; Kriegel and others, 2013) in the western Tien Shan; –0.38% a^{-1} (1963–2003; Aizen and others, 2006) and –0.76% a^{-1} (1963–2000; Niederer and others, 2008) in the northern Tien Shan; –0.11% a^{-1} (1975–2008; Pieczonka and Bolch, 2015) in the central Tien Shan; and –0.35% a^{-1} (1963–2000; Li and others, 2007) in the eastern Tien Shan. This intensive decrease of glacier area is consistent with earlier studies which showed that the highest glacier shrinkage occurred in the outer ranges of the Tien Shan and the peripheral, lower-elevation ranges near the densely populated forelands; significantly smaller rates were reported for glaciers in inner

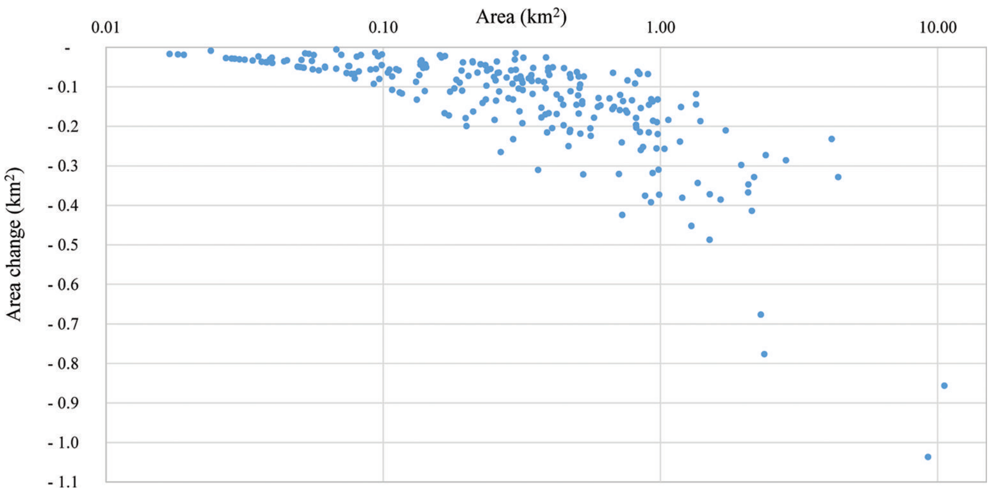

Fig. 6. Scatter plot of absolute changes in glacier area vs initial glacier size during 1989–2012.

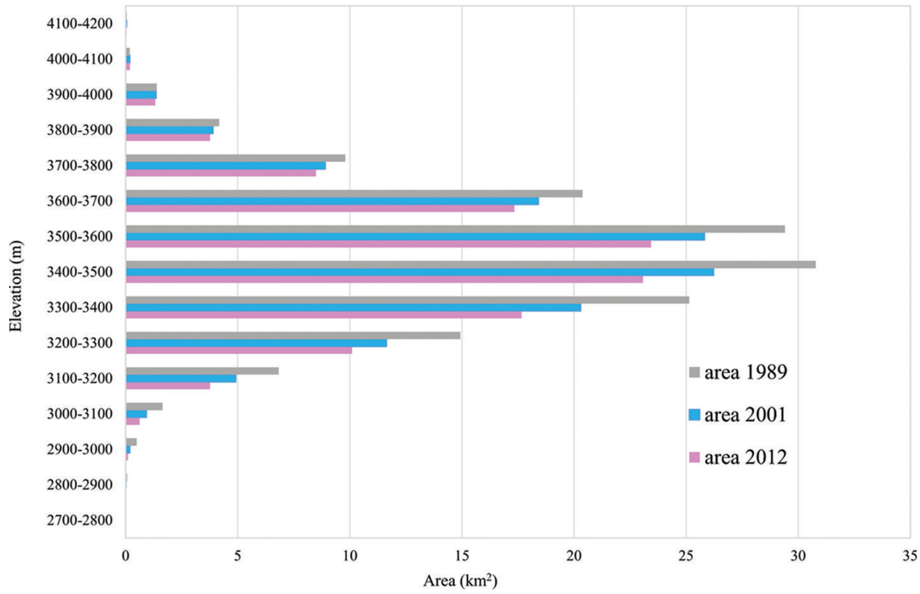

Fig. 7. Distribution of glacier areas and their changes vs elevation interval in the Karatal river basin.

ranges (Narama and others, 2010; Sorg and others, 2012). The assessments by Aizen and others (2006) for 1977–2003 in the inner region of the Tien Shan, and Narama and others (2006) for 1971–2002 in the western Tien Shan, indicated a glacial area loss of 8–9% (0.26–0.29% a^{-1}), while glaciers in the peripheral regions of the northern Tien Shan shrank considerably faster. For instance, for Zailiyskiy and Kungey Alatau, Bolch (2007) found a shrinkage rate of 0.73% a^{-1} for 1955–99. Kokarev and Shesterova (2014) studied glacier areas in the southern part of Zhetysu Alatau in a region close to our study area, and the shrinkage rate was also quite high, at ~0.86% a^{-1}. Hagg and others (2012) mapped glaciers in the Big Naryn basin during 2007. By comparing their results with the 1955 Soviet glacier inventory, they reported that the rate of decrease varied from 0.27 to 0.81% a^{-1} between mountain ranges, showing an increasing shrinkage rate from the inner to outer parts. Glaciers in the outer ranges of the Tien Shan which receive the highest precipitation volumes are particularly sensitive to climatic change due to their large mass-turnover rates (Narama and others, 2010).

Regions with mostly small glaciers are generally more sensitive to change because smaller glaciers have a shorter response time to climate change (Bahr and others, 1998; Ye and others, 2001). It is also reported that smaller glaciers, with a greater area-to-margin-length ratio, shrink faster than larger glaciers under the same ablation rate (Granshaw and Fountain, 2006). In the Karatal river basin, the vast majority of glaciers are small, with sizes <1 km^2. These glaciers cover more than half of the total area, as is common in mountains of the mid-latitudes. Our results indicate that the mean size of the glacier area in the Karatal river basin was 0.588 km^2. The difference in the shrinkage rates of glacier areas among the sub-basins in our study area can be explained by the difference in mean size and aspect. For example, Terisakkan had the highest shrinkage rate, reaching 39% from 1989 to 2012. The mean glacier size in Terisakkan was almost twice as small as that in the Kora sub-basin, where the shrinkage rate for the same period was 18%.

Although climate warming has been the main cause of glacier change during the past 56 years, the topographic factor also plays an important role. An additional reason for greater area loss may be the lower elevation of glaciers in the Karatal basin compared to other parts of the Tien Shan. An increase in local mean air temperature, with no change in precipitation, will cause an upward shift of the ELA by ~150 m for each °C of atmospheric warming (Stocker and others 2013). At lower elevations, such an upward shift of the ELA heightens the risk of the entire area of glaciers falling into the ablation zone.

All elevations showed a reduction in glacier area during 1989–2012, but the largest area changes occurred on the western and northwestern aspects. South-facing glaciers were not widespread in the study area, but individual glaciers showed a remarkable reduction in glacier area. This may be due to greater incoming solar radiation, especially on the southern aspects, because of the general trend of increasing temperatures after the late 1970s (e.g. Evans, 2006; Li and others, 2011). Moreover, most ranges of the Zhetysu Alatau, which are oriented to the west, are also under the influence of summer warm westerlies that originate over the deserts located to the south of Lake Balkhash (Aizen and others, 1997; Vandenberghe and others, 2006). Furthermore, the westerlies are long-distance carriers of fine-grained loess from the deserts of central Asia to the Tien Shan (Vandenberghe and others, 2006; Issanova and others, 2013), which pollutes glacial surfaces, intensifying the melting rate (Li and others, 2011). In particular, glaciers located on the western slopes that face strong winds and dust storms from the desert could experience intense contamination. The frequency of dust storms directed to part of the Zhetysu range has increased during the past few decades (Issanova and others, 2013), causing the shrinkage rate of our study area, located in the western Zhetysu Alatau, to be almost three times more severe (0.86% a^{-1}) than for the Bortala river in the eastern Zhetysu Alatau (0.32% a^{-1}) (Wang and others, 2014).

The Catalogue of Glaciers listed 285 glaciers, as well as 73 glaciers smaller than 0.1 km^2 which were treated as bulk samples with no information about their locations. We identified 214 glaciers, 34 of which were not listed in the Catalogue of Glaciers, suggesting that these unlisted glaciers are remnants of those glaciers that were already <0.1 km^2 by

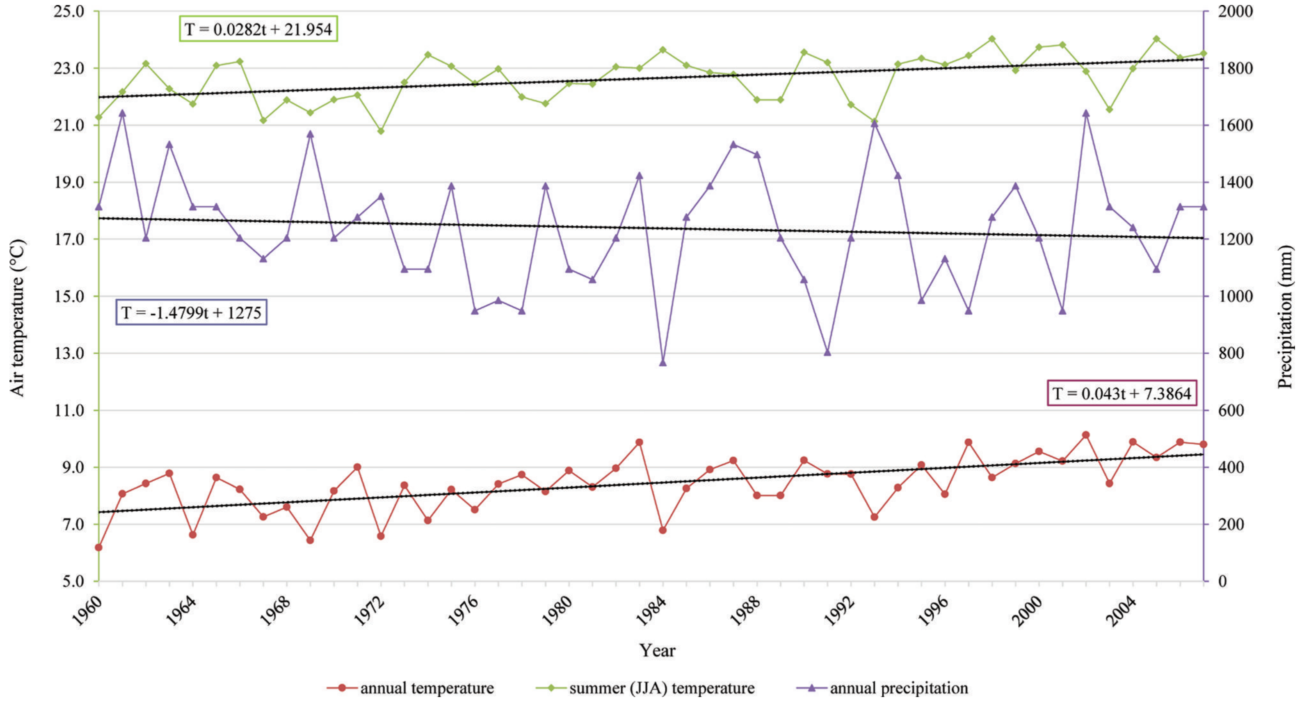

Fig. 8. Annual and summer (June–August (JJA)) temperature and annual precipitation at Taldykorgan station.

the mid-20th century. The remaining 71 glaciers that were listed and 39 smaller glaciers could not be found. Several studies (Bolch and Marchenko, 2009; Shahgedanova and others, 2010) have found differences of ~5% between their results and the Catalogue of Glaciers.

Annual mean temperature and total precipitation over the 47 year period 1960–2007 were analyzed from Taldykorgan weather station, situated near the study area. The linear trend analysis of mean temperature indicated that the average rate of temperature increase was 0.43°C $(10\,a)^{-1}$, while the summer (June–August) temperature rose 0.28°C $(10\,a)^{-1}$ (Fig. 8). From 1960 to 2007, records at the same station displayed a slight decrease in annual precipitation. Increasing temperature leads to (1) increasing energy available for ice- and snowmelt; (2) decreasing snow accumulation; and (3) lower albedo of the glacier surface (Ageta and Kadota, 1992; Fujita and Ageta, 2000; Wang and others, 2014). The temperature increase caused the rainfall rate to increase, rather than snowfall in the high-altitude glacierized areas, leading to reduced accumulation and accelerated ablation, especially during summer (Chaulagai, 2003). Between 1960 and 2007, two climatic factors, increased temperature and slightly decreased precipitation, led to significant glacier area loss.

6. SUMMARY

This study demonstrates the scientific value of detailed multitemporal remote-sensing analyses of glacier changes for the Karatal river basin, which currently lacks sufficient records of observational data. In the basin, we identified 243 glaciers with a total area of 142.8 km^2 in 1989 that had decreased to 109.3 km^2 by 2012, a loss of 33.5 km^2 (shrinkage rate 1.02% a^{-1}). Our results show higher shrinkage rates for the study area than some other glacierized areas of the Tien Shan. This phenomenon is likely connected not only to the location of our study area in the periphery of the Zhetysu Alatau, which had less favorable climatic conditions than the inner ranges, but also to smaller glacier sizes with a complete absence of debris cover. The differences in glacier area shrinkage among the sub-basins can be explained by variations in sizes, orientations and local climate conditions. No glaciers advanced during the investigation period. Clearly, complex glacier–climate interactions need to be further investigated.

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