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ORIGINAL ARTICLE

Glacier shrinkage in the Daxue and Danghenan ranges of the western Qilian Mountains, China, from 1957 to 2010

Puyu Wang[1,2] · Zhongqin Li[1,2,3] · Guobin Yu[4] · Huilin Li[1,2] · Wenbin Wang[1] · Baojuan Huai[1] · Ping Zhou[1] · Shuang Jin[1] · Lin Wang[1] · Hui Zhang[1]

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Abstract Changes in glaciers in the Daxue and Danghenan ranges were analyzed based on topographic maps, satellite images and a digital elevation model (DEM). The results indicate that from 1957/1966 to 2010, the total area and ice volume for the investigated glaciers declined by 17.21 and 24.10 % in these respective ranges. From 1957 to 2010, the total area and ice volume in the glaciers in the Daxue Range declined by 16.03 % (0.30 % a^{-1}) and 22.40 %, respectively, with a mean reduction of 0.133 km^2 for an individual glacier. These glaciers retreated by an average of 258 m (3.4 m a^{-1}). From 1966 to 2010, the total area and ice volume for the glaciers in the Danghenan Range declined by 18.32 % (0.42 % a^{-1}) and 25.70 %, with a mean reduction of 0.111 km^2 for an individual glacier. These glaciers retreated by an average of 159 m (3.6 m a^{-1}). The rate of glacier retreat on the south-facing slopes was faster than that on the north-facing slopes. The area of glaciers on the south and north slopes of the Daxue Range declined by 22.82 and 15.51 %, respectively, and the area of glaciers on the south and north slopes of the Danghenan Range declined by 22.39 and 16.76 %, respectively. An analysis of the general trend of climatic change in the study area revealed that rapidly rising air temperatures were most likely the major factor causing the loss of glacier ice within the study area. Compared with other glaciers in the eastern and middle Qilian Mountains, glaciers in the western Qilian Mountains appeared to be losing mass at a slower rate. The differences of glacier changes in the eastern, middle, and western Qilian Mountains are mainly caused by the combination of climatic conditions and glacier morphologic factors.

Keywords Fractal analysis · Glacier change · Regional differences · Western Qilian Mountains

Introduction

Mountain glaciers are sensitive indicators of climate and are commonly used for monitoring environmental and climatic changes on regional and global scales. Glacier runoff is also a major contributor to local ecological conditions, industry, and agriculture in arid regions (Shi et al. 2000). Since the 1950s, increases in temperature have caused glaciers to retreat worldwide. Numerous research studies indicate that glacier retreat is common in most of northwest China, with glaciers in several regions seriously melted (Lu et al. 2002; Wang et al. 2008, 2011a, b; Gao et al. 2011; Li et al. 2011). Glacier retreat in China has been severe in recent years. This has attracted attention worldwide because these melting glaciers can give insights into climate change allowing researchers to explore the potential effects of glacier retreat on much needed water resources in those regions. The effects of glacier melting on local water resources is significant in the continental river basin of western China, because glacier meltwater supplies play an important role in economic and social

✉ Puyu Wang
wangpuyu@lzb.ac.cn

1 State Key Laboratory of Cryospheric Sciences/Tianshan Glaciological Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

2 RWTH Aachen University, 52056 Aachen, Germany

3 College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, China

4 Gansu Fundamental Geographic Information Center, Lanzhou 730000, China

development of this arid inland basin (Ding et al. 2001; Shen et al. 2001; Yang and Zeng 2001; Wang 2010; Fan et al. 2011; Chen et al. 2012; Liu et al. 2003; Chai et al. 2013). Therefore, glacier monitoring is imperative for studying the effects of global and regional climate change and for conducting thorough environmental research in those regions.

During the 1950s–1970s, the Chinese Academy of Sciences conducted field surveys of the glaciers in the Qilian Mountains. Based on 1956 aerial photographs, an inventory of glaciers of the Qilian Mountains was completed in 1981 (Wang et al. 1981) and the baseline number of glaciers in the various river basins was assessed. This dataset provides supporting data and a scientific basis for the rational use of water resources and documentation of ongoing regional and environmental change in support of research in the Hexi area of Gansu Province (Investigation Team of the Ice/Snow Utilization of Chinese Academy of Science 1959; Wang et al. 1981; Xie et al. 1985). After the 1990s, rapidly developing remote sensing technology has been widely used to study the changes in glaciers within various regions lacking observational data for prolonged periods of time and across extended regions. Most research on glacier changes in the Qilian Mountains has focused on the eastern and middle Qilian Mountains. Research on large-scale and long-time glacier fluctuations in the western portion of the Qilian Mountain region is limited despite the fact that glaciers in this region provide important water resources for local economic development. During the past several decades, glaciers in the western Qilian Mountains have shrunk rapidly primarily as a result of climate warming. The effects of the glacier shrinkage on water resources have drawn widespread attention. Liu et al. (2003) studied glacier changes in the western Qilian Mountains using remote sensing (RS) and geographic information system (GIS). However, that study was limited by the number of available high-quality satellite images and the time period covered (until 1990). In addition, that study area centered on only the Daxueshan Range. Temperatures have increased in recent years and the increase has accelerated since 1990. Glaciers distributed within the study area were experiencing rapid and serious melting. However, this severe glacial melting has revealed regional differences in glacier mass loss and allowed for insight into the causes for these differences. In this case, revealing the regional differences of glacier changes and analyzing the factors causing these differences undoubtedly have great scientific value and have a certain practical significance for the protection of the regional glacier environment and related water resource management.

Taking this into account, glacier changes in the Danghenan and Daxue ranges of the western Qilian Mountains in the last 50 years were analyzed using satellite images covering three periods and the Chinese Glacier Inventory. It can provide the scientific basis for an assessment of glacier water resources in these arid areas.

Study area

Lying between the Gansu Province and Qinghai Province of China, the Qilian Mountains form a vast mountain system at the northeastern margin of the Qinghai-Tibetan Plateau. The study area lies at the western Qilian Mountains, 38°50′–39°60′N, 95°00′–96°90′E (Fig. 1) where the elevations of the peaks range between 4000 and 5500 m a.s.l. This area is the main formative region of the interior drainage system in the western Qilian Mountains including the Shule, Dang, and Haerteng rivers. The mountains within the study area run roughly from southeast to northwest. The study area is mainly affected by the Westerlies with annual precipitation typically between 150 and 400 mm. The temperatures tend to be higher in the eastern Qilian Mountains while the western Qilian Mountains typically remain colder. Therefore, the existence of glaciers creates a need for a large area of cold storage to be sustained. According to the Chinese Glacier Inventory (Wang et al. 1981), the Daxue Range supported 203 glaciers covering an area of 162.8 km^2, while 336 glaciers were distributed in the Danghenan Range covering an area of 186.3 km^2. The largest glacier, Laohugou Glacier No. 12, was located in the Laohugou River drainage basin with a total length of 10.8 km, area of 21.9 km^2, and total ice volume of 2.63 km^3. It ranged from 5483 to 4250 m at the terminus in elevation.

Data and methods

Topographic maps, remote sensing images, a digital elevation model (DEM), and meteorological data were used to analyze glacier and climate changes within the study area. A total of 19 topographic maps (1:50,000) obtained from aerial photographs were included. Among them, 5 and 14 topographic maps were based on aerial photographs in 1957/1966 for the Daxue and Danghenan ranges, respectively. Satellite images from the three periods were selected, including Landsat TM (Thematic Mapper) images from August 1994, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images from July 2000, and SPOT5 (Satellites Pour l'Observation de la Terre5) images from August 2010. The scale of the DEM was 1:50,000 with a grid size of 25 m $\times$ 25 m. The Landsat TM images were from the USGS (http://www.usgs.gov/), and ASTER, SPOT 5 images and DEM were from the Gansu Fundamental Geographic Information Center.

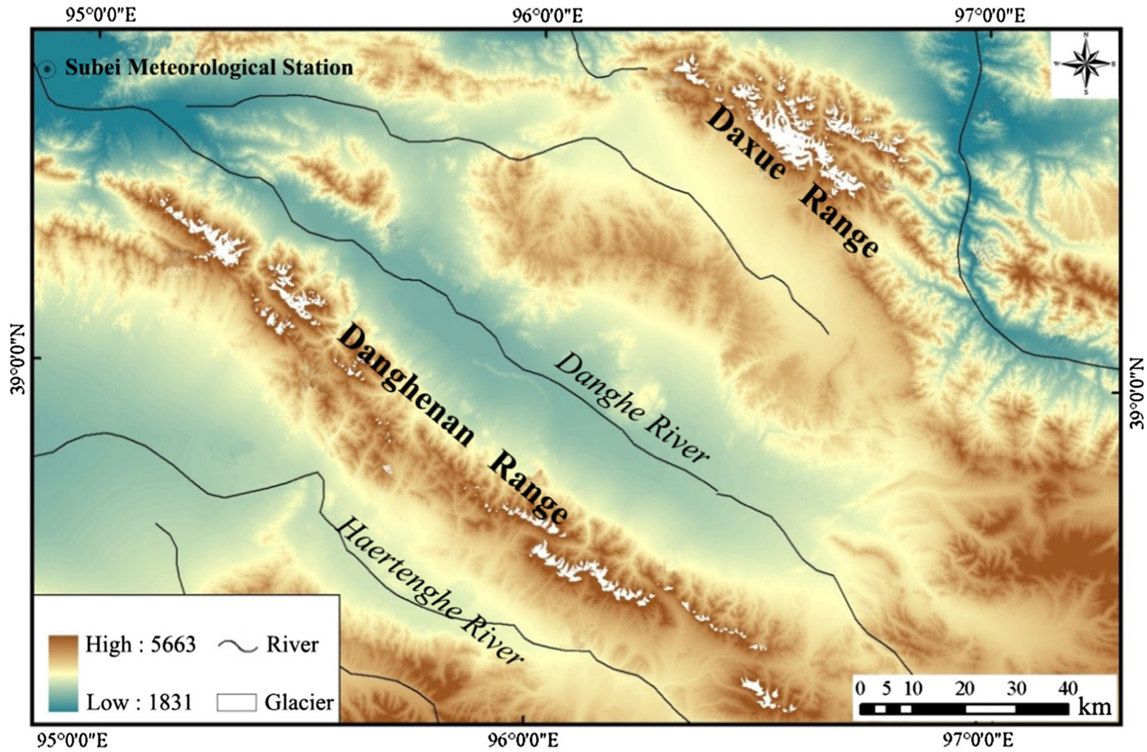

Fig. 1 Location of the study area and distribution of glaciers

Data processing included an analysis of topographic map and remote sensing images. First, the topographic maps were scanned and geometrically corrected. For each geographic map, the root of mean square error (RMSE) of the corrected topographic map was within one pixel (5 m × 5 m) in both the x and y directions. Geometrical correction and radiometric correction were completed and surface features were clearly identified on the topographic map. The remote sensing images were selected as control points. Image registration was then taken and the projection changed to UTM WGS84 (Universal Transverse Mercator World Geodetic System 1984). Concurrently, terrain correction was completely based on the DEM to reduce the influence of terrain factors on glacier classification, ensuring the accuracy of the extracted glacier information. Then the images were enhanced to determine the glacier boundary.

During the process of glacier boundary extraction, glacier boundaries during 1957/1966 were determined by direct digitizing, and glacier information (e.g., area, length) in 1994, 2000, and 2010 was obtained by manual interpretation combined with DEM analysis using ArcGIS 9.0 software (ESRI, Inc. Redlands, CA, USA). The glacier boundaries were mapped manually using false-color composite TM bands 5, 4, and 3 on the Landsat imagery with the resolution of 30 m, 3 bands in visible and near-infrared (VNIR) with 15 m resolution on ASTER images, and panchromatic SPOT5 image with 5 m resolution using ERDAS Image software. Although the manual interpretation was time-consuming and laborious, according to the GLIMS framework (Raup et al. 2007), it provided the best method of extracting glacier boundary from satellite imagery for glaciers particularly when mapping is conducted by the same person using a combination of different types of satellite images (Paul et al. 2002). Because parts of the glaciers were covered with snow and clouds, only 477 glaciers were selected for comparison research. The debris cover can reduce the accuracy of mapping. However, the debris cover of the glaciers in the Daxue Range and Danghenan Range of the western Qilian Mountains was not extensive. During the interpretation process, boundaries of glaciers with debris cover were determined by referring to DEM data and topographic maps, glacier inventory data, Google Earth, and expert knowledge to insure that glacier information extracted was accurate. Finally, glacier changes were studied by comparing glacier information in the four periods.

Various factors affecting the accuracy of the data were considered during error evaluation. Errors caused by image resolution and image geometric registration can be evaluated using an uncertainty evaluation model. Previous studies (Hall et al. 2003; Silverio and Jaquet 2005) determined the uncertainty of glacier length and area change can be estimated using Formula (1) and (2):

$$U_{\mathrm{T}} = \sqrt{\sum \lambda^2} + \sqrt{\sum \varepsilon^2} \quad (1)$$

$$U_{\mathrm{A}} = 2U_{\mathrm{T}}\sqrt{\sum \lambda^2} + \sqrt{\sum \varepsilon^2} \quad (2)$$

where U_{T} is the length uncertainty, U_{A} is the area uncertainty, λ is the spatial resolution of the image, and ε is the registration error. The calculated uncertainty of the terminus position in TM, ASTER, and SPOT 5 images are ±45.3, ±32.1, and ±14.5 m, respectively. The uncertainty of glacier area was ±0.004, ±0.001, and ±0.0008 km^2, respectively. For the error caused by the quality of a remote sensing image, such as the presence of snow and debris cover, the image can be validated and adjusted by glacier monitoring and field surveys. Through comprehensive error analysis and field validation, the estimated error of the glacier area was about ±1.5 %.

Results

Overall trend of glacier change from 1957/1966 to 2010

The area covered by glaciers in the eastern Qilian Mountains was 332.5, 309.2, 292.7 and 275.3 km^2 in 1957/1966, 1994, 2000, and 2010, respectively (Table 1). The spatial extent of glaciers declined by a total of 57.20 km^2 from 1957/1966 to 2010, accounting for a 17.20 % total loss (0.35 % a^{-1}) of the area from 1957/1966. The reduction rates varied for different periods. During 1957/1966–1994, glacier area declined by 23.3 km^2 with a rate of 0.22 % a^{-1}. During 1994–2000 and 2000–2010, glacier area declined by 16.49 km^2 and 17.4 km^2 with a rate of 0.89 and 0.59 % a^{-1}, respectively. By comparison, although the glaciers have undergone rapid shrinkage and terminus retreat during the past 50 years (a process that is ongoing), the retreat rate during 1994–2010 was especially larger than during 1957/1966–1994. During the entire studied time span (1957/1966–2010), a total of 18 glaciers disappeared completely exposing a total area of 5.49 km^2, accounting for 1.7 % of the glacier area in 1957/1966. Severe melting of glaciers has caused the glacier area and volume to decline significantly since 1957/1966.

Several researchers have calculated a relationship between glacier area S and volume V (Formula 3; Bahr 1997; Chen and Ohmura 1990; Macheret et al. 1988; Liu et al. 2003).

$$V = c \times S^{\lambda} \quad (3)$$

where the value of λ is either 1.36 or 1.25 for a glacier and an ice cap, respectively. The constant of proportionality or scaling constant c becomes irrelevant and it can be eliminated. Hence, the calculation of relationship between

Table 1 Changes of glaciers in the study area from 1957/1966 to 2010

Period	Study area				Daxue range				Danghenan range			
	Area/km^2	Area shrinkage (%)	Rate of area shrinkage (% a^{-1})	Volume change (%)	Area/km^2	Area shrinkage (%)	Rate of area shrinkage (% a^{-1})	Volume change (%)	Area/km^2	Area shrinkage (%)	Rate of area shrinkage (% a^{-1})	Volume change (%)
1957/1966	332.48				162.19				170.29			
1957/1966–1994	309.16	7.01	0.22	9.7	152.16	6.18	0.17	8.5	156.99	7.80	0.28	10.7
1994–2000	292.67	5.33	0.89	7.3	144.25	5.20	0.87	7.1	148.41	5.47	0.91	7.5
2000–2010	275.27	5.94	0.59	8.2	136.18	5.59	0.56	7.7	139.09	6.28	0.63	8.6
1957/1966–2010		17.20	0.35	24.1		16.03	0.30	22.4		18.32	0.42	25.7

volume change and area change has been improved by Bahr et al. (2009); Formula (4):

$$(1 + P_v) = (1 + P_s)^{\lambda} \quad (4)$$

where P_v is the estimated change in volume, and P_s is the change in area. The ice volume can be calculated using Formula (5):

$$P_v = (1 + P_s)^{\lambda} - 1 \quad (5)$$

A comparison of the glaciers in the Danghenan and Daxue ranges allows an analysis of the differences between glaciers in the different regions. The spatial extent of glaciers in the Danghenan Range in the southern part of the study area declined by 18.32 % (0.42 % a^{-1}) during 1966–2010 and a reduction in volume of 25.7 %. The spatial extent of glaciers in the Daxue Range in the northern part of the study area declined by 16.03 % (0.30 % a^{-1}) during 1957–2010 and a reduction in volume of 22.4 %. By comparison, the loss of glacier area and the reduction in volume were larger in the Danghenan Range in the south than in the Daxue Range in the north.

Glacier change in the Daxue Range

The 203 glaciers of the Daxue Range cover an area of 162.8 km^2 with an average area of 0.802 km^2 per glacier. In this study, 196 glaciers were clearly identified in the remote sensing images based on the 1957 topographic maps. The total glacier area was 162.2 km^2 with an average area of 0.827 km^2 per glacier.

During the past 53 years, glaciers in the Daxue Range experienced rapid shrinkage with an average reduction in area of 26.01 or 0.13 km^2 for an individual glacier (Table 1). The rate of shrinkage was about 16.03 % (0.30 % a^{-1}). However, the shrinkage rates varied in different time periods, with glaciers experience a cyclical process of "slow-fast-slow" melting (Table 1). Glaciers that covered an area of <0.10 km^2 and 1.00–5.00 km^2 accounted for 17 and 19 % of the total number of glaciers and 14 and 43 % of total glacier area, respectively. The area of these two groups of glaciers (smallest and larger, as defined above, respectively) decreased by 1.35 km^2 (57.2 % area loss) and 9.19 km^2 (13.21 %), respectively (Fig. 2a). This indicates that small glaciers had larger rate of change but a smaller absolute area change than larger glaciers, indicating that small glaciers are more sensitive to climate change.

The small glaciers in the Daxue Range experienced obvious shrinkage. Meanwhile, the glacier retreat on the southern slope was much more severe than on the northern slope. During 1957–2010, the 34 glaciers located on the southern slope lost 22.82 % of their surface area, while the 162 glaciers on the northern slope lost 15.51 %. These regional differences were attributed to two causes: first, there is a long solar radiation time for glaciers on the southern slope, an external driving force for glacier melting in the region. Second, the distribution of glaciers of different sizes influences the glacier retreat (Fig. 2b). Glaciers on the southern and northern slope that were <1.00 km^2 accounted for 94 and 76 % of the total number of glaciers and 60 and 22.4 % of the area in their respective areas. The differences in proportion of numbers and areas of glaciers that are <1.00 km^2 on the two slopes were the leading cause for different retreat rates of the glaciers on the northern and southern slopes.

The average length of glaciers in the Daxueshan Range was 1190 m in 1957 and 1009 m in 2010. From 1957 to 2010, the terminus of the 196 glaciers investigated here retreated by an average of 181 m at an average rate of 3.4 m a^{-1}. Among the 196 glaciers investigated here, 113 glaciers were <1 km long. The average glacier terminus retreated by 183 m with a terminus retreat of 32 % of the total glacier length. 58 glaciers were between 1.0 and 2.0 km long. The terminus retreated by an average of 169 m with the terminus retreat averaging 12 % of the total glacier length. 23 glaciers were >2 km long; for these, the average terminus retreat was 205 m with an average terminus retreat of 7 %. During 1957–2010, the terminus of the glaciers on the southern slope retreated at an average of 201 m, with an average retreat rate of 3.8 m a^{-1}, while the

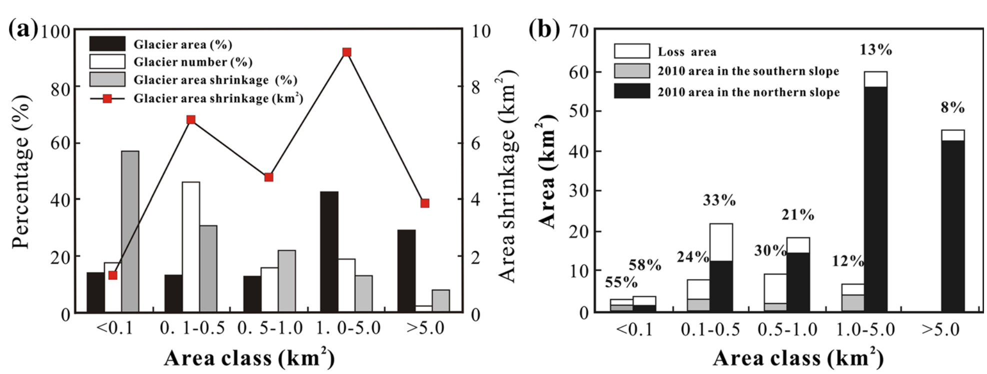

Fig. 2 Relative changes of glaciers in different area classes from 1957 to 2010 in the Daxue Range

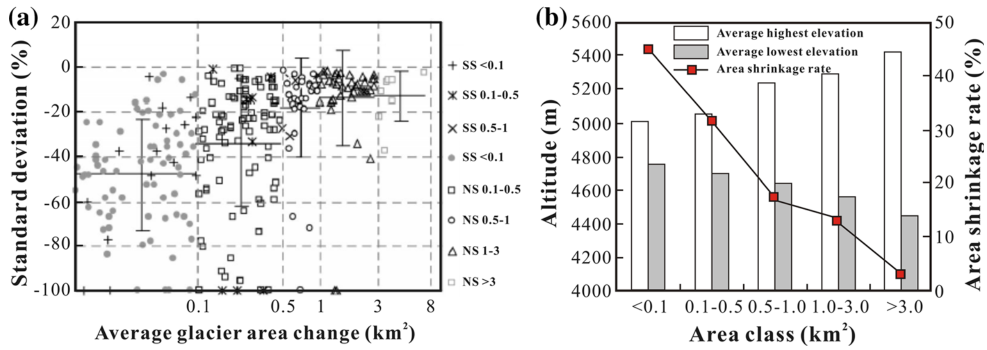

Fig. 3 Relative changes of glaciers in different size classes from 1966 to 2010 in the Danghenan Range. *SS* and *NS* in Fig. 3a represents the south and north slopes, respectively

terminus of glaciers on the northern slope retreated at an average of 177 m for the glaciers with an average rate of 3.3 m a^{-1}.

Glacier change in the Danghenan Range

A total of 281 glaciers were investigated in the Danghenan Range; these covered 170.29 km^2 and had an average area of 0.606 km^2 per glacier based on available remote sensing images. The spatial extent of these glaciers decreased by 7.80 % between 1966 and 1994, with a reduction in spatial extent of 7.80 % (0.28 % a^{-1}). During 1994–2000 and 2000–2010, the glacier area decreased by 5.47 and 6.28 % with an annual decrease rate of 0.91 and 0.63 %, for the two respective time periods. During the past 44 years, the glacier area decreased by 18.32 % with an annual rate of decrease of 0.42 % (Table 1).

The glaciers were classified into five classes based upon coverage: <0.10, 0.1–0.5, 0.5–1.0, 1.0–3.0, and >3.0 km^2; the glacier area decreased by 44.93, 31.66, 17.39, 13.29, and 3.05 % for the five classes, respectively (Fig. 3a), with standard deviations of the area reduction ratios of 25.10, 28.47, 21.72, 21.10, and 10.9, respectively. Both the glacier area change rate and its standard deviation reflect the same conclusion: an inverse relationship exists between the rate of glacier in glacier area and the original glacier area itself. Numerous small glaciers had large rates of change, causing the small glaciers to melt quickly. A total of 15 glaciers in the Danghenan Range disappeared and seven of these glaciers were <0.10 km^2 and the other eight glaciers were between 0.10–1.00 km^2. Among these, five and ten glaciers were on the southern and northern slopes, respectively. A larger number of melted glaciers were located on the northern slope simply because more small glaciers (<0.10 km^2) previously existed on the northern slope (76) than on the southern slope (17).

During 1966–2010, the average area for an individual glacier in the Danghenan Range was declined by 0.111 km^2. The terminus of 282 glaciers analyzed here retreated an average of 159 m at an average rate of 3.6 m a^{-1}. The glacier terminus of those located on the southern and northern slopes retreated by an average of 142 and 161 m with average rates of 3.2 and 3.7 m a^{-1} on the respective slopes.

For each of the five-size classes, the average highest elevation for glaciers in the Danghenan Range increased along with increasing glacier area (Fig. 3b). Conversely, the average lowest glacier elevation per size class decreased with increased glacier area. The area shrinkage rate decreased with increasing glacier area. For larger glaciers, the elevation of the terminus was generally lower and the adaptability of the glaciers to rising temperatures was higher than for smaller glaciers. The rate of loss of spatial extent was relatively small for larger glaciers. Smaller glaciers generally had a higher terminus elevation and larger loss in spatial extent than larger glaciers. With an increase in temperature, the terminus of some small and medium sized glaciers had a tendency to retreat to a higher elevation, to remain stable, or to eventually disappear. The internal factors that influence glacier stability and mass loss include the glacier orientation, the slope, the glacier types, and the supply type.

Discussion

The effects of climate change on changes in glaciers

Observations indicate that Qilian Mountains and the middle and western regions of the northern Qilian Mountains are along with climate transmitting from dry and warm to wet and warm (Shi et al. 2002, 2003; Li et al. 2003). Temperatures have generally risen since the 1950s. After the 1990s, the increase in temperature greatly accelerated and precipitation rates also increased (Jia et al. 2008). The observed changes in glaciers documented in this study are most likely the result of climate change. Temperature and precipitation determines glacier change with the summer temperatures and precipitation as the two most important factors. Summer temperatures directly determine the rate of glacier ablation and annual precipitation rates affect glacier accumulation (Cui et al. 2007; Liu et al. 2007).

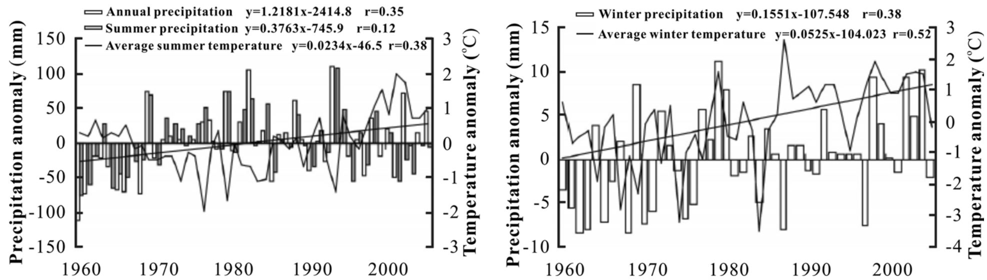

Fig. 4 Variation of mean temperature and precipitation at the Subei Meteorological Station between 1960 and 2005

The Subei Meteorological Station (39°30′N, 94°53′E, 2200 m a.s.l.; Fig. 1) was selected to study climate change within the study area. Using the daily air temperature and precipitation data of this station, linear regression allowed an analysis of the trends in temperature and precipitation (Fig. 4). During 1960–2005, the average temperature in summer (June–August) increased at a rate of 0.23 °C (10 a)$^{-1}$ and the average temperature in winter (December to February in the next year) increased at a rate of 0.53 °C (10 a)$^{-1}$. During the same period, the annual precipitation increased by 12.18 mm (10 a)$^{-1}$ and the summer precipitation increased by 3.8 mm (10 a)$^{-1}$. Snowfall in winter increased by 1.55 mm (10 a)$^{-1}$. A large amount of precipitation provides good conditions for an increase in glacier mass. However, previous studies have shown that increasing precipitation cannot compensate for mass loss to increase in temperature. Glaciers in the study area accumulate mass in summer. Although both annual and summer precipitation in the study area increased significantly over time, significant glacier melting still occurred concurrently, resulting in a net mass loss. Most likely, the main reason for the mass loss is that summer temperatures increase enhanced glacier melting while reducing the spatial extent of the zone of accumulation. Simultaneously, the increase in summer temperatures most likely caused an increase of high-elevation precipitation as rain, causing an increase in glacier melting along with a decrease of glacier accumulation. Moreover, the accumulation in winter was insufficient to make up for the glacier mass losses, causing accelerated glacier mass loss. Therefore, the glacier retreat observed in the study area was most likely primarily caused by global warming.

In general, the inter-annual variation of average temperature and precipitation in the study area is on the rise, accelerating the melting of glaciers. Among them, the annual average temperature anomaly was −0.45 °C in 1995, which is the year with the lowest temperature since 1994. During 1997–1999, an abrupt warming point occurred in 1998 with abnormal high temperatures. The annual average temperature anomaly was 1.38 °C and it was the highest temperature since 1990. The annual average temperature anomaly was 0.59 °C in 2005, which was the second lowest temperature since 1995. Changes in temperature were consistent with the observation that the glacier changes in the study area were larger in 1994–2000 and smaller in 2000–2010.

The effects of glacier spatial morphology on glacier change

Glaciers typically have complex spatial morphology. When climate change occurs, variations in glacier spatial morphology will affect the intensity of glacier melting. Meanwhile, because of the complex spatial structure, conventional statistical methods often cannot accurately simulate some of the multi-scale and multi-process glacier characteristics. Fractal theory is a nonlinear scientific theory describing a very complicated scale invariance system. Mandelbrot (1977, 1982) stated that a part is similar to the whole in some form. Self-similarity and scale invariance are an important feature of fractal objects. Because of the advantages of using fractal theory in dealing with complex systems, the theory has been widely applied in the field of geography (Dong et al. 2009) and provides new theoretical support for innovation in glacier change research. Different glaciers have different spatial graphic features and there are differences for the spatial shape for the same glacier during different stages of its evolution. Glacier type, size, shape, boundary characteristics, and spatial position relationships determine the spatial patterns of glaciers, which contain more abundant space–time evolution information related to glacier change. Based on this, fractal methods can be used to develop a more comprehensive understanding of the characteristics of the glacier change by determining the fractal dimension, stability index and the relationship between these two.

Based on glacier data collected in 1957/1966 and 2010 as described above, the relationship between area and circumference for glaciers in five different glacier classes was established using fractal theory; the fractal dimension and stability index were determined by linear fitting using Formula (6):

$$\mathrm{In}A = (2/D)\mathrm{In}P + C \quad (6)$$

where A is glacier area, P is glacier circumference, D is fractal dimension, and C is constant. D reflects the complexity and stability of the glacier being studies. A higher D value indicates a more complicated spatial structure. When $D = 1.5$, it represents random motion similar to Brownian motion, and the spatial structure of the glacier is the most unstable. The closer the D is to 1.5, the less stable the glacier structure is. According to this, Formula (7) defines a stability index indicating the response of glacier changes to climate change:

$$SK = |1.5 - D| \tag{7}$$

where a larger SK value represents a more stable of spatial structure of a glacier.

Figure 5 shows the scatter plot for glaciers of <0.10 km^2 in 1957/1966 and 2010 by taking the logarithm. Table 2 lists the fractal dimension and stability index for glaciers in the different ranks. Analysis results of the different classes of glacier area data of the four periods indicate that the stability index of glaciers <0.10 km^2 in size decreased during the 53 years of the study and the spatial structure became more unstable over time, indicating that glaciers <0.10 km^2 were more sensitive to climate change than larger glaciers and will eventually completely disappear with the current increasing trend in temperatures. The change of fractal index and stability index for glaciers >5.00 km^2 was minimal in the 53 -year study period for the five partitions, and the changes of spatial morphology were limited. D values for glaciers 0.10–0.50 km^2 in size were 1.556, 1.454, 1.539, and 1.638, respectively, for the four periods. The random motion value was close to 1.50, indicating that glaciers in the 0.10–0.50 km^2 size class were considered the most unstable structures and also experienced the greatest change during the study period. Meanwhile, the glacier stability index increased to 0.082 for glaciers in the 0.10–0.50 km^2 size class, forming a trend towards a steady state. The changes in the stability index and fractal dimension were largest for glaciers 0.50–1.00 km^2 in size, indicating that their spatial structure was the most complicated and the stability index will decline further. The change of stability index was smaller for glaciers in the 1.00–5.00 km^2 size class, reflecting the larger sensitivity of large glaciers to climate change when compared to small glaciers.

Comparison analysis

All the glaciers in the Qilian Mountains show that a general trend of area reduction, ice volume loss, and total number decrease is similar to that in other areas (Table 3). However, when compared to the glacier changes in the western, middle, and eastern Qilian Mountains, glacier changes in the study area were smaller when compared to those in the eastern and middle Qilian Mountains. In addition, Liu et al. (2002) found that glaciers in the Daxue Range decreased 4.8 % (0.14 % a^{-1}) between 1956 and 1990, which is similar to the glacier loss of 6.18 % (0.17 % a^{-1}) during 1957–1994 within the study area.

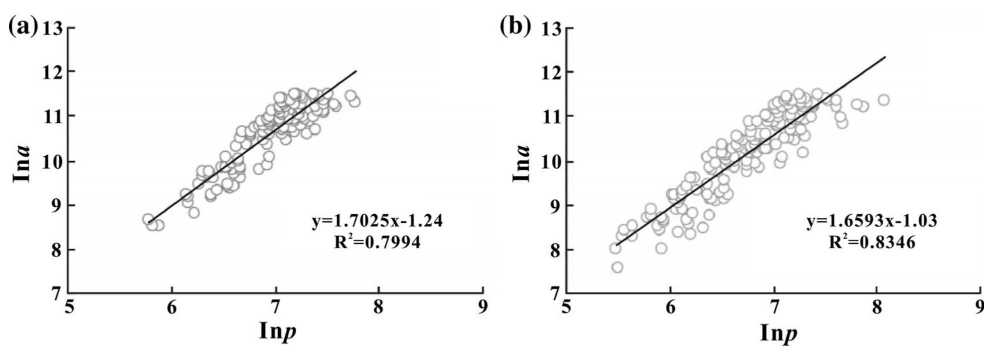

Fig. 5 Scatter plot of <0.10 km^2 size class glaciers and the ln$a$–ln$p$ relationship in the study area for **a** 1957/1966 and **b** 2010

Table 2 Changes of stability indices of glaciers with different sizes in the study area

Area class (km^2)	1957/1966		1994		2000		2010		1957/1966–2010
	Fractal dimension	Stability index	Fractal dimension	Stability index	Fractal dimension	Stability index	Fractal dimension	Stability index	Index change
<0.10	1.175	0.325	1.189	0.311	1.201	0.299	1.205	0.294	0.031
0.10–0.50	1.556	0.056	1.454	0.047	1.539	0.039	1.638	0.138	−0.082
0.50–1.00	2.628	1.128	2.466	0.966	2.350	0.850	2.327	0.827	0.301
1.00–5.00	2.021	0.521	2.010	0.510	2.003	0.503	1.995	0.495	0.026
>5.0	1.329	0.171	1.340	0.160	1.367	0.133	1.352	0.148	0.023

Table 3 Comparison of glacier changes in the Qilian Mountains in recent decades

Study area	Period	Number	Glacier area change			Source
			km^2	%	% a^{-1}	
Eastern Qilian Mountains (Lenglongling)	1972–2007	244	24.29	−23.57	−0.67	Cao et al. (2010)
Middle Qilian Mountains (Yeniugou Drainage Basin)	1956–2003	165	16.22	−25.72	−0.55	Yang et al. (2007)
Middle Qilian Mountains (Heihe Drainage Basin)	1950s/1970s–2003	335	32.41	−29.60	–	Wang et al. (2011b)
Western Qilian Mountains (Shulenanshan)	1970–2006	279	55.00	−12.80	−0.36	Zhang et al. (2011)
Western Qilian Mountains (Daxueshan, Danghenanshan)	1957/1966–2010	477	57.21	−17.20	−0.35	This study
Western Qilian Mountains (Shulehe, Danghe, Beidahe, Halahu)	1956–1990	1731	151.90	−10.30	−0.30	Liu et al. (2002)

The regional differences of glacier changes in the Qilian Mountains are most likely the result of regional differences in climate (Jia et al. 2008). The precipitation fluctuated during the past several periods and the precipitation rate was similar in eastern, middle, and western parts. Both annual temperature and summer temperature indicated that the rate of increase in the western region [0.27 °C $(10a)^{-1}$; 0.24 °C $(10a)^{-1}$] is less than the middle region [0.33 °C $(10a)^{-1}$; 0.27 °C $(10a)^{-1}$] and eastern part [0.30 °C $(10a)^{-1}$; 0.27 °C $(10a)^{-1}$], for those respective temperatures. The summer temperature increased in the west less than in the middle [0.27 °C $(10a)^{-1}$] and eastern [0.27 °C $(10a)^{-1}$] regions; this was one of the reasons causing glacier melting within the study area to be smaller than the middle and eastern regions. Moreover, the increased rate of temperature change in the western region generally decreased from south to north, which appears to be one of the main reasons that the terminus retreats of glaciers in the Danghenan Range were larger those of the Daxue Range.

Glaciers in the western region were generally larger in size, which may be another reason that glacier melting in the western region was less than that of the middle and eastern regions. The average glacier area in the study area was 0.60 km^2 in 2010, while it was 0.25 km^2 in 2003 in the Heihe River Basin of middle Qilian Mountains, and was 0.36 km^2 in 2007 in the Lenglongling of the eastern Qilian Mountains. In addition, the elevation of the glaciers in the study area was higher than glaciers in the middle and eastern regions. The average elevation of the terminus of glaciers in the Danghenan Range was 4681 m in 1966, and 4568 m in 1957 in the Daxue Range.

Conclusions

The glacier area in the study area was 332.48 km^2 in 1957/1966 and decreased by 23.32 km^2 in 1994, shrinking at a rate of 0.22 % a^{-1}. During the periods of 1994–2000 and 2000–2010, the glacier area decreased by 16.49 km^2 and 17.40 km^2, shrinking at rates of 0.89 % a^{-1} and 0.59 % a^{-1}, in the respective time periods. During the entire study period 1957/1966–2010, a total of 18 glaciers in the study area disappeared completely, including an overall glacier area reduction of 17.21 % and ice volume loss of 24.1 %. The Daxue Range had a relatively larger average glacier area. From 1957 to 2010, glacier area declined by 26.0 km^2 with an annual area reduction of 0.30 % and ice volume loss of 22.4 %. For the Danghenan Range, the average glacier area was relatively smaller. From 1966 to 2010, the glacier area decreased by 31.20 km^2 with an annual average area reduction rate of 0.42 % and volume loss of 25.7 %. The extent of the glacier retreat was very different on the north and south slopes. In the Daxue Range, the glacier area decreased by 22.82 and 15.51 % on the southern and northern slopes, respectively. The glacier area decreased by 22.39 and 16.76 % on the southern and northern slopes of the Danghenan Range, respectively. These two mountain ranges experienced differences in the retreat of their respective glacier termini, an average of 181 m with a retreat rate of 15 % (3.4 m a^{-1}) for the Daxue Range and an average of 159 m with a retreat rate of 16 % (3.6 m a^{-1}) for the Dangehenan Range. Comprehensive analysis shows that glaciers in the study area generally had a shrinking trend, especially in the 1990s, when the shrinkage was significant, while after 2000 the rate declined. Regional differences were also observed in the changes of the glaciers. The area reduction and terminus retreat for the glaciers in the Danghenan Range were stronger than those in the Daxue Range.

Glacier size including area and length were the main internal factors related to glacier shrinkage. The rate of glacier retreat was inversely correlated with glacier size. The analysis of glacier stability further confirmed that smaller glaciers experienced more significant change than larger ones. An increase in temperature, especially in summer, appeared to be the most important external driving factor driving glacier retreat.

The trend for glacier change in the study area was consistent with other regions in the Qilian Mountains. Glacier area and number has generally decreased and volume has been lost across all regions. The glacier retreat in the study area was smaller than that of the eastern and middle Qilian Mountains. Preliminary analysis showed that this occurred because of an increase in temperature in the study area and the changes were less intense than in the middle and eastern Qilian Mountains. Moreover, the average glacier area was relatively larger and the average terminus elevation was relatively higher in the study area than in other regions of the mountain, which are also important factors for determining glacier mass loss.

Glaciers are retreating across the globe and the melting has accelerated dramatically in the past few decades. The results of this study that glaciers in the Daxue Range and Danghenan Range of the western Qilian Mountains continue to retreat correspond well with other studies performed in different regions of the globe. Furthermore, it is very important for assessing potential regional hydrological responses and water supply in various rivers. Globally, the melting of glaciers contributes to sea level rise, while locally glacier retreat can change river and ecosystem dynamics, which should be paid much more attention in future.

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