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Monitoring Glacier Changes of Recent 50 Years in the Upper Reaches of Heihe River Basin Based on Remotely-Sensed Data

Bie Qiang¹, He Lei¹ and Zhao Chuan-yan²

¹ College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, China

² State Key Laboratory of Pastoral Agricultural Ecosystem, Institute of Arid Agroecology, School of Life Sciences, Lanzhou University, Lanzhou, China

E-mail: nanzhr@lzb.ac.cn

Abstract. The upper reach of the Heihe River Basin was selected as the study area. The distribution data of glaciers in the study area has been automatically derived from topographic maps made in 1960 and from Landsat TM images in 1990, 2000 and 2010 by object-oriented image interpretation method combined with expert knowledge rules. Spatial-temporal variations of glaciers were analyzed with GIS technology. Results show that glaciers have shrunk significantly by 138.90 km² during the period from 1960 to 2010. Compared with the data of 1960, 35.6% of glaciers have been retreating and the calculated average rate of glaciers retreating is 2.78 km² every year since 1960. The glacial retreating has been most significant if the glaciers have lower-elevation ablation areas and low-elevation accumulation areas. The temperature rising is the key factor of glacier retreating.

1. Introduction

Glacial fluctuation is considered to be the most reliable evidence of climatic change [1] and mountain glaciers are documented to be extremely sensitive to climate change [2, 3]. Furthermore, the runoff generated from glaciers is the major component of water resources sustaining the socioeconomic development and supporting ecological systems in world's arid and semiarid regions. The importance of glacier-melting water in contributing to water resources is imminent in northwest China where our study area (i.e., upper reach of the Heihe River Basin) is situated [4].

Recent studies have repeatedly reported an acceleration of glacier mass loss during the past half century in several key regions of China [4-6], such as the Tibetan Plateau, the Tianshan Mountains, and the Kunlun Mountains. The variation of glaciers is basically determined by the changes in temperature and in precipitation [7]. For example, a study on typical glaciers in High Asia indicated that the altitude of the equilibrium line (i.e., ELA) has fluctuated between 52 to 152 m in response to 1°C change in the summer mean temperature, and the line has fluctuated between 9 and 85 m in response to 100 mm change in the annual mean precipitation [8]. It is reported that rising of the air temperature has definitely resulted in significant losses in glacial mass balance and so often increasing precipitation was not able to reverse the losing trend of the mass balance [9].



Chinese Glacier Inventory shows that there are 2815 glaciers covering about 1930 km² in the entire Qilian Mountains and that the glaciers are the most important contributors to the runoff for all rivers in the Hexi Corridor region [10]. It should be particularly noted that glaciers can be monitored with considerably improved accuracies by combining difference data sources (e.g., aerial photographs and remote sensing images including Landsat TM/ETM, ASTER, SPOT) and by using the rapidly evolving technologies on information extraction from remotely-sensed data (e.g., supervised classification, and object-oriented classification). This study focused on monitoring glacier changes of the entire study area (i.e., the upper reach of the Heihe River Basin) with a fully-hearted acknowledgement of many previous studies on individual glaciers and on the glaciers in small watersheds [11-14].

The object of this study was to analyze the glacier changes and their responses to the climatic variations in the middle part of the Qilian Mountains. The glacial distribution data in 1960, as the baseline, were obtained by manually digitizing topographic maps that were based on 1957 aerophotogrammetric data. The glaciers distribution data for later years (i.e., 1990, 2000, 2010) were derived from Landsat TM images by object-oriented image interpretation method combined with expert knowledge rules.

2. Study area

The Qilian Mountains are situated in the northeastern margin of the Tibetan Plateau touching the Mongolia Plateau to the west and the Chinese Loess Plateau to the south. This study was conducted in the middle part of the Qilian Mountains (97.5°~101.6°E, 37.7°~39.7°N), the upper reach of Heihe River Basin (Fig. 1). The Heihe River is the second largest inland river in the arid area of northwest China with the main stream extending 821 km in length. The drainage covers an area of about 10 009 km² with an elevation ranging from 1 668 to 5 573 m and glaciers normally distribute above 4 000 m in the upper reach [15]. The annual mean precipitation is ~250 mm and the annual mean evaporation is ~1200 mm. According to the Glacier Inventory of China, 1078 glaciers were listed with a covering area of 420.55 km² and a storing ice volume of 13.67 km³ in the middle part of the Qilian Mountain.

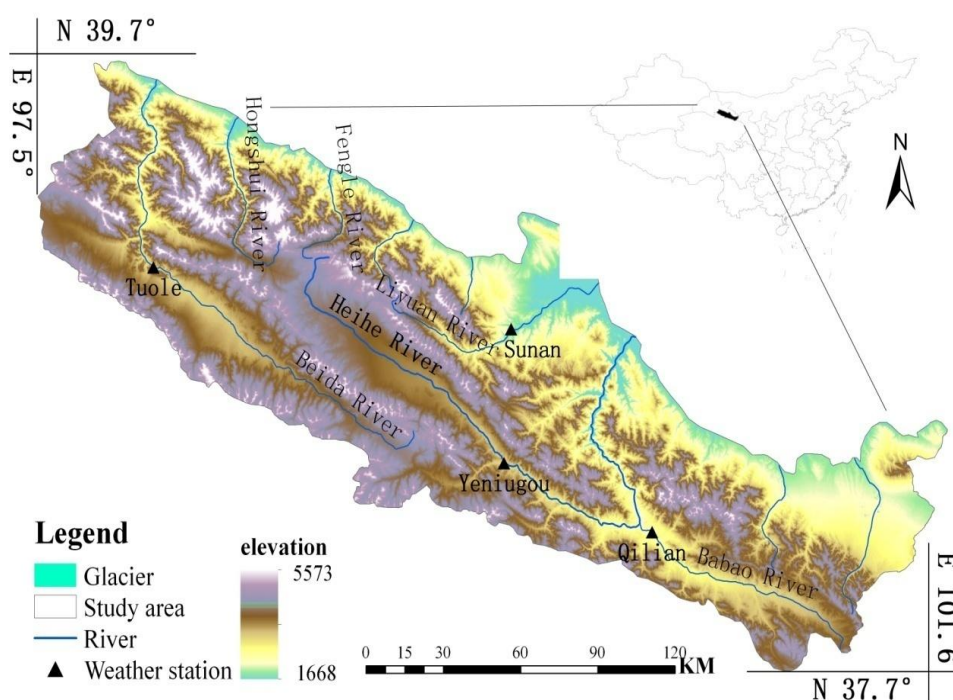


Figure 1. Location of the upper reach of Heihe River Basin

3. Data and methods

3.1. Data pre-processing

1:100 000-scale topographic maps based on 1957 aero-photogrammetric data, published by the Chinese military geodetic service, were used to extract glaciers distribution of 1960. The TM images acquired from July to August of 1990, 2000, and 2010 were used to extract glaciers distribution data of those three time intervals. The spatial resolution of these images is 30 meters. Other data used include: Chinese Glacier Inventory from Cold and Arid Regions Environmental and Engineering Research Institute (CAS), ASTER GDEM with 30 meters spatial resolution from the Ministry of Economy of Japan (METI) and also from the National Aeronautics and Space Administration of USA (NASA). The temperature and precipitation data from 1960 to 2010 at four meteorological stations (Namely: Qilian, Yeniugou, Tuole and Sunan) were obtained from Chinese Meteorological Administration (<http://www.cma.gov.cn/>).

First, we scanned topographic maps as digital maps, and then carried out geometrical rectification for digital maps in Xi'an 80 and Albers coordination system. Finally, the glaciers of 1960 were mapped manually by commercial GIS software (Arcmap) using the preprocessed topographic maps. All satellite images were geometrically corrected using the 1:100,000 topographical maps and projected into Xi'an 80 and Albers coordination system. In order to eliminate atmosphere effect, atmospheric radiation correction was made with the FLAASH model.

3.2. Glacier Outline Extraction

The glaciers of 1960 were mapped manually from topographic maps and solar illumination and slope shading effects were corrected by adopting known spectral-band ratios [16, 17]. Normalized Difference Snow/Ice Index (NDSI) has been applied widely in glacier extent extraction and the index is based on the fact that ice has high a reflectivity in visible spectrum (TM2 (0.52~0.60 μm), TM3 (0.63~0.69 μm), TM4 (0.76~0.90 μm)) and a low reflectivity in near-infrared spectrum (TM5 (1.55~1.7 μm)). NDSI can be determined using the following equation.

$$\text{NDSI} = (\text{Red} - \text{SWIR}) / (\text{Red} + \text{SWIR}) \text{ or } \text{NDSI} = (\text{TM3} - \text{TM5}) / (\text{TM3} + \text{TM5})$$

NDSI allows a spectral discrimination among snow, soil, rock, and cloud [18]. The index is efficient for snow mapping in rough topography [19]. NDSI can well delineate the boundary between the glacier terminus and the surrounding moraine and can also permits a fairly accurate inter-comparison between the bare-ice part and the glacier tongue part in different years [20].

Object-oriented classification has been used to extract glacial outlines. Image segmentation, the preliminary step in object-oriented classification, was adopted to divide the image into homogeneous and contiguous objects and the method (i.e., segmentation) was applied to such datasets as NDSI, TM spectral bands and DEM.

4. Results and discussion

4.1. Changes in glacier area

The total glacier area in the middle part of the Qilian Mountains was estimated for those four time intervals (i.e., 1960, 1990, 2000, 2010) and the estimated area was 389.63 km² (1960), 320.78 km² (1990), 267.40 km² (2000), and 250.73 km² (2010), respectively, accounting for 1.393%, 1.15%, 0.956%, 0.89% of the total area of the study area, respectively.

The glaciers in the upper reach of the Heihe River Basin experienced a significant reduction in area from 1960 to 2010 (Table 1). The area was reduced by 68.65 km² from 1960 to 1990, by 53.38 km² from 1990 to 2000, and by 16.67 km² from 1990 to 2000. The average yearly area reducing rate was 2.30 km², 5.34 km², and 1.67 km² during those three time intervals. The glacier area

shrinking percentage was $0.59\% \text{ a}^{-1}$ from 1960 to 1990, $0.78\% \text{ a}^{-1}$ from 1990 to 2000, and $0.71\% \text{ a}^{-1}$ from 2000 to 2010.

Table 1. The changes of glaciers area in the upper reach of the Heihe River Basin

	1960- 1990	1960- 2000	1960- 2010	1990- 2000	1990- 2010	2000- 2010
Retreat area /km ²	-68.85	-122.23	-138.90	-53.38	-70.05	-16.67
Retreat ratio/%	-17.67	-31.37	-35.65	-16.64	-21.84	-6.23
Retreat rate/ km ² a ⁻¹	-2.30	-3.06	-2.78	-5.34	-3.50	-1.67
Retreat rate / %a ⁻¹	-0.59	-0.78	-0.71	-1.66	-1.09	-0.62

Comparing with other glaciers in other parts of the Qilian Mountains, we found: (1) glaciers have been shrinking in all parts of the Qilian Mountains, and (2) the reduction rates vary in different region (Table 2). The largest reduction rate appears in the middle part of the Qilian Mountains where glacier area has declined by 35.6% in total during past 50 years. The second is Lenglongling, the eastern part of Qilian Mountains where the reduction rate of 28.97% from 1960s to 2000s [21]. The smallest reduction rate occurs in the western part of the Qilian Mountains (12.8%) [22]. Furthermore, it is notable that the glaciers reduction in the Qilian Mountains is faster than the glaciers in other mountains in the northwestern China. For example, the reduction rate is 13% in the Tianshan Mountains (1963-2000), and 0.4% in the West Kunlun Mountains (197-2001).

Table 2. Comparison of glaciers reduction rates among different parts of the Qilian Mountains

Region	Retreat area /%	Retreat rate /%a ⁻¹	Period /a	Data source	Method	bibliography
the eastern QLM	28.97	0.68	1960-2002	Topographic maps、ETM	visual interpretation	[21]
the Middle QLM	29.6	0.56	1950-2003	Topographic maps、ASTER	visual interpretation	[23]
the Western QLM	12.8	0.36	1970-2006	Topographic maps、ETM	visual interpretation	[22]
the eastern QLM	27.5	0.59	1956-2003	Topographic maps、ASTER	automatic interpretation	[12]
the Middle QLM	35.6	0.71	1960-2010	Topographic maps、TM	Object- oriented classification	This study

QLM: Qilian Mountains

4.2. Glacier variation along an altitudinal gradient.

The study on glacier variations along an altitudinal gradient was achieved by intersecting the present glaciers with the associated altitudinal belts. Several patterns were revealed. First, glaciers in the study area mainly distribute at elevations of 4200-5300 m and they account for 95% of the glaciers of the entire study area. The glacier area increases from an altitude of 4000 m upward with increasing altitude, But the area decreases with increasing altitude when the elevation is beyond 4700 m simply because of the reduction of mountain area where the glaciers develop. Second, the glaciers located in lower elevations are smaller and thinner than those in higher elevations and have more acute sensitivity to climate change. The glacier shrinkage mainly occurred at the elevations

ranging from 4000 to 4600 m in those three time intervals (i.e., 1960-1990, 1990-2000, 2000-2010). Third, the glaciers located above 4700 m have been stable without detectable reduction and the glacier area has even increased in some places, meaning that 4700 m is the highest limit of glacier retreat in the study area and highest limit is different from that in the Mt. Everest (6600 m) [24] and in the Keqikaer (4600 m) [25].

4.3. Typical glaciers in study area

The variations of two typical glaciers in the study area are shown in Figure 2, the left one is Huashugounao (HSG) glacier, the right one is Daogou (DG) glacier. The colors mark the glacier extents of different periods. Both are valley glaciers flowing in north-south striking with the glacier tongue lying in the north. The areas have been reduced by 319 690 m² and 1263162 m² in the past half a century, respectively. The glacial changes mainly occurred on the edges (e.g., two sides of valleys and glacier tongues) and the most significant changes occurred in the glacier tongues. For example, HSG glacier retreated by 140 m and 70 m from 1960 to 1990 and from 1990 to 2010, respectively; DG glacier retreated by 160 m, 170 m during 1960 to 1990, 1990 to 2010, respectively. It should be noted that the glacier shrinkage is not only expressed as ice retreat from the edges but also by glacier thinning and glacier fragmentation.

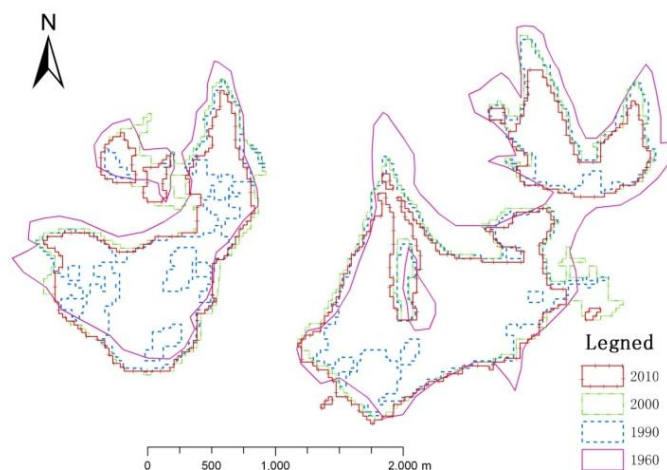


Figure 2. Change trends of the typical glaciers (the left is HSG glacier, the right is DG glacier)

4.4. Uncertainty analysis of glacier area changes

The factors affecting the accuracy of estimating glacier areas were listed as follows.

1. Glacial regions with debris covers are hard to identify either by visual interpretation or computer recognition. Field investigation should be undertaken to confirm the terminals of glaciers.
2. The accuracy for monitoring the positions of glacial tongues using satellite images is actually limited by sensor resolution. For example, a 30 m resolution for Landsat TM is certainly not high enough to accurately determine the positions of glacial tongues if glaciers are small [20].
3. The seasonal snow, which is very common form of precipitation at high elevations, may also blur the boundary of glacier area simply because snow and glacier have similar spectral features. The satellite images in our study were acquired in months of July and August when snow cover is normally at its minimum. But, the snowing immediately before the satellite passing time will certainly exaggerate the glacier area.

4.5. Glacier shrinkage related to local climate change

Figure 3 shows the trends in the annual mean temperature and the annual mean precipitation over the period from 1960 to 2005. The average increasing rate of temperature was 0.31 °C/10a. During the period from 1960 to 2005, the records at the four stations also displayed gradual increases in the

annual mean precipitation with the average increase rate of 10 mm/10a. The Increasing temperature leads to: (1) increasing energy available for ice and snow melting; (2) decreasing snow accumulation; and (3) lowering albedo of the glacier surface [26-28]. Normally, increasing precipitation enhances glacier accumulation. But increasing temperature shifted the total precipitation to liquid form and actually reduced solid precipitation in high-elevation glacial areas, leading to the reduction of accumulation and also to the acceleration of ablation.

We divide the twelve months into warm months and cold months using the monthly temperature of 0°C as the dividing line. The warm months are from April to September and the rests are the cold months. Our analysis indicated that the temperature in cold months increased significantly by about 2 °C in the past a half century (Fig. 3). The precipitation of warm months, accounting for 90% of the precipitation in a year, actually contributes nothing to snow accumulation. In other words, the increased precipitation is not able to make up the mass loss of glaciers resulted from the temperature rising. Our results are consistent with that of the Qiyi glacier within our study area [29]. To sum up, although the annual mean precipitation actually increased from 1960 to 2010, increasing summer temperature is the most significant factor for recent glacier shrinkage in the middle part of the Qilian Mountains.

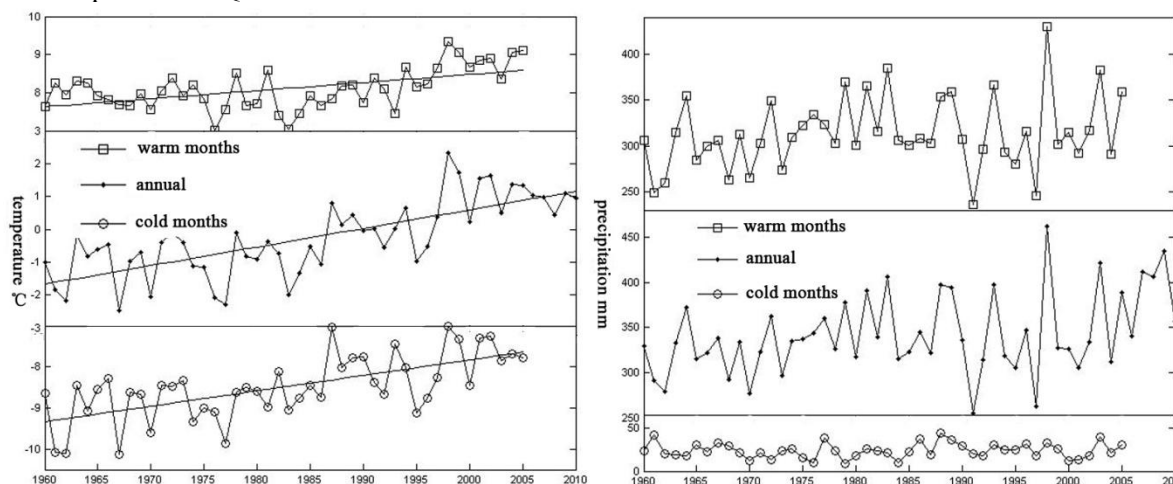


Figure 3. Changes of temperature and precipitation in the study area from 1960 to 2010

5. Conclusions

We have demonstrated that the technical methodology of glacier mapping using topographic maps and Landsat imagery is straight-forward and accurate. Manual obtaining glacial area data from topographic maps is a tedious work, which inevitably introduces human-induced uncertainties. The object-oriented classification on satellite images remedies the disadvantage to extract glacier area by using the texture and the context information of the images.

The glacier area in the middle part of the Qilian Mountains has been reduced as much as 35.6% from 1960 to 2010 primarily due to increasing warm months temperature with the interpolated annual glacier retreat rate of 0.59% a⁻¹. Our study also shows that the area reduction of glaciers in lower elevations was larger than that in higher elevations and the reduction rate of small glaciers was usually higher than that of large ones.

There are admittedly several uncertainties in our assessments. First, the methods used inevitably generate uncertainties. Second, seasonal snow covers may blur the boundary of glaciers resulting in uncertainties.

The glacier changes in the study area may strongly affect present and future water resources. To more accurately assess the contribution of glaciers to water resource availability, further in-depth investigations are needed.

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