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Glacier changes in the Sikeshu River basin, Tienshan Mountains

Lin Wang, Feiteng Wang*, Zhongqin Li, Wenbin Wang, Huilin Li, Puyu Wang

Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), Lanzhou, Gansu 730000, China

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ABSTRACT

Glaciers are widely recognized as sensitive indicators for regional climate change. This study reports changes of glaciers in the Sikeshu River basin, Tienshan Mountains, northwest China, between 1964 and 2004. Analysis of satellite images showed that the glaciated area decreased by about 15.4% (0.38% y^{-1}) from 114.6 to 96.9 km^2. The average glacier front retreat amounts to 195.3 m (4.9 m y^{-1}) during the last four decades. Data from the Jilede hydro-meteorological station in the Sikeshu River basin showed increases in both the annual mean air temperature and annual precipitation during 1964–2004. This indicates that the glacier shrinkage in the Sikeshu River basin over the last 40 years was largely due to regional climate warming that enhanced glacier ablation and overcompensated for the effects of increased precipitation on the glacier mass balance. Glaciers smaller than 0.5 km^2 in area experienced the strongest retreat, whereas glaciers larger than 2 km^2 in area experienced gentle recession but may be the main contributors in the future to river runoff. Glacial shrinkage in the Sikeshu River basin is likely to continue with the temperature increase expected in coming decades.

1. Introduction

Changes in mountain glaciers are a natural indicator of climate change (Oerlemans, 1994, 2005). Moreover, glacier runoff is the major contributor to water resources that are used to support the sustainable development of the environment, industry and agriculture in arid regions of northwest China (Yao et al., 2004). Glacier change also leads to glacial hazards such as glacial lake outburst flooding in some regions (Narama et al., 2010a,b; Bolch et al., 2011). However, owing to the remote location and dispersed distribution of glaciers, there has been little glacier monitoring in northwest China. Thus, there is a very limited dataset derived from continual glacier observation, and application of other techniques is desirable. Satellite data is used for regional detection and analysis of glaciers and glacier changes (Paul et al., 2002; Khalsa et al., 2004).

Mean annual air temperatures rose dramatically in the 20th century (IPCC, 2001). This has caused increasing glacier retreat in many parts of the world (Haeberli and Beniston, 1998). Glacier area is estimated to have decreased by 25–35% in the Tienshan Mountains (Narama et al., 2006; Bolch, 2007; Kutuzov and Shahgedanova, 2009), and by 30–35% in the Pamirs (Yablokov, 2006) during the 20th century. In Altai, the glacier area has decreased by 9–27% since 1952 (Narozhniy and Zemtsov, 2011).

Atmospheric warming in northwest China has been found to be stronger than in other areas, with summer warming particularly severe since the mid 1980s (Shi et al., 2007). In China, the glacier area loss since the 1960s is estimated to about 14.3%, and is more pronounced in the Chinese Himalaya, Qilian Mountains and Tienshan Mountains, but with small recessions in the hinterland of the Tibetan Plateau (Li et al., 2006; Yao et al., 2012). Glacier shrinkage in the Tienshan Mountains is likely to continue with the temperature increase expected in the coming decades (Sorg et al., 2012). Initial results provided valuable information on glacier change in the Tienshan Mountains. However, most of the studies have been conducted in the western and central Tienshan Mountains, with few in the eastern region (Narama et al., 2010a,b; Hagg et al., 2012a). This paper reports on the current state of glaciers and on potential problems related to the observed glacier shrinkage during 1964–2004 in the Sikeshu River basin. In addition, we analyze hydrometeorological time series and try to connect glacier behavior with regional climate variations.

2. Study area

The Sikeshu River basin (43°53′–44°58′ N, 83°37′–84°30′ E) is located on the north slope of the Tienshan Mountains, southwest of the Junggar basin (Fig. 1). The Sikeshu River has a total length of 137 km and a catchment area of about 6669 km^2, with about 5% glacierization (Shang, 2011). It is one of the primary glacier regions

* Corresponding author.
E-mail address: wangfeiteng@lzb.ac.cn (F. Wang).

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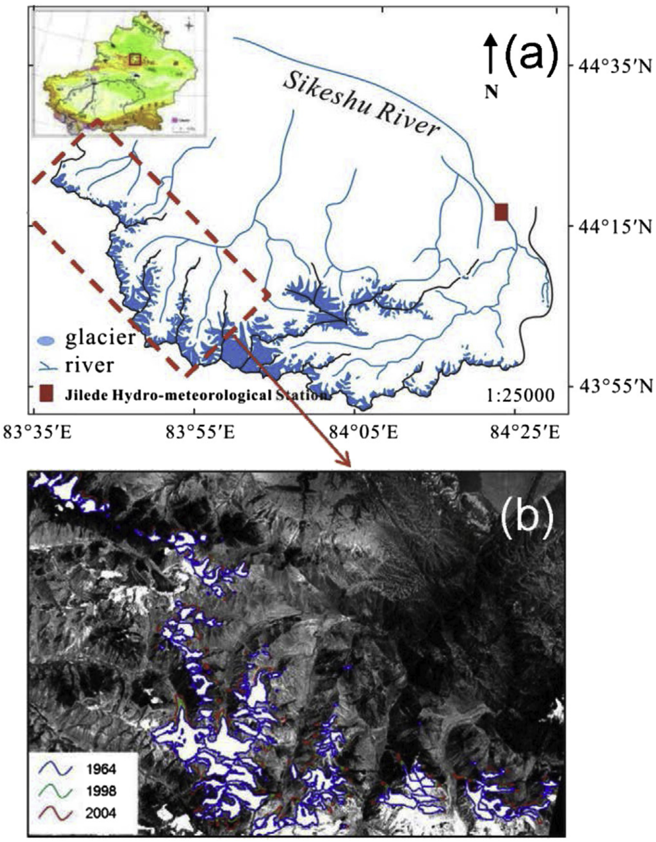

Fig. 1. Location of Shikeshu River basin. (a) the location of the study region,(b) An example of glacier delineation on the ASTER image.

in the source region of Ebinur Lake Basin, and is the main fresh water source for the cities of Usu and Kuytun, population of 0.22, and 0.31 million, respectively (NPCC, 2010). According to the Chinese Glacier Inventory (CGI), which was accomplished in 2002 (Shi, 2008), there were 364 glaciers within the entire Sikeshu River basin. These glaciers had a total estimated area of 336.25 km^2, with a mean glacier area of 0.92 km^2 in 1964 (Liu and Ding, 1986).

Climatically, the Tienshan Mountains are characterized by interactions between the Westerlies and the Siberian High over complex mountain topography (Aizen et al., 1995). The precipitation is mainly from the moisture carried by the westerlies in summer, and the winter temperature is controlled by the Siberian High (Aizen et al., 1995). The dominant weather patterns are orographic thunderstorms in summer and cold-dry anticyclones in winter. Precipitation varies horizontally (west-east gradient) between 400 and 600 mm at altitudes of 1500–2700 m a.s.l. The glaciers in this region are the summer accumulation type. Typically, 70% of the precipitation occurs between May and September (Shang, 2011).

Glacier runoff discharge and meteorological data were measured at the Jilede hydro-meteorological station (44°22′N, 84°25′E, 1050 m a.s.l., catchment area 921 km^2). This station was established in 1954 at the lower basin of the Sikeshu River (Fig. 1). The observations were carried out from May to September each year, where the observed water level records are converted to discharges based on rating curves. Over 95% of the annual runoff at the stations occurs during the observation period, whereas for the rest of the year, the streams are mostly frozen. At this station, the mean annual, summer (June to August), and winter (December to February) of precipitation and air temperature are 262.2, 120.0, and 19.7 mm, and 8, 22.5, −11.3 °C, respectively, during 1954–2006 (Tang, 2009; Ge and Zhu, 2010; Shang, 2011). The summer zero degree isothermal line is situated between 3700 and 4100 m a.s.l.(Liu and Ding, 1986). The equilibrium line altitude is situated around 3710 m a.s.l. (Liu and Ding, 1986).

3. Data and methods

To compare recent changes in glacier area, Landsat 5, ASTER images and historical topographic maps were used in this study (Table 1). One Landsat 5 image (1998) with a ground resolution of 30 m was downloaded from the USGS (United States Geological Survey) web server (Table 1). Two ASTER images with a ground resolution of 15 m were taken on August 25th 2004. These images cover the most heavily glaciated part of the investigated area. Seasonal snow, shadow, and clouds may be identified as glacier pixels, resulting in overestimation (Nakano et al., 2013). The debris cover may be identified as rocks, resulting in underestimation in these regions. Excellent images ensure clear glacier boundaries, minimizing uncertainty. For this study, image selection for glacier mapping was guided by acquisition at the end of the ablation period, cloud-free conditions, and lack of snow fields adjacent to glaciers. Data assessments conducted under the Global Land Ice Measurements from Space (GLIMS) framework confirmed that artificial interpretation remains the best tool for extracting higher-level information from satellite images for glaciers, especially debris-covered glaciers (Paul et al., 2004; Raup et al., 2007). A total of 8 topographic maps (1:50 000), derived from aerial photographs acquired in 1964 by the Chinese Military Geodetic Service, were analyzed. A digital elevation model (DEM) of the Sikeshu River basin at the 1:50 000 scale (DEM5) was created by contour digitization and interpolation from the 1:50 000 topographic maps. The satellite images were orthorectified by combine the advantages of multispectral remote sensing (mapping of clean ice and vegetation free regions) with a DEM, which was derived from shuttle radar topographic mission (SRTM) (Paul et al., 2004) and PCI Geomatica 9.1 Orthoengine software (Kutuzov and Shahgedanova, 2009; Svoboda and Paul, 2009). Geocorrection and co-registration were established using ERDAS Imagine 9.0 software. Clearly distinguishable terrain features that could be identified on each image were selected from the topographic maps. On average, 30–50 ground control points were collected for each pair of images to obtain satisfactory root-mean-square error (RMSE) values (10 m). All images and maps were presented in a Universal Transverse Mercator (UTM) coordinate system referenced to the 1984 World Geodetic System (WGS84).

Table 1
Data sources used in this study.

Source	Satellite ID	Date	Resolution or scale	Cloud cover
Topographic map	–	1964	1:50000	–
Landsat 5	LT51450291998245BIK00	02/09/1998	30 m	0%
ASTER	AST-L1A.04082505251004090500 81	25/08/2004	15 m	0%
ASTER	AST-L1A 0.04082505251904090500 82	25/08/2004	15 m	0%

The glacier outlines for 1964, 1998 and 2004, from the topographic maps and satellite images were used in this study, respectively. The outlines were mapped manually with the DEM using commercial GIS software (ArcView), as well as using the topographic maps and satellite images. ArcView is a useful tool for extracting detailed information from satellite imagery of glaciers

(Raup et al., 2007), particularly when mapping is conducted by the same person using a combination of different types of imagery (Paul et al., 2002). A DEM with a grid spacing of 25 m was used to derive the elevation and slope orientation data for the glaciers. Area and other parameters of the glaciers in different time periods can be computed from the extracted glacier polygons, resulting in a total sample of 145 glaciers. The glacier length is the longest flowline of the entire glacier, which was measured from the lowest to the highest point of the glacier (Lopez et al., 2010). The mean length of glaciers is the average length of all the glaciers that were measured.

The main errors in remotely sensed glacier studies are due to glacier boundary extraction, sensor resolution, and co-registration. The first error can only be reduced through field verification and glaciological experience. In this study, the Haxilegen Glacier No. 51 (43°44′N, 84°23′E, 30 km from the Sikeshu River basin) was surveyed in August 2004 using RTK-GPS (micrometer accuracy). The results show that there is about 0.8% difference in length and 0.5% difference in area between our 200 surveyed points and the glacier mapping generated from ASTER and Landsat data. For the latter two types of error, the uncertainty of remote-sensing images can be evaluated (Ye et al., 2006). For multiple images, its linear uncertainty (UL) can be expressed as:

$$U_L = \sqrt{\sum \lambda^2} + \sqrt{\sum \delta^2} \tag{1}$$

where U_L is the measurement uncertainty of the glacier terminus, λ is the original pixel resolution of each individual image or map, and δ is the registration error of each individual image to the topographic map.

Correspondingly, the area uncertainty between multiple images can be deduced and expressed as:

$$U_A = \sum \lambda^2 \times \frac{2 \times U_L}{\sqrt{\sum \lambda^2}} + \sum \delta^2 \tag{2}$$

where U_A is the measurement uncertainty of the glacier area and U_L is the linear uncertainty. In our case, the glacier terminus and area measurement uncertainty can be calculated using Eqs (1) and (2), and the resulting values are 28.7 m and 0.001 km^2, respectively.

4. Results and discussion

4.1. Characteristics of glacier distribution

A total of 145 glaciers with an area of 96.9 km^2 has been identified and mapped on the satellite imagery in 2004. Hanging and cirque glaciers are the dominant types. Fig. 2 shows the distribution of glacier coverage in the Sikeshu River basin, according to the glacier size class (<0.1, 0.1–0.5, 0.5–1, 1–2, 2–5 and >5 km^2). The vast majority of glaciers (80.7%) are smaller than 1 km^2. These glaciers contain more than a third of the total area, which is a common feature in mountains of the mid-latitudes (Hagg et al., 2012b). About 16.0% of the glaciers have an area of 1–5 km^2, and account for 56.7% of the total area. No glacier is larger than 10 km^2, only one glacier is larger than 5 km^2 and accounts for 25% of the total area. Small glaciers are prevalent in this region.

The lowest position of any glacier tongue in the Sikeshu River basin is about 2600 m a.s.l., but 85% of glaciers terminate above 3400 m a.s.l. The median elevation, which is widely used to estimate the long-term mean equilibrium line altitude (Braithwaite and Raper, 2009), is approximately 3828 m a.s.l. The distribution of the glacier aspect was determined using ASTER-GDEM and shows the dominant orientation is north and northeast in most cases (Fig. 3).

4.2. Changes in glacier area

A comparison of the three inventories shows that the glaciers have undergone rapid retreat during the last 40 years (Table 2). The glaciated area of the Sikeshu River basin decreased from 114.6 km^2 in 1964 to 96.9 km^2 in 2004, resulting in a relative ice cover loss of 15.4% (0.38% y^{-1}). As a result, the number of glaciers decreased from 150 to 145. Among these glaciers, 140 (96%) glaciers shrank by approximately 17.92 km^2, 5 (2%) glaciers grew by about 0.33 km^2 and 5 (2%) glaciers disappeared. The maximum area loss occurred in the 1.0–5.0 km^2 size class, which decreased in total area from 69.4 to 54.5 km^2, or 21.5%. The number of the smallest size class (<0.1 km^2) increased from 41 to 46, which is due to the larger glaciers melt down into several smaller glaciers, while the number of glaciers between 1 and 5 km^2 decreased from 31 to 24. At the same time, the mean length change of all analyzed glaciers between 1964 and 2004 was 195.3 m (4.9 m y^{-1}). On average, the glaciers lost 15.6% of their length.

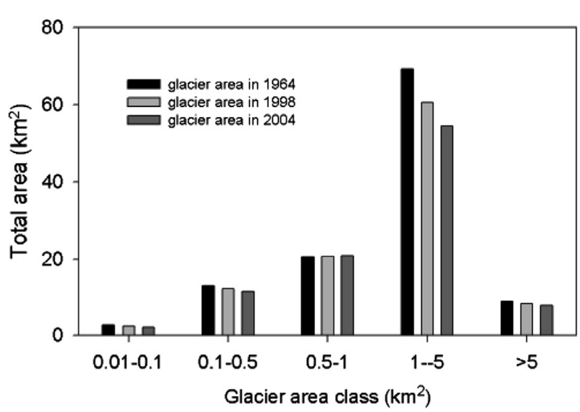

Fig. 2. Glacier number and area in the Sikeshu River basin in 1964, 1998, and 2004.

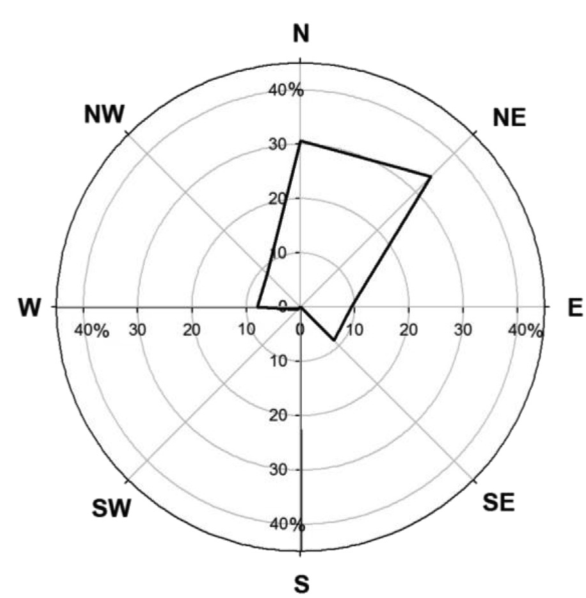

Fig. 3. Distribution of glacier area by orientation classes in the Sikeshu River basin in 2004.

Table 2
Changes in glacier area and number in the Sikeshu River basin, 1964–2004.

Glacier area class (km^2)	Area (km^2)				Number			
	1964	1998	2004	Relative (%) (1964–2004)	1964	1998	2004	Relative (%) (1964–2004)
0.01–0.1	2.7	2.4	2.2	−18.5	41	45	46	12.2
0.1–0.5	13.0	12.2	11.4	−12.3	48	45	44	−8.3
0.5–1	20.5	20.6	20.9	2.0	29	30	30	3.4
1–5	69.4	60.5	54.5	−21.5	31	25	24	−22.6
>5	9.0	8.3	7.9	−12.2	1	1	1	0
Total	114.6	104.1	96.9	−15.4	150	146	145	−3.3

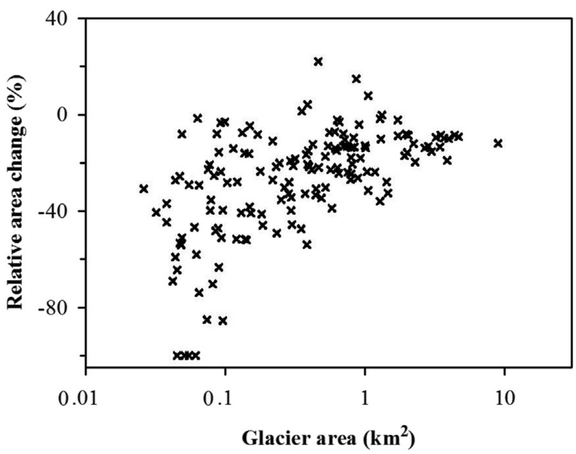

Fig. 4. The relationship between glacier area and relative area change (%) for 1964–2004 in the Sikeshu River basin.

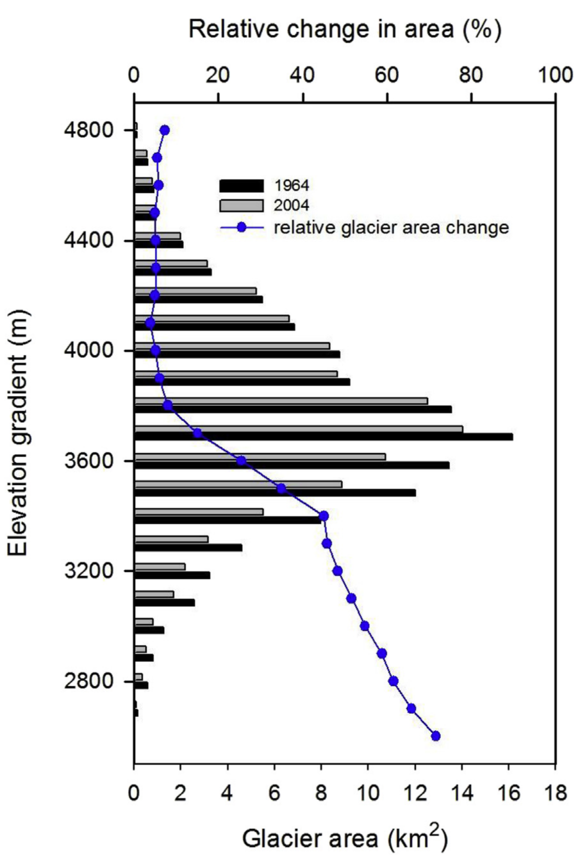

Fig. 5. Glacier area distribution versus elevation interval in the Sikeshu River basin.

The relative changes in glacier areas also varied with glacier size as seen in Fig. 4. Small glaciers (<1 km^2) had a large range of change from−100% to+22%. In contrast, the relative shrinkage of distinct glaciers (>1 km^2) for each glacier was small, although large glaciers lost comparatively large areas at lower elevations. Fig. 5 shows the elevational distribution of glacier extent in the Sikeshu River basin. Percentage reductions in glacier area generally decrease with increasing altitude. The termini of small glaciers are particularly sensitive to climatic changes (Knight, 1998; Nesje and Dahl, 2000), and small glaciers are distributed over a wide elevation range, 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.

4.3. Recent glacier shrinkage related to local climate changes

Glacier variation is related to several climatic factors such as air temperature, precipitation, wind, and solar radiation. For Central Asian small continental glaciers (<5 km^2), studies have indicated that a 1C° increase in air temperature can cause glacier equilibrium lines to rise by 52–152 m in altitude, whereas a 100 mm increase in annual precipitation can lower them by 9–85 m (Zhang et al., 1998). Air temperature is considered to be one of the most important factors governing glacial fluctuations (Houghton et al., 2001). Increasing levels of precipitation are not sufficient to offset the effects of warmer temperatures in some areas, such as the Tarim River Basin in Northwestern China (Liu et al., 2006). However, precipitation seasonality may also affect the climatic sensitivity of the glacier mass balance (Fujita 2008).

The annual temperature at the Jilede hydro-meteorological station demonstrated an increasing trend from 1953 to 2005, particularly after 1995 (Fig. 6). The linear trend of air temperature was 0.34 °C per decade. The trend is similar to that averaged over the entire Xinjiang Uygur Autonomous Region [0.33 °C per decade] (Liu et al., 2009). In a larger spatial scope, the air temperature in this area is generally in phase with other locations throughout the Tienshan. According to Aizen et al. (1997), the average increase in air temperature over central and western Tienshan was 0.01 °C y^{-1} with slightly lower values below 2000 m a.s.l. during the period 1940–1991, which is lower than that from the Jilede hydro-meteorological station. During the corresponding period, the records at this station displayed a gradual increase in annual precipitation. However, the temperature increase caused an increase in liquid precipitation instead of solid precipitation in the high-altitude glacierized area for the glaciers with less accumulation, especially with summer accumulation, leading to reduced accumulation and accelerated ablation. Climate time series show that increasing temperatures in the basin were responsible for the reduction in glacier area between 1964 and 2004.

4.4. Glacier volume changes and effect on regional water resources

The northern foot of the Tienshan Mountains represents a vital ribbon of economic development in the Xinjiang region. The Usu and Kuytun cities located in the lowland of the Sikeshu River, which rely on glacier meltwater for domestic water, irrigation, industry, and hydropower (Kang et al., 2002). As economic activities and population increase, the water shortage in the Usu and Kuytun cities are a puzzling problem that limits economic development and domestic water use.

The loss in glacier area has been accompanied by a loss in volume. It is difficult to precisely calculate the ice volume. At present, glacier volume is known for less than 0.1% of the estimated global population of more than 200 000 glaciers. For this reason, indirect estimates of ice volume are necessary based on various theoretical

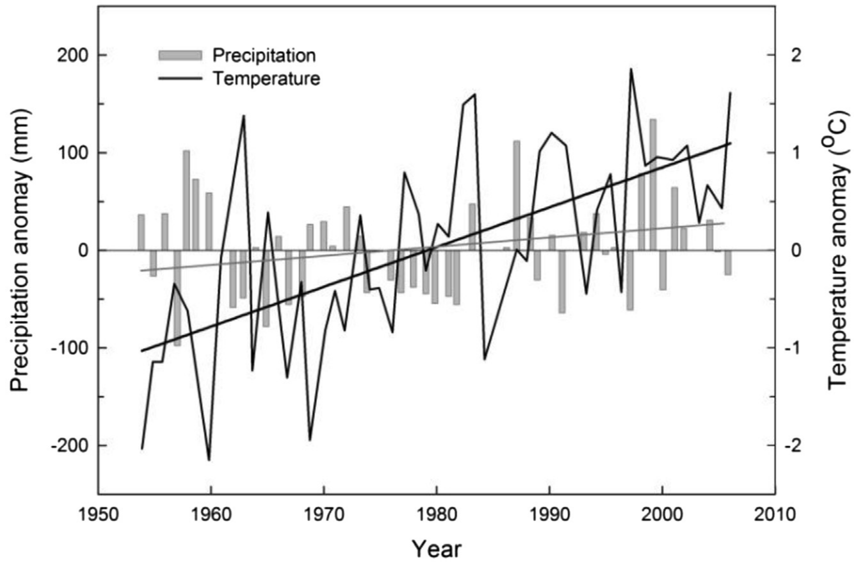

Fig. 6. The anomaly of temperature and precipitation during 1955–2004 at the Jilede hydro-meteorological station in the Shikeshu River basin.

and statistical approaches. Of these indirect methods, volume-area scaling is the most widely applied approach for regional and global-scale glacier inventories. For Tienshan glaciers, four volume-area scaling laws were found in the literature (Table 3). There were 128 glaciers with a total glacier area of 106.00 km^2 were located above the Jilede hydro-meteorological station in 1964. Thus, based on these equations, the ice volume has decreased by 3.25–5.31 km^3, which is approximately 29.25–47.79 $\times$ 10^8 m^3 water equivalent (assuming an ice density of 900 kg m^{-3}) during the period 1964–2004. Water resources in the Sikeshu River basin increased by 29.25–47.79 $\times$ 10^8 m^3 as a result of the loss of ice volume during the period studied.

Table 3
Estimated glacier volume of the Sikeshu River basin by different area–volume scaling laws.

	Equation	Glacier volume (km^3)			
		1964 (A = 106.00 km^2)	1998 (A = 104.10 km^2)	2004 (A = 89.68 km^2)	Change (1964–2004)
Shi et al. (1981)	$0.0361 \cdot A^{1.406}$	25.41	24.78	20.10	5.31
Chen and Ohmura (1990)	$0.0285 \cdot A^{1.357}$	15.97	15.58	12.72	3.25
Macheret et al. (1988)	$0.0298 \cdot A^{1.379}$	18.50	18.04	14.69	3.81
Liu et al. (2003)	$0.04 \cdot A^{1.35}$	21.69	21.17	17.30	4.39

Annual runoff at the Jilede hydro-meteorological station ranges from 2.27 $\times$ 10^8 m^3 y^{-1} to 4.27 $\times$ 10^8 m^3, with a mean value of 3.02 $\times$ 10^8 m^3 y^{-1}. The total discharge was 120.8 $\times$ 10^8 m^3 y^{-1} at this station during the period 1964–2004. A comparison of the glacier mass loss with the total discharge indicates that glacial meltwater accounts for 24.2–39.6 % of the river runoff.

Fig. 7 presents annual runoff anomalies at the Jilede hydro-meteorological station from 1955 to 2004. There has been a general increase in glacier runoff in the river basin. Since the mid-1990s, especially, this trend has become more pronounced. With the marked increase in temperature in the Sikeshu River basin since the mid-1990s, an increasing amount of additional fresh water is very likely to be released from glacier storage, resulting in dramatic increase in glacier runoff. 1998 was the warmest year during the period 1953–2005 in the Sikeshu River basin (Fig. 6), and the discharge reached a maximum. So, we can conclude the high discharge in 1998 was most likely due to glacier mass loss.

Accurate estimation of changes in future runoff is difficult and needs more detailed observation parameters and use of hydrological models. Future discharge was simulated by assuming a doubling of atmospheric CO_2 and a 50% deglacierization in the headwaters of the Urumqi river (Hagg et al., 2007). The results suggest a higher flood risk in spring and early summer, becoming a runoff deficiency after a higher degree of deglaciation is reached. Further increases in temperature and precipitation are predicted for the 21st century, which means that additional water is expected to be released from glacier storage, thus modifying the current stream flow regime. It would also result in more flooding problems in the near future and a water shortage towards the end of the century.

5. Conclusion

Using remote sensing data, we have determined that continuous glacial recession has occurred over the past 40 years in the Sikeshu River basin, Tienshan Mountains. The results showed that the glaciated area decreased by about 15.4% (0.38% y^{-1}) from 114.6 to 96.9 km^2. The average glacier front retreat amounts to 195.3 m (4.9 m y^{-1}). Data from the Jilede hydro-meteorological station in the Sikeshu River basin showed increases in both the annual mean air temperature and annual precipitation during 1953–2005. This indicates that the glacier shrinkage in the Sikeshu River basin over

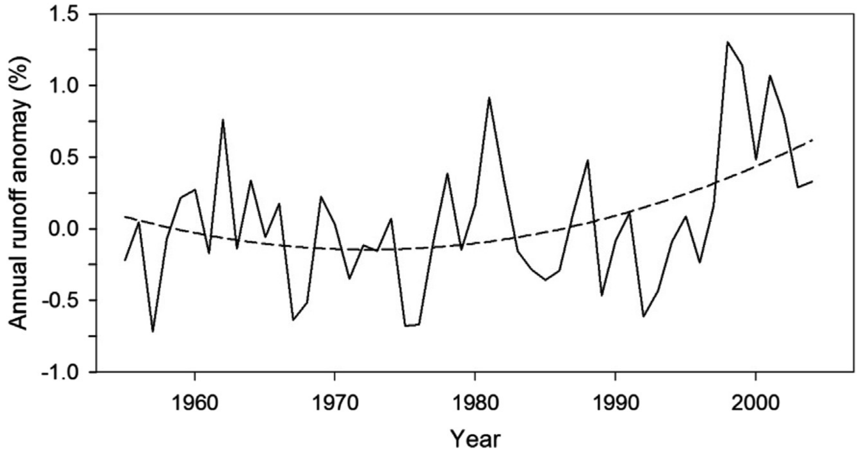

Fig. 7. Annual runoff anomalies records at Jilede hydro-meteorological station during recent decades. Dashed lines are the second-order polynomial fit curves.

the last 40 years was largely due to regional climate warming that enhanced glacier ablation and overcame the effects of increased precipitation on the glacier mass balance.

An understanding of the present state of glaciers is needed to contribute to the reasonable development and utilization of regional water resources, water cycle models, and regional economic planning. However, the volume of glaciers was estimated using empirical equations with uncertainties. Therefore, the effect of glacier change on water resources has been limited to qualitative analyses. Glacier area changes are affected not only by climate fluctuations, but also by factors such as glacier dynamics and glacier dimensions. Unfortunately, there is no glacier mass balance record and glacier dynamics information for the study region. More detailed research with the aid of reliable glacier field data is needed to confirm the calculations made here.

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