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Glacier changes in the Qilian Mountains in the past half-century:

Based on the revised First and Second Chinese Glacier Inventory

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Abstract: Glaciers are the most important fresh-water resources in arid and semi-arid regions of western China. According to the Second Chinese Glacier Inventory (SCGI), primarily compiled from Landsat TM/ETM+ images, the Qilian Mountains had 2684 glaciers covering an area of 1597.81±70.30 km^2 and an ice volume of ~84.48 km^3 from 2005 to 2010. While most glaciers are small (85.66% are <1.0 km^2), some larger ones (12.74% in the range 1.0–5.0 km^2) cover 42.44% of the total glacier area. The Laohugou Glacier No.12 (20.42 km^2) located on the north slope of the Daxue Range is the only glacier >20 km^2 in the Qilian Mountains. Median glacier elevation was 4972.7 m and gradually increased from east to west. Glaciers in the Qilian Mountains are distributed in Gansu and Qinghai provinces, which have 1492 glaciers (760.96 km^2) and 1192 glaciers (836.85 km^2), respectively. The Shule River basin contains the most glaciers in both area and volume. However, the Heihe River, the second largest inland river in China, has the minimum average glacier area. A comparison of glaciers from the SCGI and revised glacier inventory based on topographic maps and aerial photos taken from 1956 to 1983 indicate that all glaciers have receded, which is consistent with other mountain and plateau areas in western China. In the past half-century, the area and volume of glaciers decreased by 420.81 km^2 (–20.88%) and 21.63 km^3 (–20.26%), respectively. Glaciers with areas <1.0 km^2 decreased the most in number and area recession. Due to glacier shrinkage, glaciers below 4000 m completely disappeared. Glacier changes in the Qilian Mountains presented a clear longitudinal zonality, i.e., the glaciers rapidly shrank in the east but slowly in the central-west. The primary cause of glacier recession was warming temperatures, which was slightly mitigated with increased precipitation.

Keywords: glacier change; glacier inventory; glacier volume; climate change; Qilian Mountains

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1 Introduction

Alpine glaciers are important components of the cryosphere (Kargel *et al*., 2014), act as natural recorders and indicators of climate change (Orelemans *et al.*, 1998; Shi and Liu, 2000), and are important water resources as "alpine solid reservoirs" (Xie *et al*., 2005). As the country with the most alpine glaciers in the mid-low latitude regions of the world, China has 48571 glaciers covering a total area of 5.18×10^4 km^2, which accounts for 7.1% of the world glacier area outside the Antarctic and Greenland (Liu *et al*., 2015). Glaciers and glacial meltwater are the most important fresh-water resources and play critical roles in maintaining fragile ecological balance and sustainable development of socio-economic activities in western China, especially in arid and semi-arid regions (Liu *et al*., 1999; Zhang *et al*., 2012). The Hexi Corridor, nurtured by glacial meltwater from the Qilian Mountains, is an important route for trade and cultural communication connecting Europe and Asia, and constitutes part of the Silk Road Economic Belt. Therefore, glacier changes in the Qilian Mountains have a great significance for Gansu and Qinghai provinces, and the entire nation.

Similar to glacier changes in western China, glaciers are in a state of mass loss, recession and thinning in the Qilian Mountains due to climate warming (Liu *et al*., 1999; Zhang M J *et al*., 2011; Wang *et al*., 2013). From the Little Ice Age (LIA) to 1990, the glaciers in the western Qilian Mountains generally receded; glacier area and volume has been characterized by larger reductions in the south and east compared to the north and west. About 95% of glaciers receded at a rate of ~419 m/a during the period 1956–2000 (Liu *et al*., 2002; Liu *et al*., 2006). The area of glaciers in the central Qilian Mountains decreased 21.7% from 1956 to 2003, and glacier areas reduced 29.6% and 18.7% in the Heihe River and Beida River basins, respectively (Chen *et al*., 2013). Bie *et al*. (2013) showed that the area of glaciers in the Heihe River basin decreased 138.90 km^2 (–35.6%) from 1960 to 2010 and hypothesized that glaciers in this region were an intensive recessional type. Glaciers in the Lenglongling range, located in the eastern Qilian Mountains, also showed an overall recession, with some glaciers disappearing completely (Cao *et al*., 2010; Zhang *et al*., 2010). Tian *et al*. (2014) indicated that glaciers had an accelerated retreat in the Qilian Mountains since the 1990s. Based on Shuttle Radar Topography Mission (SRTM) and Ice, Cloud, and land Elevation Satellite (ICESat) data, Wang *et al*. (2013) calculated glacier volume loss in the Qilian Mountains and estimated an annual mass loss of $534.2 \pm 399.5 \times 10^6$ m^3 w.e. at the beginning of the 21st century, which clearly has high uncertainty. Due to the different data sources adopted by scholars and the study period, together with the area error in the First Chinese Glacier Inventory (FCGI) and complexity of glacier interpretation based on remote sensing (Paul *et al*., 2010; Yao *et al*., 2012), a more systematic study of glacier change and regional differentiation is necessary for the Qilian Mountains. Based on the revised FCGI and latest Second Chinese Glacier Inventory (SCGI) datasets, this paper analyzes glacier change in the Qilian Mountains for the past half-century. Furthermore, the study characterizes glacier change and provides a basis for rational utilization of water resources in this region.

2 Study area

The Qianlian Mountains (36°30′–39°30′N, 93°30′–103°00′E) are located in the northeastern margin of the Tibetan Plateau and are composed of a series of parallel mountains and valleys with a NW trend (Figure 1). Starting from Wushaoling in the east and ending at Dangjin Shankou (Pass) in the west, and stretching from the Hexi Corridor to the Qaidam Basin along the north–south direction, the Qilian Mountains have an approximate length of 800 km and width of 300 km (You and Yang, 2013). The Qilian Mountains are divided into three parts: eastern (Wuwei–Laji Mountain), central (Jiuquan–Delingha), and western (Yingzui Mountain–Da Qaidam), and are bounded by Qinghai Lake and Har Lake to the southwest (Wang *et al*., 1981). The terrain gradually rises from northeast to southwest, with Mount Tuanjie as the highest peak (also known as Kangze'gyai, 5826 m). This region has a plateau continental climate; the western region is controlled by westerly winds and the eastern region is influenced by the southeast and southwest monsoons. The annual average temperature is 5°C and annual precipitation is 250 mm. The precipitation mainly occurs in summer and gradually decreases from east to west.

According to the SCGI, in the Qilian Mountains, there are 2683 glaciers with an area of 1597.81 km^2, accounting for 3.09% of total glacier area in China, and ranking 9th out of the 14 mountains and plateaus in western China with glaciers (Liu *et al*., 2015). Glacier types include continental glaciers in the central and eastern regions and polar glaciers in the western region (Shi and Liu, 2000). In the SCGI, glaciers in the Qilian Mountains are categorized by region: the Hexi (5Y4) and Qaidam (5Y5) interior areas of the Eastern Asia interior drainage (5Y), and Datong River basin (5J4) of the Yellow River exterior drainage (5J) (Shi, 2005). Specifically, the Hexi interior area includes the Shiyang, Heihe, Beida, Shule, and Danghe rivers located in the northern Qilian Mountains, and the Qaidam interior area includes the Haltang, Iqe, Tatalin Gol, Bayan Gol, and Buh rivers in the south.

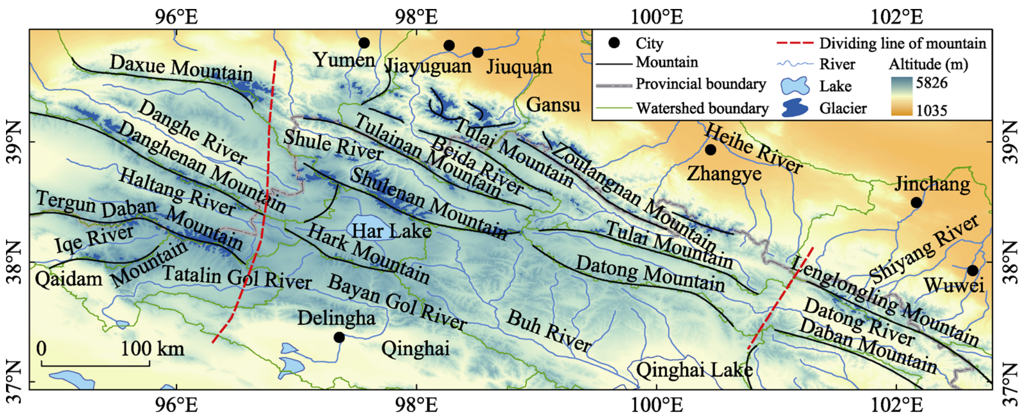

Figure 1 The distribution of glaciers in the Qilian Mountains

3 Data and methods

3.1 Data sources

In the FCGI dataset for the Qilian Mountains published in 1981, the number and area of glaciers were manually derived from aerial topographic maps in the 1960s (Wang *et al*., 1981). In this study, the same aerial topographic maps used in the FCGI and other maps from different periods were collected to digitalize glacier boundaries. The data sources used in the revised FCGI dataset included 46 topographic maps with a scale of 1:100,000 and 18 topographic maps with a scale of 1:50,000. Furthermore, they were classified into three periods: 1956–1957, 1966–1978, and 1983. The area of glaciers illustrated in topographic maps from 1956, 1957, 1966, 1973, and 1975 accounted for ~90% of the total area of glaciers in the Qilian Mountains. The data sources adopted in the SCGI dataset were 16 Landsat TM/ETM+ remote sensing images with little cloud and snow cover; the path/row numbers were 132034, 133033, 134033, 134034, 135033, 135034, 136033, 136034, and 137033 and were freely downloaded from the USGS website (http://glovis.usgs.gov). The months of these remote sensing images were mainly concentrated in June–September from 2005 to 2009.

The digital elevation model (DEM) data used in the revised FCGI and SCGI were topographic maps and SRTM V4.1, respectively. The latter was provided by the Consultative Group on International Agricultural Research (CGIAR, http://srtm.csi.cgiar.org). The annual temperature and precipitation data in the Qilian Mountains for the period 1961–2010 were extracted from the 0.5°×0.5° gridded dataset for monthly temperature and precipitation in China provided by the China Meteorological Data Service Center (http://data.cma.cn).

3.2 Glacier inventory

According to the World Glacier Inventory (WGI), the FCGI dataset for the Qilian Mountains was completed from 1979 to 1980 by Chinese glaciologists (Wang *et al*., 1981). However, limited by technological conditions at that time, the area of each glacier was manually measured using the grid method or planimeter instrument, which has a worse precision than values calculated using GIS software (Yao *et al*., 2012). To improve the accuracy of glacier area and provide a comparison with the SCGI dataset, the manual digitalization method was adopted to revise the FCGI dataset. Procedures included scanning topographic maps, geometric rectification, heads-up digitalizing, calculating the geometric parameters of a glacier, and artificial verification of each glacier's attributes. The statistics from the revised FCGI dataset demonstrated that there were 3000 glaciers with an area of 2014.96 km^2 in the Qilian Mountains, which is larger than the previous result, i.e., the original number of glaciers was 2815 with an area of 1931 km^2 (Wang *et al*., 1981). The methods used in the SCGI dataset have been described in detail by Liu *et al*. (2015) and Guo *et al*. (2015).

3.3 Error estimation

There are usually two methods to estimate the error in glacial extent based on artificial visual interpretation. One is field investigation and the other is a comparison with high-resolution remote sensing images (Yan and Wang, 2013). Due to the steep terrain and severe climate in the glaciated region, it is very difficult to verify the interpretation precision of glaciers using field investigation. Therefore, the latter method has been widely adopted for error estimation of glacier interpretation based on remote sensing images (Racoviteanu *et al*., 2009; Kargel *et al*., 2014). For the SCGI dataset, experienced researchers manually revised the boundaries of automatically derived glaciers (Liu *et al*., 2015). Although the SCGI dataset was created using visual interpretation that can be viewed as true glacier values, there were still some errors, such as the offset of pixel. In this study, the errors caused by spatial resolution of topographic maps and satellite remote sensing images were considered, which are calculated with the following formula:

$$\varepsilon = N \cdot A/2 \tag{1}$$

where ε is the error (m^2); N is the number of pixels located in the boundary of glacier; A is the size of glacier boundary symbol on the topographic map or the area of one pixel in the remote sensing image, which are 729 m^2 for a topographic map with a scale of 1:100,000 and 900 m^2 for Landsat TM/ETM+ images, respectively. The results showed that the errors in glacier area in the FCGI and SCGI datasets for the Qilian Mountains due to image spatial resolution were ±105.90 km^2 (±5.26%) and ±70.30 km^2 (±4.40%), respectively.

3.4 Methods for calculating glacier area change

The change in glacier area was defined as the difference between the corresponding glacier areas in the FCGI and SCGI datasets. Due to the time span in the FCGI dataset, two methods, the rate and relative rate of glacier area change, were proposed to compare the glacier change in different basins, which are calculated as follows:

$$V_{GAC} = \frac{GA_s - GA_f}{Y_{f-s}} \tag{2}$$

$$PV_{GAC} = \left[\left(\frac{GA_s}{GA_f} \right)^{1/Y_{f-s}} - 1 \right] \times 100\% \tag{3}$$

where V_{GAC} is the rate of glacier area change ($km^2 \cdot a^{-1}$); PV_{GAC} is the relative rate of glacier area change ($\% \cdot a^{-1}$); and GA_s and GA_f are glacier areas (km^2) in the SCGI and FCGI, respectively. Y_{f-s} is the time interval (a, year) between the FCGI and SCGI, which can be obtained from the following formula:

$$Y_{f-s} = \frac{\sum_{i=1}^{m} A_i \cdot Y_i}{\sum_{i=1}^{m} A_i} - \frac{\sum_{j=1}^{n} A_j \cdot Y_j}{\sum_{j=1}^{n} A_j} \tag{4}$$

where A_i and Y_i are the area of glacier i and its acquisition year in a basin in the SCGI dataset, respectively; A_j and Y_j are the area of glacier j and its acquisition year in this basin in the FCGI dataset, respectively; and m and n are the total number of glaciers in the basin in the SCGI and FCGI datasets, respectively.

3.5 Methods for calculating ice volume

Measurements of glacier thickness by GPR or drilling have only been conducted on a few glaciers; therefore, calculating glacier ice volume over a wide area depends on empirical formulas (Gärtner-Roer *et al*., 2014). The ice volume–area relation for a glacier is generally expressed using:

$$V = cA^{\lambda} \tag{5}$$

where V denotes the ice volume of glacier (km^3); A is the area of glacier (km^2); and c and λ are empirical coefficients. In this study, the values of c and λ proposed by Radić and Hock (2010), Grinsted (2013) and Liu *et al*. (2003) were adopted.

4 Results and discussion

4.1 The contemporary distribution of glaciers in the Qilian Mountains

4.1.1 General glacier characteristics

There were 2684 glaciers with an area of 1597.81 km^2 and ice volume of 88.48 km^3 in the Qilian Mountains during the period 2005–2010. As shown in Figure 2, a clear feature of glaciers in the Qilian Mountains was that glaciers with areas <1.0 km^2 accounted for the largest number of glaciers, while glaciers with areas in the range of 1.0–5.0 km^2 accounted for the most glacierized area. Specifically, there were 2299 glaciers with areas <1.0 km^2, which accounted for 85.66% of the total number of glaciers in the Qilian Mountains. As glacier size increased, the number of glaciers rapidly decreased. There was only one glacier with an area >20 km^2, Laohugou Glacier No.12, with an area of 20.42 km^2. The area of glaciers appeared to have a normal distribution. Glaciers classified with areas between 2.0 km^2 and 5.0 km^2 accounted for the largest area (372.37 km^2); glaciers classified with areas between 1.0 km^2 and 2.0 km^2 accounted for the second largest area, 305.67 km^2. Together, these two area classes accounted for 42.44% of the total glacierized area in the Qilian Mountains. There were 858 glaciers with areas <0.1 km^2, which had a total area of 41.50 km^2 (2.60% of total glacierized area); this was approximately double the area of Laohugou Glacier No.12.

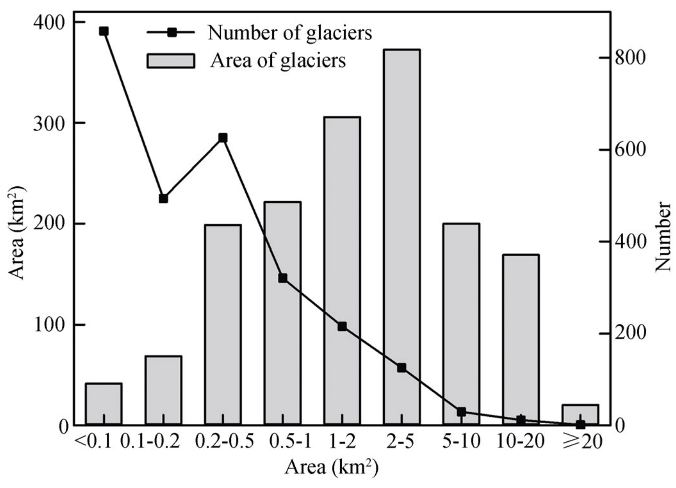

Figure 2 The total glacierized area and number of glaciers in different size classes in the Qilian Mountains between 2005 and 2010

4.1.2 Glacier altitude distribution

The primary terrain factors that influence the number and size of glaciers are the absolute elevation of the host mountain and relative elevation above the equilibrium line (Shi, 2000). Due to geologic structures and tectonics, the elevation gradually decreases from southwest to northeast in the Qilian Mountains. Although 30% of the mountainous area in the Qilian Mountains is above 4000 m, the glacierized area above the same altitude only occupies 1.29% of the total alpine area, which implies that it is poorly suited for glacier development. In general, the Qilian Mountains are divided into five sub-regions: (1) alpine and gorge region in the north, (2) alpine region upstream of the Shule and Danghe rivers, (3) moderately eroded alpine and valley region in the south, (4) alpine and basin region around Qinghai and Har lakes, and (5) strongly eroded valley region close to the Huang River. Due to high relief, strong erosion, and broken surfaces, glacier areas were usually smaller in the first sub-region. However, in the second sub-region, glaciers had larger areas and formed larger glaciated regions around the main peak in the Daxue, Shulenan, and Tergun Daban mountains with good terrain conditions for glacier development. The altitude in the fifth sub-region was very low, so there were no glaciers.

The statistical analysis based on an altitude interval of 50 m showed that the hypsography of the glacier area in the Qilian Mountains was in normal distribution (Figure 3). Glaciers developed in the elevation band of 4000–5800 m, and glaciers located between 4800 and 5200 m. formed the main glacier bodies, accounting for 58.15% of the total area of glaciers. The glacier terminus with the lowest altitude (38°17′N, 100°19′E, 4017.8 m) was located in the Panjia River basin (5Y422F) on the north side of Tulai Mountain. Affected by parallel mountains and valleys with NW orientation, the median altitude of glaciers gradually rose from 4483.8 to 4820.2 m. along the Lenglongling, Zoulangnan, and Tulai mountains in the EW direction, which is similar to the trend in the equilibrium-line altitude (ELA) for the Qilian Mountains proposed by Su *et al*. (2014). The median altitudes of glaciers were between 5003.7 and 5097.2 m. in the wide western alpine region, including the Daxue, Shulenan, Danghenan, and Tergun Daban mountains. The highest median altitude (5234.1 m) of glaciers was located in the Qaidam Mountains.

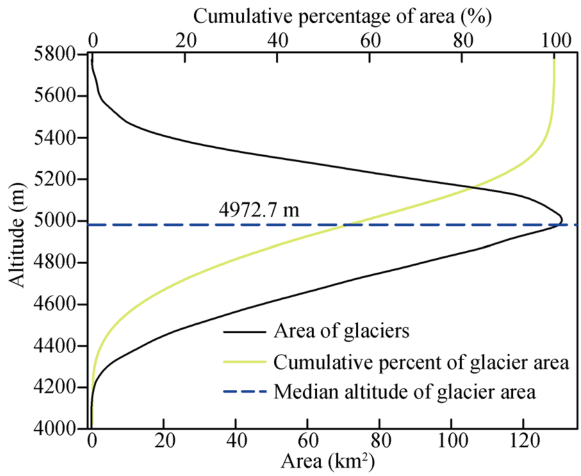

Figure 3 Hypsography of glacier area in the Qilian Mountains

4.1.3 The distribution of glaciers in different drainage systems

As described in Section 2, glaciers in the Qilian Mountains were assigned to three drainage basins, categorized as 5Y4, 5Y5, and 5J4. Table 1 lists the statistics of glaciers in different drainage systems. Clearly, most glacier resources were in the Hexi interior area, in both area and number of glaciers, followed by the Qaidam interior area and Datong River basin. In the sub-basins, the Shule River basin had the most plentiful glaciers, with an area and ice volume accounting for 31.91% and 35.11% of the corresponding glacier totals in the Qilian Mountains, respectively. The average area of glaciers was the largest and the ice volume of glaciers was the second largest in the Haltang River basin, although the number of glaciers was fewer than in the Beida, Heihe, and Dang River basins. The basin with the least glacier resources was the Bayan Gol River, which only had 10 glaciers covering an area of 2.20 km^2. Although there were 375 glaciers with an area of 78.33 km^2 in the Heihe River, the second largest inland river in China, the average glacier area was the least of the 11 sub-basins.

Table 1 Glacier statistics by drainage basin in the Qilian Mountains

Basin (Code)	Sub-basin (Code)	Number		Area		Average area(km^2)	Volume	
			(%)	(km^2)	(%)		(km^3)	(%)
Datong River (5J4)	Datong River (5J42)	68	2.53	20.83	1.30	0.31	0.73	0.86
Hexi interior area (5Y4)	Shiyang River (5Y41)	97	3.61	39.94	2.50	0.41	1.55	1.83
	Heihe River (5Y42)	375	13.97	78.33	4.90	0.21	2.39	2.83
	Beida River (5Y43)	577	21.50	215.27	13.47	0.37	8.75	10.36
	Shule River (5Y44)	660	24.59	509.87	31.91	0.77	29.66	35.11
	Danghe River (5Y45)	318	11.85	203.77	12.75	0.64	10.08	11.93
	Total	2027	75.52	1047.18	65.54	0.52	52.43	62.07
Qaidam interior area (5Y5)	Buh River–Qinghai Lake (5Y51)	24	0.89	10.27	0.64	0.43	0.42	0.50
	Haltang River (5Y56)	268	9.99	283.52	17.74	1.06	17.58	20.81
	Har Lake (5Y57)	108	4.02	78.73	4.93	0.73	4.56	5.40
	Iqe River–Tatalin Gol River (5Y58)	179	6.67	155.08	9.71	0.87	8.69	10.29
	Bayan Gol River (5Y59)	10	0.37	2.20	0.14	0.22	0.06	0.07
	Total	589	21.94	529.8	33.16	0.90	31.31	37.07

4.1.4 The distribution of glaciers in different provinces

Based on administrative divisions, glaciers in the Qilian Mountains were located within cities of Jiuquan, Zhangye, and Wuwei in Gansu Province and the autonomous prefectures of Haixi and Haibei in Qinghai Province (Table 2). There were 1492 glaciers with a total area of 760.96 km^2 and an ice volume of 37.94 km^3 in Gansu Province. The glaciers in the Qilian Mountains play a dominant role in Gansu province and their area and ice volume accounted for 94.99% and 95.09% of the corresponding provincial glacier totals (Liu *et al*., 2015). They were mostly distributed in Jiuquan and Zhangye. Although the number of glaciers in Zhangye was more than that in Jiuquan, the area and ice volume of glaciers located in the latter was two and three times the former, respectively. Wuwei only had 35 glaciers, with an area of 6.32 km^2 and volume of 0.17 km^3; it was the municipal level administrative unit with the least glacier resources in this region. Due to the inconsistency between the main ridge of the Qilian Mountains and the provincial boundary of Gansu and Qinghai, all the glacial melt-

Table 2 Glacier statistics by province in the Qilian Mountains

Province	City/Autonomous Prefecture	Number		Area		Volume	
			(%)	(km^2)	(%)	(km^3)	(%)
Gansu	Jiuquan	718	26.75	508.99	31.86	28.17	33.35
	Zhangye	739	27.53	245.65	15.37	9.60	11.36
	Wuwei	35	1.31	6.32	0.40	0.17	0.20
	Total	1492	55.59	760.96	47.63	37.94	44.91
Qinghai	Haixi	825	30.74	729.79	45.67	42.79	50.65
	Haibei	367	13.67	107.06	6.70	3.75	4.44
	Total	1192	44.41	836.85	52.37	46.54	55.09

water on the northern side of the Qilian Mountains flows into rivers in Gansu Province; the downstream Datong River (Liancheng–Honggu segment) receives the meltwater from glaciers located in Qinghai Province. Therefore, there were 2363 glaciers with an area of 1351.53 km^2 and ice volume of 70.74 km^3, and the meltwater was available in Gansu Province.

Qinghai Province had 1192 glaciers with an area of 836.85 km^2 and ice volume of 46.54 km^3 in the Qilian Mountains. Although the number of glaciers in Haixi Mongol and Tibetan Autonomous Prefecture was twice that in the Haibei Tibetan Autonomous Prefecture, the area and ice volume of glaciers of the former were much greater than in the latter. Outside of the Qilian Mountains, glaciers in Qinghai Province are distributed in the Kunlun, Tanggula, and Bayan Har mountains. The number, area, and ice volume of glaciers in the Qilian Mountains accounted for 31.35%, 21.26%, and 16.94% of the corresponding glacier totals in Qinghai Province, respectively.

4.2 Glacier change in the Qilian Mountains in the past half-century

4.2.1 The change of number, area, and volume of glaciers

Statistics from the FCGI and SCGI datasets demonstrated that the area of glaciers in the Qilian Mountains decreased by 420.81 km^2 (–20.88%) during the period 1956–2010. In total, 509 glaciers, with an area of 55.12 km^2, completely disappeared; and 122 glaciers decreased in area from 241.35 km^2 to 193.90 km^2 and split into 262 smaller glaciers. In addition, there were 55 glaciers, with an area of 3.67 km^2, that were not in the original FCGI dataset. Tian *et al*. (2014) suggested that the glacier areas in the Qilian Mountains were 2041.50 km^2 and 1575.82 km^2 in the 1990s and 2010s, respectively; the reduction in glacier area was 465.68 km^2, or –22.81%. Some previous studies (e.g. Ding, 2002; Cao *et al*., 2010; Zhang *et al*., 2010, 2011; Bie *et al*., 2013) have indicated that glaciers retreated in the Qilian Mountains between the 1950s and 1990s. However, in the FCGI dataset, the glacier areas in the 1990s were >2014.96 km^2, indicating that Tian *et al*. (2014) overestimated the glacier area change in the Qilian Mountains. In the past half-century, the glacier areas in Gansu and Qinghai decreased by 218.97 km^2 (–22.39%) and 198.44 km^2 (–19.17%), respectively.

As listed in Table 3, the ice volume of glaciers and their change were the largest using the empirical constants proposed in Grinsted (2013); the smallest values were calculated using the empirical constants in Radić and Hock (2010). The results from Liu *et al*. (2003) were in the middle. The average ice volume loss of glaciers based on the three methods was 21.63 km^3 in the Qilian Mountains for the past 50 years. The rates of glacier ice volume loss were between –5.38 km^3/10a and –5.67%/10a.

Table 3 Glacier volume changes in the Qilian Mountains based on three sets of empirical constants

Ice volume of glaciers in the FCGI (km^3)	Ice volume of glaciers in the SCGI (km^3)	Glacier volume change			Method of glacier volume calculation	Reference
		km^3	km^3/10a	%/10a		
101.90	81.30	–20.60	–5.12	–5.65	V=0.0365$A^{1.375}$	Radić and Hock (2010)
109.86	87.52	–22.34	–5.56	–5.69	V=0.0433$A^{1.29}$	Grinsted (2013)
108.44	86.49	–21.95	–5.46	–5.66	V=0.04$A^{1.35}$	Liu *et al*. (2003)

4.2.2 Characteristics of glacier change

An analysis of the relative area change compared to the initial glacier area indicated greater relative loss for smaller glaciers and greater absolute loss for larger glaciers in the Qilian Mountains (Figure 4). There were 999 glaciers in the size class <0.5 km^2; their area loss percentage was >50% and accounted for 33.32% of the total number of glaciers. The area of glaciers in the size class <0.1 km^2 decreased by 271.01 km^2, which was 64.40% of the total area loss. Although the area loss of some glaciers in the size class ⩾5.0 km^2 exceeded 1.0 km^2, their small quantities resulted in a percentage <5.0%. Hence, the glaciers in the <1.0 km^2 size class overwhelmingly dominated, in both absolute area change and relative area change of the glaciers in the Qilian Mountains.

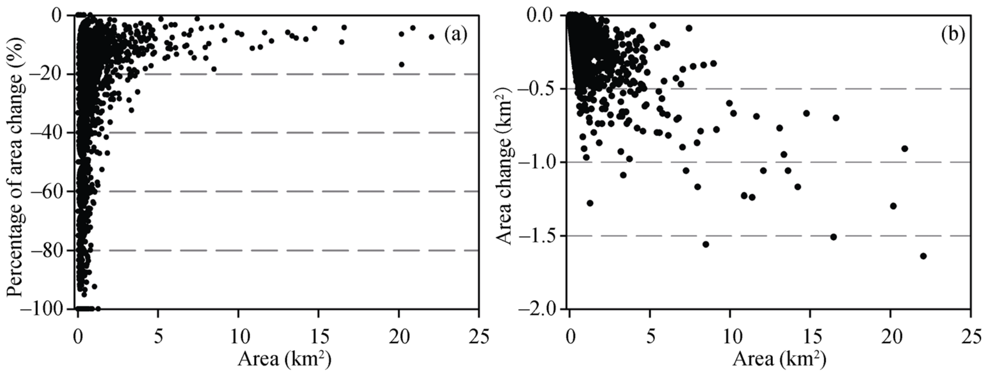

Figure 4 Percentage and area changes in glaciers in the Qilian Mountains from 1956 to 2010

Analysis of glacier hypsography showed that ice coverage above 5500 m remained almost unchanged while the highest absolute ice loss occurred around 4650 m (Figure 5). The percentage of glacier area change gradually decreased with increasing elevation. Alarmingly, glaciers below 4000 m disappeared. Although the area loss percentage of glaciers below 4250 m exceeded 80% of their initial area, the absolute area loss of glaciers between 4350 and 5100 m constituted the main body of loss, >15.0 km^2 in each 50 m elevation band and 84.24% of the total area loss of glaciers.

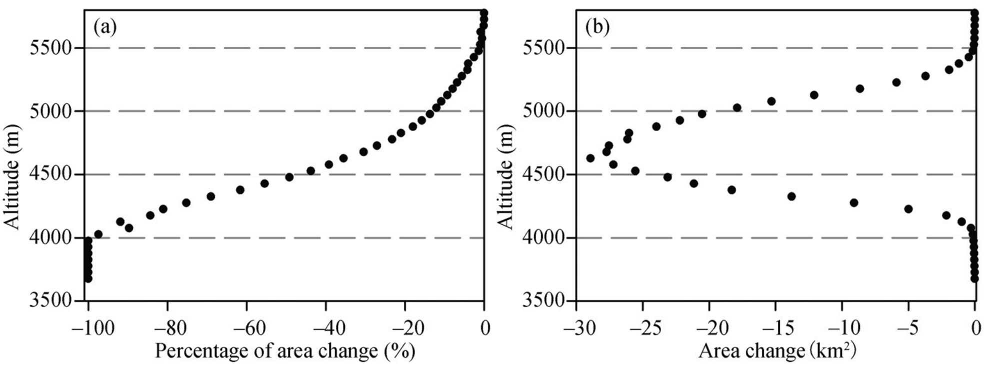

Figure 5 Altitudinal characteristics of glacial changes in the Qilian Mountains from 1956 to 2010

The highest number and area of glaciers were oriented northward, followed by the northeast and northwest orientations (Figure 6). There were similar numbers of glaciers oriented south, southeast, and southwest, although glacier area with a southwest orientation was the greatest of these three. The number of glaciers oriented westward was more than that oriented eastward, but the area of the former was less than the latter. Statistical analysis indicated that glacier change was consistent with the size of glaciers in all orientations, except for the northwest. The largest and least absolute area losses of glaciers were in the north and south orientations, which were –210.34 km^2 and –5.03 km^2, respectively. From the perspective of relative area change, glaciers oriented eastward showed the largest decrease (–32.72%), followed by the southwest, southeast, west, and north orientations, which were between –29.91% and –23.73%. Notably, the area loss of glaciers with a northwest orientation was the least (–1.85 km^2 and –0.95%), which was possibly related to the intensive westerly.

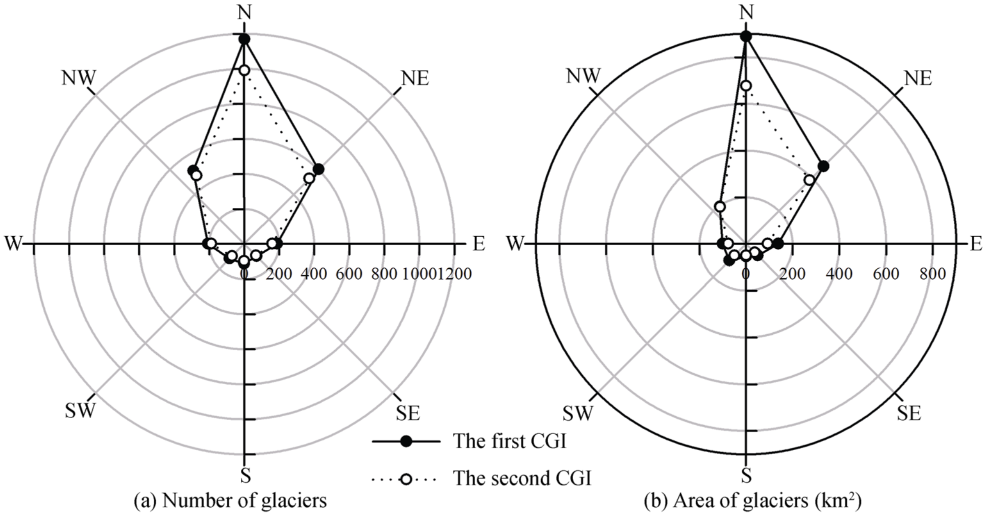

Figure 6 Orientation characteristics of glacial changes in the Qilian Mountains from 1956 to 2010

4.2.3 The regional differences in glacier change

The area change rates of glaciers in 11 drainage basins in the Qilian Mountains in the period 1956–2010 were clearly different (Figure 7). The most rapid decrease in glacier area occurred in the Shule River basin (5Y44) with a rate of –24.5 km^2/10a, followed by the Beida River basin (5Y56) and Heihe River basin (5Y42), with rates of –21.7 km^2/10a and –17.0 km^2/10a, respectively. The Haltang River basin (5Y56), which has the second largest area of glaciers, had a rate of –9.7 km^2/10a. The lowest rate, –0.2 km^2/10a, was found in the Bayan Gol River basin (5Y59), which was likely due to the basin having the lowest area of glaciers.

A comparison of relative rates of glacier area change indicates that the Datong River basin (5J42) had the fastest decrease, –19.97%/10a, followed by the Heihe River basin (5Y42) and Shiyang River basin (5Y41), with relative rates of –15.67%/10a and –14.21%/10a, respectively. The relative rates were similar in the Beida River (5Y45), Buh River–Qinghai Lake (5Y51), and Bayan Gol River (5Y59) basins, between –9.49%/10a and –7.81%/10a. The relative rates of five basins located in the west of Har Lake were slower, with absolute values below 4.45%/10a. The Iqe River–Tatalin Gol River basin (5Y58) in the westernmost region had the lowest relative rate, –2.96%/10a. The average relative rate of glacier area change was –2.43%/degree in the longitudinal direction, which indicated an accelerating trend in glacier area recession from west to east in the Qilian Mountains.

Generally, glacier survival, development, and evolution are closely related to climate change (Duan *et al.*, 2009; Xie and Liu, 2010; Wang *et al.*, 2011). Temperature has a strong effect on glacier change over longer time scales and larger spatial extents, while precipitation influences glacier advance or retreat over short times and small scales (Gao *et al.*, 2000).

In the recent five decades, temperature has significantly increased in the Qilian Mountains. The average rate of temperature rise has been approximately 0.5°C/10a, but up to 1°C/10a, since the 1990s (Wang *et al*., 2009). Annual precipitation has also increased and has been mainly concentrated in the summer; however, changes in precipitation are also regionally varied (Wang *et al*., 2009; Zhang *et al*., 2014). The most recent studies have demonstrated that there has been a trend toward warm and dry in the spring, autumn, and winter and warm and wet in the summer along the Hexi Corridor (Wang *et al*., 2009; Lin *et al*., 2014). However, these studies have used data from sparsely distributed metrological stations in the Qilian Mountains; therefore, it has been difficult to examine regional differences in temperature and precipitation. In this study, the 0.5°×0.5° gridded dataset of monthly temperature and precipitation was adopted to analyze inter-decadal variability in the Qilian Mountains. There has been an obvious trend in temperature increases in summer, as shown in Figure 8. The

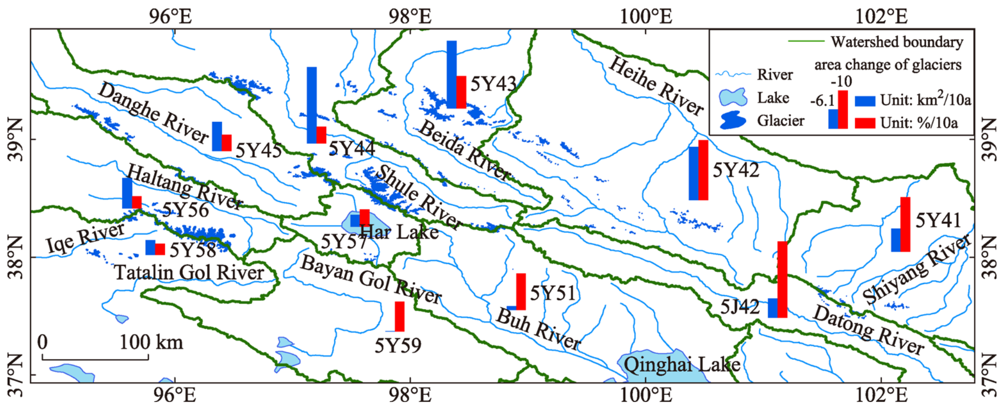

Figure 7 Area changes of glaciers in different drainage basins in the Qilian Mountains from 1956 to 2010

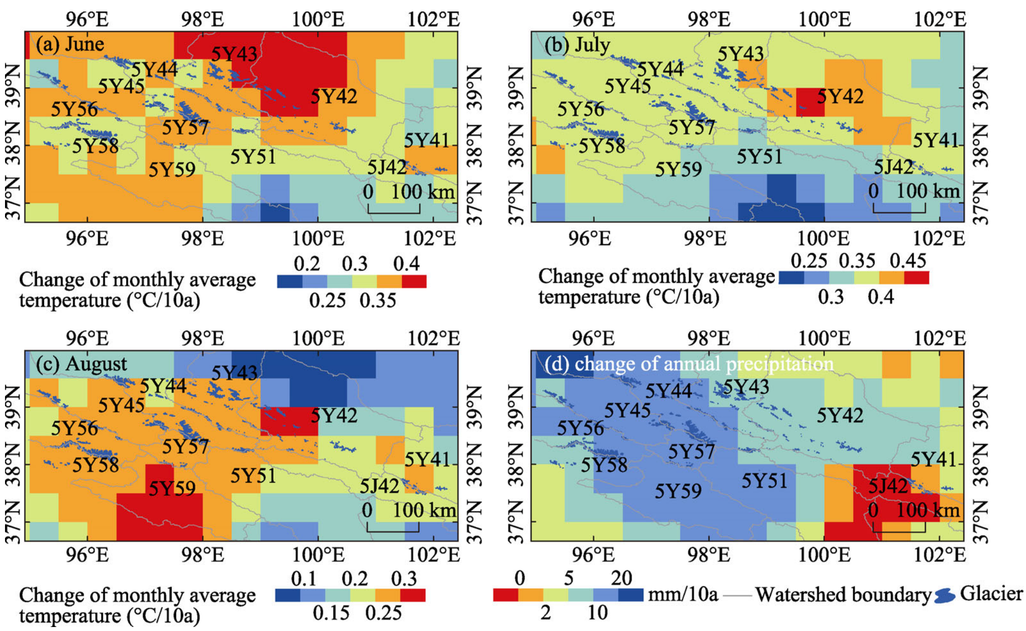

Figure 8 Change in summer temperature, (a) June, (b) July, (c) August, and (d) annual precipitation in the Qilian Mountains from 1961 to 2010

rate of temperature rise generally exceeded 0.2°C/10a and the Heihe River witnessed the highest temperature rise in June, July, and August. The change in annual precipitation gradually increased from east to west. Except for the Datong River, the rate of precipitation increase was above zero; notably, precipitation increases were as high as 10.0–20.0 mm/10a in the western alpine regions around the Tulainan, Danghenan, and Tergun Daban mountains. It is likely that the larger recession of glaciers was due to increasing temperature in the central–eastern parts of the Qilian Mountains. The temperature also rose in the western region, but the increased precipitation mitigated glacier mass loss to some extent. However, the mass gain from increased precipitation could not fully balance the mass loss from rising temperatures, which resulted in the overall recession of glaciers in the Qilian Mountains.

5 Conclusions

This study presented the current status and characteristics of glacier change in the Qilian Mountains based on the FCGI and SCGI datasets. Some conclusions are drawn as follows:

(1) There were 3000 glaciers with an area of 2014.96 km^2 in the revised FCGI dataset for the Qilian Mountains, which was more than previously published. A statistical analysis of the latest SCGI dataset demonstrated that there were 2684 glaciers with an area of 1597.81 ± 70.30 km^2 and ice volume of ~84.48 km^3 in the Qilian Mountains for the period 2005–2010. Glaciers in the Qilian Mountains were distributed in Gansu and Qinghai provinces, which respectively had 1492 glaciers covering 760.96 km^2 with an ice volume of 37.94 km^3 and 1192 glaciers covering 836.85 km^2 with an ice volume of 46.54 km^3.

(2) Glaciers in the <1.0 km^2 size class accounted for the largest number of glaciers, while glaciers in the 1.0–5.0 km^2 size classes accounted for the largest area of glaciers in the Qilian Mountains. The largest glacier was Laohugou Glacier No.12 with an area of 20.42 km^2 in 2009. More than 58% of the total glacier area was located between 4800 and 5200 m in elevation. The average median elevation of glacier area was 4972.7 m, and gradually rose from 4483.8 to 5234.2 m from east to west.

(3) The Shule River basin included the largest area and ice volume of glaciers, 31.91% and 35.11% of the total corresponding values. The drainage basin with the least glacier resources was the Bayan Gol River, with a glacierized area of only 2.20 km^2. The Heihe River, the second largest inland river in China, had the minimum average glacier area, 0.21 km^2.

(4) The area and ice volume of glaciers in the Qilian Mountains decreased 420.81 km^2 (–20.88%) and 21.63 km^3 (–20.26%) from 1956 to 2010, respectively. The primary decline in glacier resources was in the <1.0 km^2 glacier size class. Due to rapid glacial recession, glaciers below 4000 m completely disappeared and area loss of glaciers below 4500 m was up to 50% of the initial area. The glacier area reduction between 4350 and 5100 m accounted for 84.24% of the total area loss. The number and area of glaciers decreased in all directions. The area of glaciers decreased fastest for glaciers with eastern orientation and slowest for glaciers with northwestern orientation. The highest reduction in glacier area occurred for those oriented north, –210.34 km^2.

(5) There was an obvious longitudinal zonality in glacier change in the Qilian Mountains, i.e., the glaciers were rapidly receding in the east but more slowly in the central and western regions. The difference of relative rate was largest between the east and west; for example,

the relative rate of area loss was between –14.21%/10a and –19.97%/10a in the Datong River and Shiyang River basins, while it was only –2.96%/10a in the Iqe River–Tatalin Gol River basin. The main factor that most influenced glacier recession was warming temperature, although increased precipitation mitigated glacier mass loss to some extent.

References

Bie Q, Qiang W L, Wang C *et al*., 2013. Monitoring the glacier variation in the upper reaches of the Heihe River based on remote sensing in 1961–2010. *Journal of Glaciology and Geocryology*, 35(3): 574–582. (in Chinese)

Cao B, Pan B T, Gao H S *et al*., 2010. Glacier variation in the Lenglongling Range of eastern Qilian Mountains from 1972 to 2007. *Journal of Glaciology and Geocryology*, 32(2): 242–248. (in Chinese)

Chen H, Li Z Q, Wang P Y *et al*., 2013. Change of glaciers in the central Qilian Mountains. *Arid Zone Research*, 30(4): 588–593. (in Chinese)

Ding Y H, 2002. Assessment of Environmental Evolution in Western China Volume II: Predictions on Environment Change in Western China. Beijing: Science Press. (in Chinese)

Duan J P, Wang L L, Ren J W *et al*., 2009. Progress in glacier variations in China and its sensitivity to climatic change during the past century. *Progress in Geography*, 28(2): 231–237. (in Chinese)

Gao X Q, Tang M C, Feng S, 2000. Discussion on the relationship between glacial fluctuation and climate change. *Plateau Meteorology*, 19(1): 9–16. (in Chinese)

Gärtner-Roer I, Naegeli K, Huss M *et al*., 2014. A database of worldwide glacier thickness observations. *Global and Planetary Change*, 122: 330–344.

Grinsted A, 2013. An estimate of global glacier volume. *The Cryosphere*, 7: 141–151.

Kargel J S, Leonard G J, Bishop M P *et al*., 2014. Global Land Ice Measurements from Space. Heidelberg: Springer.

Lin S, Li H Y, Dang B *et al*., 2014. The latest evidences of a warm-wet climatic shift in Hexi Corridor, Gansu. *Journal of Glaciology and Geocryology*, 36(5): 1111–1121. (in Chinese)

Liu C H, Kang E S, Liu S Y *et al*., 1999. Study on the glacier variation and its runoff responses in the arid region of northwest China. *Science in China Series D*, 29(S1): 55–62. (in Chinese)

Liu S, Sun W, Shen Y *et al*., 2003. Glacier changes since the Little Ice Age maximum in the western Qilan Shan, northwest China, and consequences of glacier runoff for water supply. *Journal of Glaciology*, 49(164): 117–124.

Liu S Y, Ding Y J, Li J *et al*., 2006. Glaciers in response to recent climate warming in western China. *Quaternary Sciences*, 26(5): 762–771. (in Chinese)

Liu S Y, Shen Y P, Sun W X *et al*., 2002. Glacier variation since the maximum of the Little Ice Age in the western Qilian Mountains, Northwest China. *Journal of Glaciology and Geocryology*, 24(3): 227–233. (in Chinese)

Liu S Y, Yao X J, Guo W Q *et al*., 2015. The contemporary glaciers in China based on the Second Chinese Glacier Inventory. *Acta Geographica Sinica*, 70(1): 3–16. (in Chinese)

Orelemans J, Anderson B, Hubbard A *et al*., 1998. Modelling the response of glaciers to climate warming. *Climate Dynamics*, 14(4): 267–274.

Paul F, Barry R G, Cogley J G *et al*., 2010. Recommendations for the compilation of glacier inventory data from digital sources. *Annals of Glaciology*, 50(53): 119–126.

Racoviteanu A E, Paul F, Raup B *et al*., 2009. Challenges and recommendations in mapping of glacier parameters from space: Results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA. *Annals of Glaciology*, 50(53): 53–69.

Radić V, Hock R, 2010. Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. *Journal of Geophysical Research*, 115, F01010. doi: 10.1029/2009JF001373.

Shi Y F, 2000. Glaciers and Their Environments in China: The Present, Past and Future. Beijing: Science Press.

(in Chinese)

Shi Y F, 2005. A Concise China Glacier Inventory. Shanghai: Shanghai Science Popular Press. (in Chinese)

Shi Y F, Liu S Y, 2000. Pre-estimation for the response of China glaciers to global warming in the 21st century. *Chinese Science Bulletin*, 45(4): 434–438. (in Chinese)

Su Z, Zhao J D, Zheng B X, 2014. Distribution and features of the glaciers' ELAs and the decrease of ELAs during the Last Glaciation in China. *Journal of Glaciology and Geocryology*, 36(1): 9–19. (in Chinese)

Tian H, Yang T, Liu Q, 2014. Climate change and glacier area shrinkage in the Qilian Mountains, China, from 1956 to 2010. *Annals of Glaciology*, 55(66): 187–197.

Wang H J, Zhang B, Jin X H et al., 2009. Spatio-temporal variations analysis of air temperature and precipitation in Qilian mountainous region based on GIS. *Journal of Desert Research*, 29(6): 1196–1202. (in Chinese)

Wang S J, Zhang M J, Li Z Q *et al*., 2011. Response of glacier area variation to climate change in Chinese Tianshan Mountains in the past 50 years. *Acta Geographica Sinica*, 66(1): 38–46. (in Chinese)

Wang Y Z, Ren J W, Qin D H *et al*., 2013. Regional glacier volume changes derived from satellite data: A case study in the Qilian Mountains. *Journal of Glaciology and Geocryology*, 35(3): 583–592. (in Chinese)

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

Xie Z C, Feng Q H, Wang Xin *et al*., 2005. Modeling the response of glacier system to climate warming: Taking glaciers in China as an example. *Research of Soil and Water Conservation*, 12(5): 77–82. (in Chinese)

Xie Z C, Liu C H, 2010. Introduction to Glaciology. Shanghai: Shanghai Science Popular Press. (in Chinese)

Yan L L, Wang J, 2013. Study of extracting glacier information from remote sensing. *Journal of Glaciology and Geocryology*, 35(1): 110–118. (in Chinese)

Yao X J, Liu S Y, Guo W Q *et al*., 2012. Glacier change of Altay Mountain in China from 1960 to 2009: Based on the Second Glacier Inventory of China. *Journal of Natural Resources*, 27(10): 1734–1745. (in Chinese)

You L Y, Yang J C, 2013. Geomorphology in China. Beijing: Science Press. (in Chinese)

Zhang H W, Lu A X, Wang L H *et al*., 2010. Glacier change in the Lenglongling Mountain monitored by remote sensing. *Remote Sensing Technology and Application*, 2010, 25(5): 682–686. (in Chinese)

Zhang H W, Lu A X, Wang L H *et al*., 2011. Glacier change in the Shulenan Mountain monitored by remote sensing. *Journal of Glaciology and Geocryology*, 33(1): 8–13. (in Chinese)

Zhang J T, He X J, Shangguan D H *et al*., 2012. Impact of intensive glacier ablation on arid regions of northwest China and its countermeasure. *Journal of Glaciology and Geocryology*, 2012, 34(4): 848–854. (in Chinese)

Zhang L, Zhang Q, Feng J Y *et al*., 2014. A study of atmospheric water cycle over the Qilian Mountains (I): Variation of annual water vapor transport. *Journal of Glaciology and Geocryology*, 36(5): 1079–1091. (in Chinese)

Zhang M J, Wang S J, Li Z Q *et al*., 2011. Variation of glacier area in China against the warming in the past 50 years. *Acta Geographica Sinica*, 66(9): 1155–1165. (in Chinese)