Journal of Earth Science, *Vol. 22*, *No. 4*, *p. 539–548*, *August 2011* *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-011-0195-4

Rapid Shrinking of Glaciers in the Middle Qilian Mountain Region of Northwest China during the Last ~50 Years

Puyu Wang* (王璞玉)
State Key Laboratory of Cryospheric Sciences/Tien Shan Glaciological Station, *Cold and Arid Regions Environmental and Engineering Research Institute*, *Chinese Academy of Sciences*, *Lanzhou* 730000, *China*
Zhongqin Li (李忠勤)
State Key Laboratory of Cryospheric Sciences/Tien Shan Glaciological Station, *Cold and Arid Regions Environmental and Engineering Research Institute*, *Chinese Academy of Sciences*, *Lanzhou* 730000, *China*;
College of Geography and Environment Sciences, *Northwest Normal University*, *Lanzhou* 730070, *China*
Wenyu Gao (高闻宇)
College of Geography and Environment Science, *Northwest Normal University*, *Lanzhou* 730070, *China*

ABSTRACT: During the past five decades, fluctuations of glaciers were reconstructed from historical documents, aerial photographs, and remote sensing data. From 1956 to 2003, 910 glaciers investigated had reduced in area by 21.7% of the 1956 value, with a mean reduction for the individual glacier of 0.10 km^2. The relative area reductions of small glaciers were usually higher than those of large ones, which exhibited larger absolute loss, indicating that the small glaciers were more sensitive to climate change than large ones. Over the past ~50 years, glacier area decreased by 29.6% in the Heihe (黑河) River basin and 18.7% in the Beidahe (北大河) River basin, which were the two regions investigated in the Middle Qilian (祁连) Mountain region. Compared with other areas of the Qilian Mountain region, the most dramatic glacier shrinkage had occurred in the Middle Qilian Mountain region, mainly resulting from rapid rising temperatures. Regional differences in glacier area changes are related to local climate conditions, the relative proportion of glaciers in different size classes, and other factors.

KEY WORDS: glacier change, regional difference, remote sensing, Middle Qilian Mountain region.

INTRODUCTION

Mountain glaciers are sensitive climate indicators and thus subject to monitoring of environmental and climate changes (Oerlemans, 2005, 1994). As a temperate country at low latitudes, China has the most abundant mountain glacier resources, with 46 298 glaciers having a total estimated volume of 5 590 km^3 (Shi, 2000). 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 and semiarid regions, especially in Northwest China (Yao et al., 2004). Recent evidence

This study was supported by the National Basic Research Program of China (Nos. 2010CB951003 and 2007CB411501) and the National Natural Science Foundation of China (Nos. 91025012 and J0930003/J0109).
*Corresponding author: wangpuyu862@163.com

Manuscript received September 28, 2010.
Manuscript accepted December 30, 2010.

suggests an acceleration of glacier mass loss in several key regions in China with the climatic warming, such as Tibetan plateau, Tianshan, and Kunlun Shan (Li Z X et al., 2010; Shangguan et al., 2007; Li B L et al., 2006; Ye et al., 2006; Jin et al., 2005; Yang et al., 2003; Fujita et al., 2000), which has attracted wide attention.

Research on large-scale and long-time glacier fluctuations in the Qilian Mountain region is limited despite the fact that the glaciers in this region provide important water resources for local economic development. There has been some research work in the Qilian Mountains. From the late 1950s to the late 1980s, scientists from the Chinese Academy of Sciences (CAS) conducted some glacier expeditions in this region (Liu et al., 1992; Xie et al., 1985; Academia Sinica, 1959). Liu et al. (2003) analyzed fluctuations of glaciers in the western Qilian Mountains from the Little Ice Age to 1990. However, glaciers in the Qilian Mountain region have experienced mass loss prominently owing to an increase in temperature of 0.5±0.2 ℃ over the past 50 years in Northwest China (Li et al., 2003). Therefore, it is necessary and urgent to do further research on recent glacier changes in the other parts of the Qilian Mountain region.

Taking this into account, this article concentrates on the glacier changes in the Middle Qilian Mountain region. Glaciers, acting as a huge alpine reservoir that regulates annual runoffs, are a reliable water source for oases and for the sustainable development of the ecological environment, industry, and agriculture in this region (Shen et al., 2001; Shi, 2001; Yang, 1991). According to the image interpretation method provided by World Glacier Monitoring Service (WGMS), historical data (topographic maps and aerial photographs) are available for comparison with advanced spaceborne thermal emission and reflection radiometer (ASTER) images in order to estimate changes of glaciers in the Middle Qilian Mountain region.

STUDY AREA

The Qilian Mountains (36.5ºN–39.5ºN, 93.5ºE–103ºE) are located on the northeastern edge of the Tibetan plateau. Their northern part is the Hexi corridor of Gansu Province, and the southern part includes the Qaidam basin and the Qinghai Lake of Qinghai Province. The region of interest lies in the middle part of the Qilian Mountains, in the head water of rivers such as the Heihe and Beidahe (Fig. 1). The Heihe is the second largest inland river in the arid area of Northwest China, with the main stream extending 821 km in length. The drainage area, south of the Yingluo gorge, has catchments accounting for about 10 009 km^2 with an elevation ranging from 1 700 to 4 823 m a.s.l., characterized by high precipitation, low evaporation, and low temperature (Chen et al., 2005; Lan et al., 2005; Gao and Li, 1991).

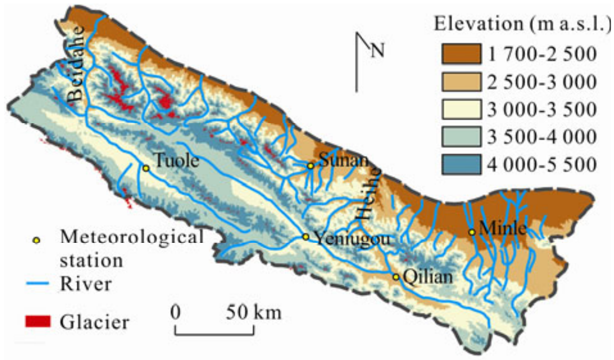

Figure 1. Sketch map showing the study area and distribution of glaciers.

According to the Glacier Inventory of China I (Qilian Mountains) (Wang et al., 1981), 1 078 glaciers were listed with a total estimated area and volume of 420.55 and 13.67 km^3, respectively, including 428 glaciers of the Heihe and 650 glaciers of the Beidahe. These data were compiled in 1979 on the basis of aerial photographs acquired largely in 1956, but partly in 1957 and 1966, and topographic maps based on the aerial photographs.

DATA AND METHODS

Data Processing and Uncertainty Assessment

To compare recent changes in glacier area over the past ~50 years, 10 ASTER images taken from June to September 2003 and 2004 (9 in 2003 and 1 in 2004) with the resolution of 15 m and 50 topographic maps (1 : 50 000) derived from aerial photographs acquired during 1956 to 1978 (40 in 1956, 3 in 1957, 5 in 1966, and 2 in 1978) by the Chinese Military Geodetic Service were analyzed. Therefore, the study period can be considered to be approximately from 1956 to 2003. All images were obtained for the (nearly) cloud-free conditions and for the ablation period when the extent of snow cover was minimal to reduce potential uncertainty in glacier boundary delineation due to snow cover, which were the best choices since 2000. A digital elevation model (DEM) with resolution of 30 m, provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China, was used for the orthorectification of ASTER images using methodologies described by Toutin (2002) and Kääb (2004) and PCI Geomatica 9.1 Orthoengine software. Geocorrection and co-registration were established using ERDAS Imagine 9.0 software. The clearly distinguishable terrain features were selected from topographic maps that could be identified on each image. On average, 30 to 50 GCPs have been collected with the root mean square error (RMSE) value <1.0 pixel (15 m) in both x and y directions. All images and maps were presented in a Universal Transverse Mercator (UTM) coordinate system referenced to the World Geodetic System of 1984 (WGS84).

Glacier Outline Extraction

The glacier outlines are mapped manually with the DEM by commercial GIS software (ARCVIEW), using the topographic maps and ASTER images (Fig. 2), which is a useful tool for extracting detailed in formation from satellite imagery for glaciers (Raup et al., 2007a), particularly when mapping is conducted by the same person using a combination of different types of imagery (e.g., aerial photographs and ASTER) (Paul et al., 2002). Area and other parameters of the glaciers in different periods can be computed from the extracted glacier polygons, resulting in a total sample of 910 glaciers. For some images and sections containing clouds or fresh snow cover, the outlines of some glaciers were not validated accurately, which were omitted. Supra-glacial debris cover is a factor reducing the accuracy of mapping as it contributes to the overall accuracy of the glacier outline. However, glaciers are debris-free in this particular case.

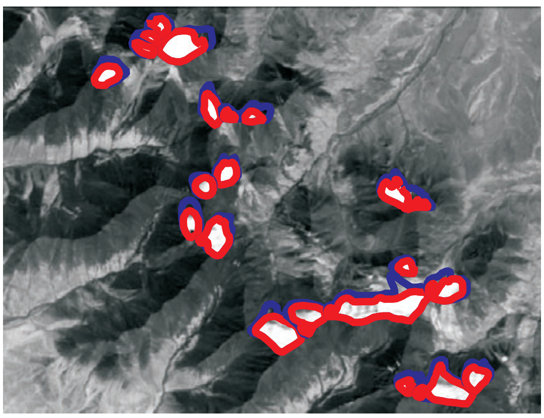

Figure 2. Example of the glacier outlines extraction from ASTER images and topographic maps. Red glacier outlines are of 2003 and blue outlines of 1956.

RESULTS

Characteristics of Glacier Distribution

The characteristics of glacier distribution in the study region are investigated by analyzing statistically the relations between topographic parameters (Fig. 3) and the glaciers using the extracted glacier polygon data in 2003. The relationship between area and number of glaciers and aspect shows clearly regional characteristics of glacier distribution. Thus, 721 glaciers with areas of 245.79 km^2 that account for 79.0% of the total area are located in the three sectors, northwest, north, and northeast, similar to other regions of the Northern Hemisphere (Evans, 2006). The number of glaciers smaller than 1.0 km^2 in the three aspects occupies 93.1% of the total value in 2003.

Figure 4 presents the distribution of glacier coverage in the Middle Qilian Mountain region, Heihe

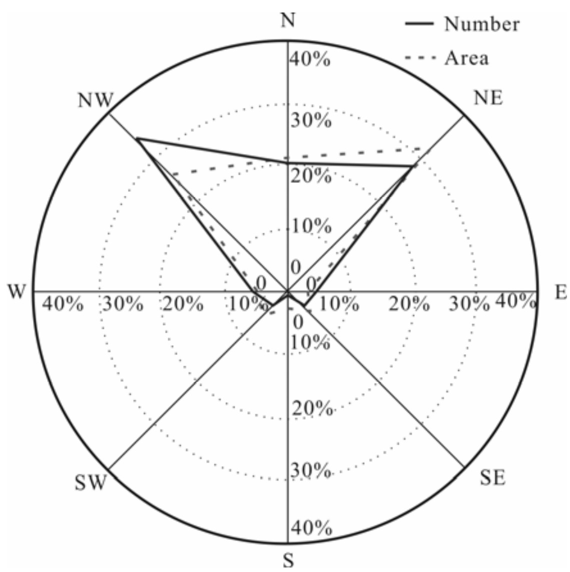

Figure 3. Distribution of glacial number and area with different aspects in 2003/2004.

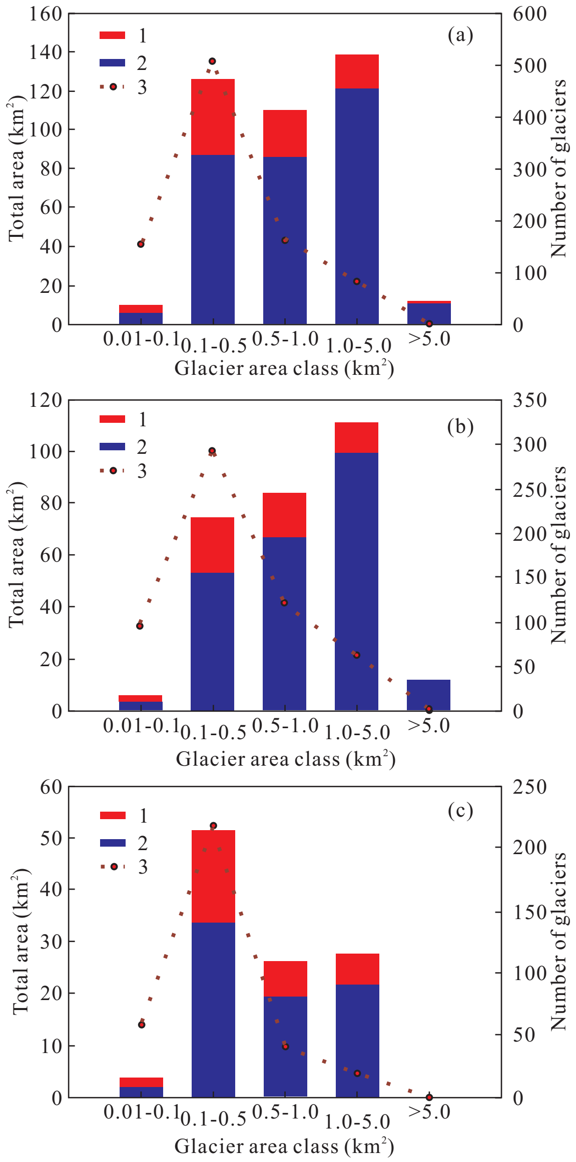

Figure 4. Glacier area, number, and area loss by glacier size class for 1956 to 2003 in the Middle Qilian Mountain region (a), including the Beidahe River basin (b) and the Heihe River basin (c). 1. Glacier area loss; 2. glacier area in 2003; 3. number of glaciers.

River basin, and Beidahe River basin from approximately 1956 to 2003 according to the glacier size class (0.01–0.1, 0.1–0.5, 0.5–1.0, 1.0–5.0, and >5.0 km^2). In the Middle Qilian Mountain region, about 90.4% of all glaciers in 2003 are smaller than 1.0 km^2 with a contribution of about 57.6% to the total area, while only two glaciers in this sample are larger than 5.0 km^2 with a total area of 10.92 km^2. Moreover, about 9.3% of the glaciers with the area of 1.0–5.0 km^2 account for 39.0% of the total area. Glaciers with the area of 0.01–0.1, 0.1–0.5, and 0.5–1.0 km^2 account for 15.6%, 56.9%, and 18.0% of the total numbers, respectively, and the summation of their areas contributes more than half of the total areas. Therefore, small glaciers (<1.0 km^2) form a remarkable part of the number and area cover in this region. In the Heihe River basin, about 97.2% of all glaciers are smaller than 1.0 km^2 with a contribution of about 82.5% to the total area, while only 2.8% in this sample are larger than 1.0 km^2 and contribute 17.5% to the total area. No glaciers are larger than 5.0 km^2. In the Beidahe River basin, small glaciers with area <1.0 km^2 occupy 57.2% of the total area and glaciers in 1.0–5.0 km^2 size class have largest proportion of the total area (42.5%).

Changes in Glacier Area from 1956 to 2003

The glacier areas determined from the ASTER images allowed for an analysis of the change in area between 1956 and 2003 (Table 1). The results show that the total area of the 910 studied glaciers had decreased by 21.7% of the 1956 value from 397.41 to 311.02 km^2 with the area reduction of 0.10 km^2 for an individual glacier. Three glaciers, which enlarged their areas, with the largest increasing rate <5%, were smaller than 1.0 km^2 and located on the lee side of the ridges. Accumulation on such glaciers depends primarily on snow drift and their behavior is determined by local conditions rather than climatic variations. All the glaciers in Colorado are of the same type (Raup et al., 2007b). The overriding importance of local conditions for the behavior of small glaciers has also been noted by Surazakov et al. (2007) for the Altai. The rates of glacier shrinkage were 29.6% and 18.7% for the Heihe River basin and the Beidahe River basin, respectively. Thirty-one glaciers at lower elevations with area <1.0 km^2, which were present on the topographic maps, had disappeared completely by 2003, 16 of which were smaller than 0.1 km^2, 12 in 0.1–0.5 km^2 and the others in 0.5–1.0 km^2. Thirteen of the 31 disappeared glaciers were located in the Heihe River basin and the others in the Beidahe River basin. The average terminus retreat was 189 m with the reduction rate of 20.6%. The glacier shrinkage shows obvious regional differences, which was strongly affected by the obvious differences in climatic conditions, due to the long distance from east to west of the Middle Qilian Mountain region. The annual temperature for the Middle Qilian Mountain region, including Beidahe River basin and Heihe River basin, showed increases with the range of 0.54–0.92 ℃ from 1950s to the present. The precipitation of the west was mainly affected by vapor transport of the Atlantic Ocean brought by the West Circulation, showing increased tendency, while the east was affected by the vapor transport of the Indian Ocean and Pacific Ocean brought by the Southeast and Southwest monsoons, showing decreased tendency in the recent decades (Lan et al., 2004). The precipitation determines glacier accumulation, because the Beidahe River basin was larger than the Heihe River basin, directly affecting the regional differences of the glacier shrinkage for the Middle Qilian Mountain region. Moreover, the proportion of glaciers smaller than 1.0 km^2 in the Heihe River basin was higher (94.3%) than the Beidahe River basin (88.7%).

The rate of shrinkage varied between glaciers of different size. The pattern of relative changes in glacier area between 1956 and 2003 is illustrated by Fig. 5. In 1956, 90.8% of glaciers were smaller than 1.0 km^2 and occupied 62.0% of the glacierized area. These glaciers accounted for 78.4% of the total loss. This is a larger contribution than that observed in the Swiss Alps, where small glaciers accounted for 44% of the total loss between 1973 and 1999 occupying 18% of the glaciated area (Paul et al., 2004). Glaciers in the size class of 0.01–0.1 km^2 had lost 44.5% of their total areas with the average area reduction of

Table 1 Glacier area changes between 1956 and 2003 in the Middle Qilian Mountain region

Basin	1956		2003		Glacier changes		
	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Percentage (%)
Heihe River basin	335	109.35	322	76.94	-13	-32.41	-29.6
Beidahe River basin	575	288.06	557	234.08	-18	-53.98	-18.7
Total	910	397.41	879	311.02	-31	-86.39	-21.7

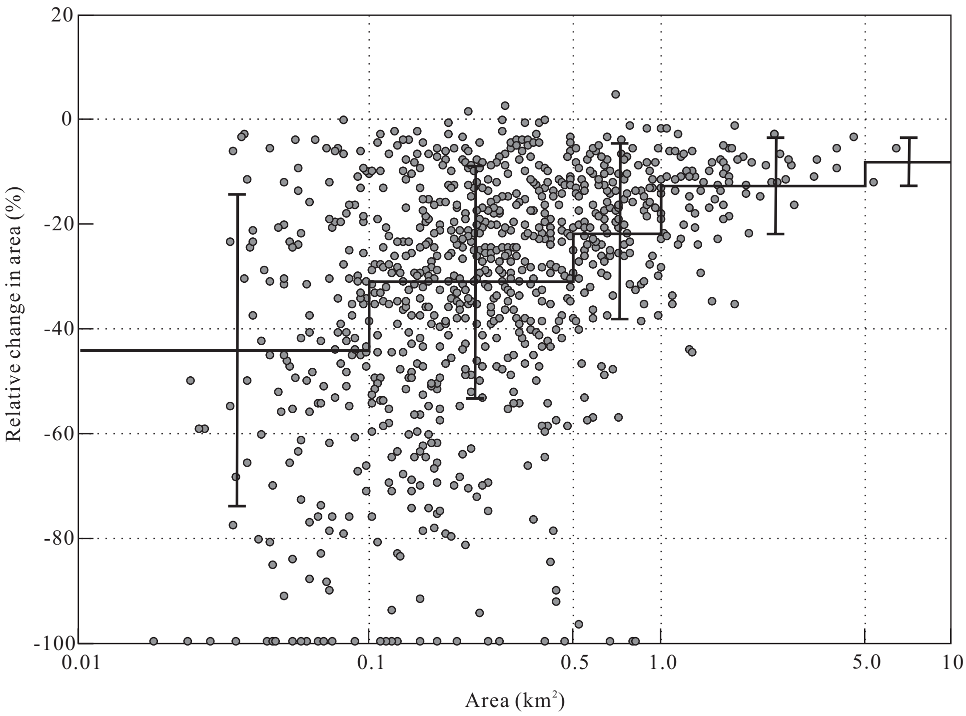

Figure 5. Relative changes in glacier area of different sizes in the Middle Qilian Mountain region from 1956 to 2003. Mean values of glacier area change (horizontal line) together with standard deviation (vertical bars) are given for four area classes (0.01–0.1, 0.1–0.5, 0.5–1.0, 1.0–5.0, and >5.0 km^2).

0.03 km^2. Glaciers larger than 1.0 km^2 had only lost 12.3% of their areas. However, the average area reduction reached to 0.22 km^2. In addition, the area reduction rates were 31.2% (0.08 km^2) for 0.1–0.5 km^2, 21.7% (0.15 km^2) for 0.5–1.0 km^2, 12.7% (0.22 km^2) for 1.0–5.0 km^2, and 8.3% (0.49 km^2) for >5.0 km^2, respectively. As for the area changes of glaciers in different size, the relative changes of small glaciers were usually higher than those of large ones, which exhibit larger absolute loss. This indicated that the small glaciers were more sensitive to climate change than large glaciers (Nesje and Dahl, 2000; Knight, 1998; Jóhannesson et al., 1989). The standard deviations of glacier area changes for glaciers in 0.01–0.1, 0.1–0.5, 0.5–1.0, 1.0–5.0, and >5.0 km^2 were 29.80, 22.35, 16.90, 9.22, and 4.66, respectively. The scatter of individual changes was strongly increasing towards smaller glaciers, which further demonstrated the particularly sensitive of small glaciers to climate change.

DISCUSSION

Recent Glacier Shrinkage Related to Local Climate Change

The evolution of temperature and precipitation during the periods of the year that better represented the glacial mass balance was analyzed to show the relation between climatic trends and glacier shrinkage. Changes of the glaciers in the study area were predominantly influenced by summer temperature (June–August) and annual precipitation. Therefore, daily air temperature and precipitation data from five high altitude meteorological stations in the Middle Qilian Mountain region (Table 2, Fig. 1) with a long period of observations were used. All the data we used were from 1960 to 2005.

An average of the summer temperature anomalies from the 46 years means (1960–2005) as well as annual precipitation was analyzed over the same time period from the five closest stations in the study area. Figure 6 shows the trends in summer temperature and annual precipitation over the period 1960 to 2005. The linear trend analysis of mean temperatures indicated that the average rate of summer temperature increase was 0.27 ℃/10a. During the corresponding period, the records at the five stations displayed a gradual increase in annual precipitation, with the average rate of 12.56 mm/10a. Increasing summer temperature leads to (1) an increased amount energy available for ice and snow melt, (2) decreased snow accumulation (and increased proportion of liquid precipitation), and (3) lower albedo of the glacier surface (Hagg and Braun, 2005; Dikich and Hagg, 2004; Fujita and Ageta, 2000; Ageta and Kadota, 1992). The increase of precipitation has provided good conditions for the glacier accumulation. However, the increase of summer temperature caused the increase of liquid precipitation instead of solid precipitation in the high-altitude glacierized area for the glaciers with summer accumulation, leading to the reduction of accumulation and the acceleration of ablation. Moreover, the linear trend analysis indicated that the average increase rate of winter precipitation (0.28 mm/10a) was less, which cannot make up the mass loss of glaciers, resulting in the accelerated melting. It is consistent with the research results of the Qiyi glacier of this region (Sakai et al., 2006). Although the annual precipitation increased slightly from 1960 to 2005, generally increasing summer temperature leads to significant glacier melt, which seems to be the most significant factor for recent glacier shrinkage in the Middle Qilian Mountain region.

Table 2 Meteorological stations used in this study (locations are shown in Fig. 1)

Meteorological station	Lat. (N)	Lon. (E)	Altitude (m)	Observation period
Minle	38.45º	100.82º	2 272	1958–2005
Sunan	38.83º	99.62º	2 311	1957–2005
Qilian	38.18º	100.25º	2 789	1957–2005
Tuole	38.80º	98.42º	3 368	1957–2005
Yeniugou	38.62º	99.35º	3 180	1960–2005

Lat.. latitude; Lon.. longitude.

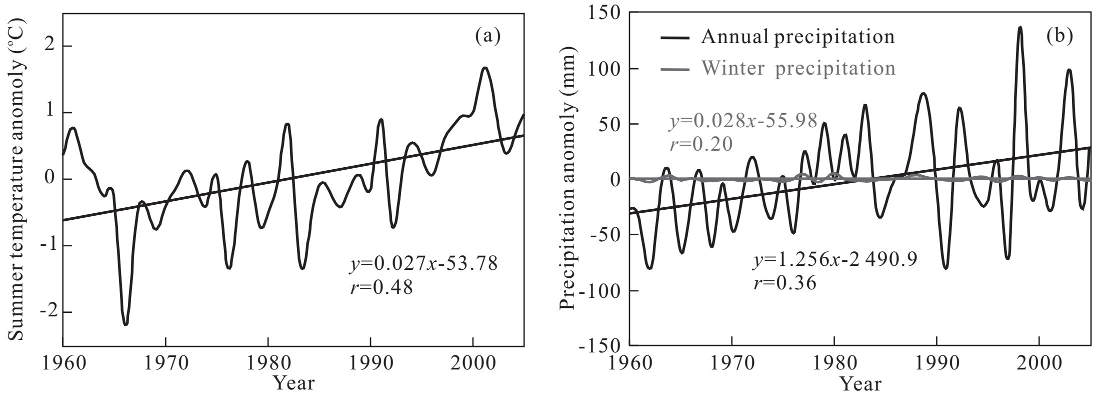

Figure 6. (a) Summer temperature (June–August) and (b) annual and winter precipitation (November–March) for 1960 to 2005 in the five meteorological stations in the study area.

Regional Differences in Glacier Area Changes in the Qilian Mountain Region

While using remote sensing data and geographical information systems is informative for understanding glacier changes over large regions, comparison was made with other glaciers in the Qilian Mountains of Northwest China. Two points emerged from the comparison studies: (1) glaciers in the Qilian Mountain region are shrinking and (2) the rates of shrinkage vary in different regions as illustrated by Table 3. The largest shrinkage rate was in the Middle Qilian Mountain region, where glacierized area had declined by 21.7% during the past ~50 years, according to this study. The second was Lenglongling, eastern Qilian Mountain region, with the shrinkage rate of 28.97% from 1960s/1970s to 2002 (Zhao, 2009). The smallest decrease in glacier area was in the western Qilian Mountain region (12%) (Liu et al., 2003). Study of glacier changes in the western Qilian Mountain region was limited from 1956 to 1990 and the reduction rate would probably change with the rapid temperature increasing, which can cause the comparison of results to be misleading; however, due to the lack of data, there may be no better way than to compare the area reduction rate for time periods that are as close as possible.

Furthermore, the shrinkage rate of glaciers in the Qilian Mountain region appears to be faster than the other glaciers in the Middle Chinese Tien Shan (13% in 1963–2000), West Kunlun Shan (0.4% in 1970–2001), Tarim Interior River basin (3.3% in 1960s/1970s–1999/2001), and Xinjiang Uyger Autonomous region (11.7% in 1960s/1970s–2002/2006) in western China (Li Z Q et al., 2010; Shangguan et al., 2009, 2007; Li B L et al., 2006). Mass balance observation of the Qiyi Glacier in the Middle Qilian Mountains had further demonstrated this result. The Qiyi Glacier experienced positive mass balance of about 360 mm/a in the 1970s and 4 mm/a in the 1980s. However, the recent observation shows that mass balances of the glacier were -810 mm in 2001/2002 and -316 mm in 2002/2003, respectively, suggesting that the glacier was thinning dramatically (Pu et al., 2005). In the last 2 to 3 years, the glacier has been characterized by strong negative mass balance and its snow line has gone up steadily. Now, the equilibrium line of the glacier has reached the highest altitude since the glacier has been observed. The intensive mass loss of the glacier in the recent years represents the sensitive response to the climatic warming. Against the background of global warming, it is expected that the glacier will experience negative mass balance, thinning, shrinking, and rising snow line.

Glacier variation is driven by climate change, especially temperature and precipitation. It shows a significant temperature increase in the Qilian Mountain region in the late 1980s, especially after 1990s, which basically agrees with the climate change in Northwest China, indicating obvious response to global warming (Jia et al., 2008). According to the study of Jia et al. (2008), the regional differences of climate changes in the Qilian Mountains were analyzed using the monthly temperature and precipitation data of the selected eight stations in the study area. The annual and summer temperature in the eastern, middle, and western Qilian Mountain region both

Table 3 Comparison of glacier changes in the eastern, middle, and western Qilian Mountain region

Qilian Mountain region	Study area	Period	Number of glaciers	Area change km^2	%	Source
Eastern	Lenglongling	1960s/1970s–2002	244	-29.85	-28.97	Zhao, 2009
Middle	Middle Qilian Mountain	1956–2003	335	-86.39	-21.7	This study
Western	Western Qilian Mountain	1956–1990	1 731	-151.9	-12	Liu et al., 2003

showed a significant upward trend with a mean trend of 0.30, 0.33, and 0.27 ℃/10a for the annual temperature and 0.27, 0.27, and 0.23 ℃/10a for the summer temperature. The growth rates of the annual and summer temperature for the middle and eastern Qilian Mountain region are relatively large, especially in the middle. The annual precipitation fluctuated with the mean rate of 10.0, 12.6, and 12.2 mm/10a. In contrast, while the precipitation was almost fluctuating, the comparative rapid increase in temperature was an important factor that resulted in the more intensive ablation of glaciers in the middle than the other areas of the Qilian Mountain region.

Moreover, taking into account of the influence of the glacier size distribution, the average areas of glaciers in the Lenglongling, Middle Qilian Mountain region, and western Qilian Mountain region were 0.41 km^2 (2002), 0.35 km^2 (2003), and 0.62 km^2 (1990), respectively. In contrast, glaciers in the Middle Qilian Mountain region were comparatively small and about 90.4% of all glaciers are smaller than 1.0 km^2. Small glaciers in particular respond quickly and sensitively to the temperature increasing by retreating, which is another important reason for the strong glacier melt in the Middle Qilian Mountain region.

The strong ablation of the glaciers in the Middle Qilian Mountain region was also influenced by the location of the glaciers, elevation, length, orientation, type, configuration, velocity, and other indexes (Evans and Cox, 2010; Hodgkins et al., 2007). Debris cover (produced by englacial material brought to the ice surface or from falling rocks), a factor that can considerably reduce the ablation processes on a glacial surface, is nonexistent in the Middle Qilian Mountain region and does not require consideration in this study. Cia et al. (2005) pointed out that there seems to be a minimum response time (of very few years) between temperature and precipitation changes and the shrinkage of glaciers in the Maladeta massif (Central Pyrenees). As the lag time for a glacier to react to climatic fluctuations depends mainly on its size and its latitudinal location, climate changes, even if subdued, are felt faster and more precisely by smaller glaciers located in warmer settings than by larger glaciers in higher latitudes. As for the small elevation span for the glaciers in this study, the equilibrium line altitude will continue to rise with the climatic warming, and most of the glaciers will be in the ablation area. It is estimated that glaciers in the Middle Qilian Mountain region will experience more intensive shrinkage in the future.

CONCLUSIONS

Glaciers in the Middle Qilian Mountain region decreased significantly in area from 1956 to 2003 and 21.7% of the area had been lost, including 29.6% in the Heihe River basin and 18.7% in the Beidahe River basin, primarily due to increasing summer temperatures. The shrinkage of the glaciers shows differences between glaciers of different sizes. The relative area reductions of small glaciers were usually higher than those of large ones, which exhibit larger absolute loss. This indicated that the small glaciers were more sensitive to climate change than large glaciers. Compared with the other glaciers in the Qilian Mountain region, the shrinkage of the glaciers in the Middle Qilian Mountain region was the largest. The regional differences of the glacier changes in both Middle Qilian Mountain region and the Qilian Mountain region were mainly influenced by the regional climate conditions, initial glacier area, elevation span, terminus elevation, and other factors.

ACKNOWLEDGMENTS

We are grateful to the Environmental and Ecological Science Data Center for West China for maintaining parts of data. Thanks also go to Bruce Raup for polishing the writing. This study was jointly supported by the National Basic Research Program of China (Nos. 2010CB951003 and 2007CB411501) and the National Natural Science Foundation of China (Nos. 91025012 and J0930003/J0109).

REFERENCES CITED

Academia Sinica, 1959. Report of the Investigation of Modern Glaciers in the Qilian Mts., Investigation Team of Ice/Snow Utilization (Special Issue I). Science Press, Beijing (in Chinese)

Ageta, Y., Kadota, T., 1992. Predictions of Changes of Glacier Mass Balance in the Nepal Himalaya and Tibetan Plateau: A Case Study of Air Temperature Increase for Three Glaciers. *Annals of Glaciology*, 16: 89–94

Chen, Y., Zhang, D. Q., Sun, Y. B., et al., 2005. Water Demand Management: A Case Study of the Heihe River Basin in China. *Physics and Chemistry of the Earth*, 30(6–7): 408–419

Cia, J. C., Andres, A. J., Sanchez, M. A., et al., 2005. Responses to Climatic Changes since the Little Ice Age on Maladeta Glacier (Central Pyrenees). *Geomorphology*, 68(3–4): 167–182

Dikich, A. N., Hagg, W., 2004. Climate Driven Changes of Glacier Runoff in the Issyk-Kul Basin, Kyrgystan. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 39: 75–86

Evans, I. S., 2006. Local Aspect Asymmetry of Mountain Glaciation: A Global Survey of Consistency of Favoured Directions for Glacier Numbers and Altitudes. *Geomorphology*, 73(1–2): 166–184

Evans, I. S., Cox, N. J., 2010. Climatogenic North-South Asymmetry of Local Glaciers in Spitsbergen and Other Parts of the Arctic. *Annals of Glaciology*, 51(55): 16–22

Fujita, K., Ageta, Y., Pu, J. C., et al., 2000. Mass Balance of Xiao Dongkemadi Glacier on the Central Tibetan Plateau from 1989 to 1995. *Annals of Glaciology*, 31: 159–163

Fujita, K., Ageta, Y., 2000. Effect of Summer Accumulation on Glacier Mass Balance on the Tibetan Palteau Revealed by Mass-Balance Model. *Jounal of Glaciology*, 46: 244–252

Gao, Q. Z., Li, F. X., 1991. Case Study of Rational Development and Utilization of Water Resources in the Heihe River Basin. Gansu Science and Technology Press, Lanzhou. 1–228 (in Chinese)

Hagg, W., Braun, L., 2005. The Influence of Glacier Retreat on Water Yield from High Mountain Areas: Comparison of Alps and Central Asian. In: de Jong, C., Collins, D., Ranzi, R., eds., Climate and Hydrology in Mountain Areas. John Wiley & Sons, Ltd., West Sussex. 263–275

Hodgkins, R., Fox, A., Nuttall, A. M., 2007. Geometry Change between 1990 and 2003 at Finsterwalderbreen, a Svalbard Surge-Type Glacier, from GPS Profiling. *Annals of Glaciology*, 46: 131–135

Jia, W. X., He, Y. Q., Li, Z. X., et al., 2008. The Regional Difference and Catastrophe of Climatic Change in Qilian Mt. Region. *Acta Geographica Sinica*, 63(3): 257–269 (in Chinese with English Abstract)

Jin, R., Li, X., Che, T., et al., 2005. Glacier Area Changes in the Pumqu River Basin, Tibetan Plateau, between the 1970s and 2001. *Journal of Glaciology*, 51(175): 607–610

Jóhannesson, T., Raymond, C., Waddington, E., 1989. Time-Scale for Adjustment of Glaciers to Changes in Mass Balance. *Journal of Glaciology*, 35(121): 355–369

Kääb, A., 2004. Mountain Glaciers and Permafrost Creep. In: Methodical Research Perspectives from Earth Observation and Geoinformatics Technologies: [Dessertation]. University of Zurich, Zurich. 205

Knight, P. G., 1998. Glaciers. Stanley Thornes Ltd., Cheletenham

Lan, Y. C., Ding, Y. J., Kang, E. S., 2004. Variations and Trends of Temperature and Precipitation in the Mountain Drainage Basin of the Heihe River in Recent 50 Years. *Plateau Meteorology*, 23(5): 723–727 (in Chinese with English Abstract)

Lan, Y. C., Ding, Y. J., Liu, J. Q., et al., 2005. Change of Water Resources in Mountainous Area of Heihe River under Global-Warming Scene. *Journal of Desert Research*, 25(6): 863–868 (in Chinese with English Abstract)

Li, B. L., Zhu, A. X., Zhang, Y. C., et al., 2006. Glacier Change over the Past Four Decades in the Middle Chinese Tien Shan. *Journal of Glaciology*, 52(178): 425–432

Li, D. L., Wei, L., Cai, Y., et al., 2003. The Present Facts and the Future Tendency of the Climate Change in Northwest China. *Journal of Glaciology and Geocryology*, 25(2): 135–142 (in Chinese with English Abstract)

Li, Z. Q., Li, K. M., Wang, L., 2010. Study on Recent Glacier Changes and Their Impact on Water Resources in Xinjiang, North Western China. *Quaternary Sciences*, 30(1): 96–106 (in Chinese with English Abstract)

Li, Z. X., He, Y. Q., Pu, T., et al., 2010. Changes of Climate, Glaciers and Runoff in China's Monsoonal Temperate Glacier Region during the Last Several Decades. Q*uaternary International*, 218(1–2): 13–28

Liu, C. H., Song, Y. P., Jin, M. X., 1992. Recent Change and Trend Prediction of Glaciers in Qilian Mountain. In: Lanzhou Institute of Glaciology and Geocryology Memoirs 7, Academia Sinica, Lanzhou. 1–9 (in Chinese with English Abstract)

Liu, S. Y., Sun, W. X., Shen, Y. P., et al., 2003. Glacier Changes since the Little Ice Age Maximum in the Western Qilian Shan, Northwest China, and Consequences of Glacier Runoff for Water Supply. *Journal of Glaciology*, 49(164): 117–124

Nesje, A., Dahl, S. O., 2000. Glaciers and Environmental Change. Oxford University Press, New York

Oerlemans, J., 1994. Quantifying Global Warming from the Retreat of Glaciers. *Science*, 264(5156): 243–245

Oerlemans, J., 2005. Extracting a Climate Signal from 169 Glacier Records. *Science*, 308(5722): 675–677

Paul, F., Kääb, A., Maisch, M., et al., 2002. The New Remote-Sensing-Derived Swiss Glacier Inventory: I. Methods. *Annals of Glaciology*, 34: 355–361

Paul, F., Kääb, A., Maisch, M., et al., 2004. Rapid Disintegration of Alpine Glaciers Observed with Satellite Data. *Geophysical Research Letters*, 31(21): L21402

Pu, J. C., Yao, T. D., Duan, K. Q., et al., 2005. Mass Balance of the Qiyi Glacier in the Qilian Mountains: A New Observation. *Journal of Glaciology and Geocryology*, 27(2): 199–204 (in Chinese with English Abstract)

Raup, B., Racoviteanu, A., Jodha, S., et al., 2007a. The GLIMS Geospatial Glacier Database: A New Tool for Studying Glacier Change. *Global and Planetary Change*, 56(1–2): 101–110

Raup, B., Kääb, A., Kargel, J. S., et al., 2007b. Remote Sensing and GIS Technology in the Global Land Ice Measurements from Space (GLIMS) Project. *Computers & Geosciences*, 33(1): 104–125

Sakai, A., Fujita, K., Duan, K., et al., 2006. Five Decades of Shrinkage of the July 1st Glacier, Qilian Mountains, China. *Journal of Glaciology*, 52(176): 11–16

Shangguan, D. H., Liu, S. Y., Ding, Y. J., et al., 2007. Glacier Changes in the West Kunlun Shan from 1970 to 2001 Derived from Landsat TM/ETM Plus and Chinese Glacier Inventory Data. *Annals of Glaciology*, 46: 204–208

Shangguan, D. H., Liu, S. Y., Ding, Y. J., et al., 2009. Glacier Changes during the Last Forty Years in the Tarim Interior River Basin, Northwest China. *Progress in Natural Science*, 19(6): 727–732

Shen, Y. P., Liu, S. Y., Wang, L. L., et al., 2001. Fluctuations of Glacier Mass Balance in Watersheds of Qilian Mountains and Their Impact on Water Resources of Hexi Region. *Journal of Glaciology and Geocryology*, 23(3): 244–250 (in Chinese with English Abstract)

Shi, Y. F., 2000. Glaciers and Their Environments in China—The Present, Past and Future. Science Press, Beijing (in Chinese)

Shi, Y. F., 2001. Estimation of the Water Resources Affected by Climatic Warming and Glacier Shrinkage before 2050 in West China. *Journal of Glaciology and Geocryology*, 23(4): 333–341 (in Chinese with English Abstract)

Surazakov, A. B., Aizen, V. B., Aizen, E. M., et al., 2007. Glacier Changes in the Siberian Altai Mountains, Ob River Basin, (1952–2006) Estimated with High Resolution Imagery. *Environmental Research Letters*, 2(4): 045017

Toutin, T., 2002. DEM from Stereo Landsat 7 ETM+ Data over High Relief Areas. *International Journal of Remote Sensing*, 23(10): 2133–2139

Wang, Z. T., Liu, C. H., You, G. X., et al., 1981. Glacier Inventory of China I (Qilian Mountains). Lanzhou Institute of Glaciology and Cryopedology, Academia Sinica, Lanzhou (in Chinese)

Xie, Z. C., Wu, G. H., Wang, L. L., 1985. Recent Fluctuations of Glaciers in the Qilian Mountains. In: Lanzhou Institute of Glaciology and Geocryology Memoirs 5, Academia Sinica, Lanzhou. 82–90 (in Chinese)

Yang, J. P., Ding, Y. J., Chen, R. S., et al., 2003. Causes of Glacier Change in the Source Regions of the Yangtze and Yellow Rivers on the Tibetan Plateau. *Journal of Glaciology*, 49(167): 539–546

Yang, Z. N., 1991. Glacier Water Resources in China. Gansu Science and Technology Press, Lanzhou. 81–150 (in Chinese)

Yao, T. D., Wang, Y. Q., Liu, S. Y., et al., 2004. Recent Glacial Retreat in High Asia in China and Its Impact on Water Resources in Northwest China. *Science in China* (*Series D*), 47(12): 1065–1075

Ye, Q. H., Kang, S. C., Chen, F., et al., 2006. Monitoring Glacier Variations on Geladandong Mountain, Central Tibetan Plateau, from 1969 to 2002 Using Remote Sensing and GIS Technologies. *Journal of Glaciology*, 52(179): 537–545

Zhao, L. Q., 2009. A Study of Glacier Changes and Surface Dust on Lenglongling Glaciers in the Qilian Mountains: [Dissertation]. Lanzhou University, Lanzhou. 1–57 (in Chinese with English Abstract)