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Five decades of glacier changes in the Hulugou Basin of central Qilian Mountains, Northwest China

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Abstract: The Heihe River Basin is the second largest inland river basin in the arid regions of Northwest China. Glaciers provide a large proportion of water resources for human production and living. Studies of glacier changes and their impact on water resources in the arid lands are of vital importance. A joint expedition was carried out in 2010 for investigating glaciers in the Hulugou Basin, which is located in the upper reaches of Heihe River. Therefore, glacier changes in the Hulugou Basin of central Qilian Mountains during the past 50 years were analyzed in this study by comparing topographic maps, satellite images, digital elevation models and field observation data from different periods. Results showed that the total area of the 6 glaciers in the Hulugou Basin decreased by 0.590±0.005 km^2 during the period 1956–2011, corresponding to a loss of 40.7% over the total area in 1956. The average area reduction rate of the 6 glaciers is 0.011 km^2/a. During the past five decades, the glacier shrinkage was accelerated. The changes in glacier ice surface elevation ranged from –15 to 3 m with an average thinning of 10±8 m or an annual decrease of 0.23±0.18 m (0.20±0.15 m/a water equivalent) for the period 1956–2000. The area of Shiyi Glacier in the Hulugou Basin decreased from 0.64 km^2 in 1956 to 0.53 km^2 in 2011 with a reduction rate of 17.2%. The Shiyi Glacier had been divided into two separated glaciers because of severe melting. Comparative analysis showed that glacier shrinkage in the Hulugou Basin is more serious than that in the other regions of Qilian Mountains.

Keywords: glacier change; ice surface elevation change; climate change; Shiyi Glacier; Hulugou Basin

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Mountain glaciers are not only sensitive climate indicators but also important water resources. Glacier melt water plays an important role in the inter-annual change of river runoff and is used to support the sustainable development of environment, industry and agriculture in the arid regions, especially in Northwest China. Water shortages and ecological problems are serious in the Qilian Mountains, and are the main bottlenecks restraining the local social and economic development. Glaciers account for a large proportion of water resources for agriculture in the irrigated oasis of Hexi Corridor (Investigation Team on Utilization of Snow and Ice Resources in Mountain Regions, Academia Sinica, 1958; Wang et al., 1981; Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences (CAS), 1992). Therefore, studying glacier changes in the Qilian Mountains and their impact on water resources in the arid regions is of vital importance.

Glacier melt water supply from the Heihe River Basin and Beidahe River Basin of central Qilian Mountains is prominent in the water resources of Hexi Corridor. The Heihe River Basin is the second largest inland river basin in the arid regions of Northwest China. Several glaciological and environmental expeditions to the Qilian Mountains have been organized by CAS from the late 1950s to the late 1970s. Glaciological research in China was initiated on Qiyi

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Glacier of central Qilian Mountains in 1958; subsequently, several large-scale investigations have been carried out (Lanzhou Institute of Glaciology and Geocryology, CAS, 1985; Sakai et al., 2006). Moreover, a few studies about glacier changes in the central Qilian Mountains were implemented (Pu et al., 2005; Yang et al., 2007; Song et al., 2008; Wang et al., 2011; Yan et al., 2012). In October 2010, a joint expedition was carried out to investigate glaciers in the Hulugou Basin in the upper reaches of Heihe River by Tianshan Glaciological Station, CAS and Qilian Alpine Ecology and Hydrology Research Station, CAS. In the Heihe River Basin, small glaciers are dominant and most of them are hanging glaciers or small cirque-valley glaciers (Wang et al., 1981). Shiyi Glacier, a combination of hanging glacier and valley glacier in the Hulugou Basin, was hence selected in this study as a reference glacier for the Heihe River Basin after the first survey on 1st October 2010.

In this study, we conducted detailed analyses of recent glacier changes including glacier area and ice surface elevation during the past 50 years in the Hulugou Basin of central Qilian Mountains by comparing topographic maps, satellite images, digital elevation models and field observation data from the different periods.

1 Study area

The Qilian Mountains (36°30'–39°30'N, 93°30'–103°00'E), located in the inland of Eurasia, are a marginal mountain system in the northeastern Tibetan Plateau. To the northern part of Qilian Mountains is the Hexi Corridor of Gansu province, and to the southern part are the Qaidam Basin and the Qinghai Lake of Qinghai province. According to the Glacier Inventory of China (Wang et al., 1981), 1,078 glaciers with a total area of 420.55 km^2 and a volume of 13.67 km^3 are located in the central Qilian Mountains (428 glaciers in the Heihe River Basin and 650 glaciers in the Beidahe River Basin), accounting for 37.7% and 21.3% of the total quantity (2,859) and area (1,972.50 km^2) of glaciers throughout Qilian Mountains, respectively.

The Hulugou Basin (38°12'–38°17'N, 99°50'–99°54'E; 2,960–4,820 m asl) is located in the upper reaches of Heihe River in the central Qilian Mountains (Fig. 1). The basin has a gourd shape with a total area of 22.5 km^2. There are 6 glaciers in the Hulugou Basin with a total area of 1.45 km^2, forming the sources of Heihe River (Wang et al., 1981). Shiyi Glacier is the largest glacier in the Hulugou Basin with the area of 0.53 km^2 in 2011. In the Hulugou Basin, the area with the elevation above 4,200 m is mostly covered by mountain glaciers and seasonal snow, accounting for 8.4% of the total basin area (Chen et al., 2013). The basin is situated in the transitional zone from the Tibetan Plateau to the arid region. The topography is complex and features a distinct vertical zonality from glacier to snow, frozen soil, alpine cold desert, alpine brush, mountain meadow and meadow from high to low elevations. The basin is remarkably influenced by the continental climate with large diurnal temperature variations. The precipitation is relatively plentiful with most occurring from July to September, and increases with elevations increasing (Chen et al., 2013). Glaciers and snow cover are important water sources and glacier melt water plays an especially vital role in the ecosystem.

2 Data and methods

2.1 Data and processing

In this study, we used topographic maps, satellite images, digital elevation models (DEMs) and field survey data in the different periods to determine glacier changes in the Hulugou Basin. The historical data selected was 1956 topographic map with the scale of 1:50,000 derived from aerial photograph. The systematic errors of the topographic map were <±11 m over slopes <15° and <±19 m over slopes >25° (State Bureau of Surveying and Mapping, 2007). The topographic map was firstly scanned with a resolution of 300 dpi and then rectified geometrically so that the error was less than one pixel.

The modern satellite images were an ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) image in September 2003 with the resolution of 15 m and a Landsat Enhanced Thematic

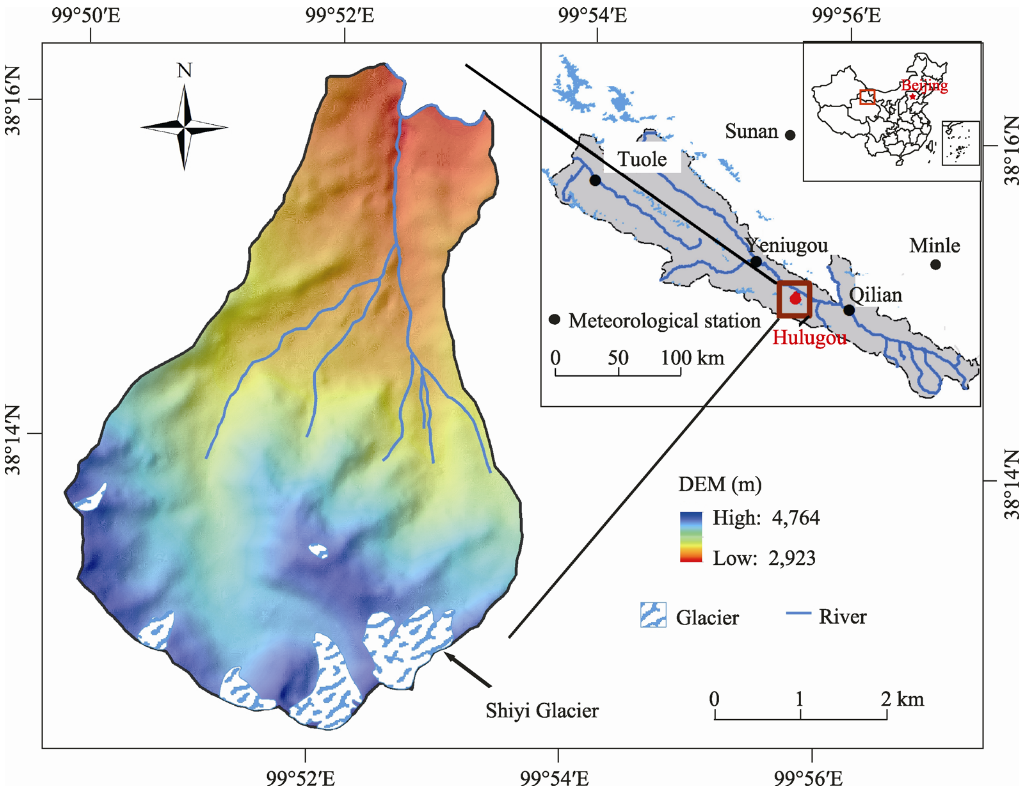

Fig. 1 Location of the study area and distribution of the glaciers

Mapper Plus (ETM+) in August 2011 with the panchromatic resolution of 15 m by the U.S. Geological Survey (USGS; http://www.usgs.gov). Although the null-data striping resulting from SLC failure (SLC-off) existed in Landsat ETM+ imagery, it was obtained in (nearly) cloud-free conditions during periods with minimal snow cover so as to reduce the potential uncertainty in glacier boundary delineation. The satellite image processing was conducted by the software ENVI. The images were orthorectified using methodologies described by Paul et al. (2004). Geocorrection and co-registration were then taken and clearly distinguishable terrain features were selected from topographic maps that could be identified on the satellite images. Twenty ground control points were collected with the root mean square error (RMSE) limited to less than one pixel in both the x and y directions.

Field-based measurement of the glacier terminus was conducted using real-time kinematic global positioning system (RTK-GPS; Unistrong E650) in October 2010. The survey error was 0.10–0.30 m for geodetic-quality GPS receivers (Rivera et al., 2005). The Shuttle Radar Topography Mission (SRTM) DEM in 2000 was in geographic coordinates with a 3 arc second (90 m) resolution (http://srtm.csi.cgiar. org). The absolute and relative 90% vertical accuracies were ±16 and ±6 m, respectively; whereas the horizontal accuracy was about ±20 m (Rodriguez et al., 2005; Strozzi et al., 2012). All data were presented in a Universal Transverse Mercator (UTM) coordinate system referenced to the 1984 World Geodetic System (WGS84).

2.2 Glacier change and accuracy analysis

Ice surface elevation changes of glaciers were obtained by comparing multi DEMs. The 1956 DEM (10 m×10 m) was produced by digitizing the 20 m contours and spot heights from topographic maps, interpolated and filtered with 10-m cell size. The differences between 1956 DEM and 2000 SRTM were then investigated. A total of 250 elevation points selected within the surrounding non-glaciated areas were used to estimate the error of ice surface elevation changes, and the result showed an error within ±8 m. Determination of glacier area changes mainly depended on the delineation of the glaciers from various data in the different periods. The glacier boundaries were mapped manually with the DEM using commercial GIS software (ArcGIS), as well as using topographic maps, satellite images and GPS survey data. Artificial interpretation is the best method for extracting higher-level glacier boundary information confirmed by the Global Land Ice Measurements from Space (GLIMS) (Raup et al., 2007).

The uncertainty of the mapped glacier outlines from satellite imagery is an important but difficult topic in glacier mapping. Numerous error terms need to be considered for a sound assessment of the uncertainty in the derived area changes. Most of these errors are from two parts. One includes the correct interpretation of glacier boundaries, and can be reduced through field verification and glaciological experience. The other includes the uncertainty related to the spatial resolutions of the satellite images and uncertainty due to the errors in imagery registration (Ye et al., 2006). Uncertainty in the measurements of glacier terminus and area can be estimated by Eq. 1.

$$U_S = \sum a^2 \times \frac{2(\sqrt{\sum a^2} + \sqrt{\sum b^2})}{\sqrt{\sum a^2}} + \sum b^2. \qquad (1)$$

Where, U_S is the uncertainty in glacier area for an individual glacier, a is the resolution of each image, and b is the registration error of each image to the topographic map. The resulting uncertainty in the glacier area is within 0.005 km^2.

3 Results and discussion

3.1 Changes of glacier area and ice surface elevation

Changes of glacier area and ice surface elevation in the Hulugou Basin are shown in Table 1 and Fig. 2. The total area of the 6 glaciers in the Hulugou Basin decreased by 0.590±0.005 km^2 from 1956 to 2011 (Table 1). This reduction accounted for 40.7% of the area in 1956. During the period of 1956 to 2011, the annual area reduction of the 6 glaciers was 0.011 km^2 with an decrease of 0.002 km^2/a for an individual glacier, showing a trend of accelerated melting. During 1956–2003, the total glacier area decreased by 0.260 km^2 from 1.450 to 1.190 km^2 with an annual reduction of 0.005 km^2. The decrease of annual area during the period 2003–2010 was 0.026 km^2, which was more than 5 times of that during 1956–2003. Especially, the total glacier area decreased by 0.150 km^2 in 2010–2011, which was almost 6 times of that during 2003–2010. Field survey found that one glacier in the basin disappeared. In addition, the smallest glacier studied in this study was not included in the Glacier Inventory of China. Comparison of DEMs in the different periods indicated that ice surface elevation changes of glaciers in the Hulugou Basin during 1956–2000 ranged from –15 to 3 m (Fig. 2). This corresponded to an average ice surface elevation decrease of 10±8 m or an annual decrease of 0.23±0.18 m, which equals to the water equivalent of 0.20±0.15 m/a, assuming a density value of 850±60 kg/m^3 (Huss, 2013).

Table 1 Changes of glaciers in the Hulugou Basin of central Qilian Mountains from 1956 to 2011

Glacier	Period	Area change	
		(km^2)	(km^2/a)
Hulugou Basin	1956–2003	0.260	0.005
	2003–2010	0.180	0.026
	2010–2011	0.150	0.150
	1956–2011	0.590	0.011
Shiyi Glacier	1956–2003	0.050	0.001
	2003–2010	0.050	0.007
	2010–2011	0.010	0.010
	1956–2011	0.110	0.002

The relationship between ice surface elevation changes and elevation at intervals of 50 m for Shiyi Glacier is shown in Fig. 3. The result indicated that the glacier ablation becomes more serious with the decrease of elevation, which is consistent with the result of Wang et al. (2012). The area of Shiyi Glacier reduced from 0.64 km^2 in 1956 to 0.53 km^2 in 2011, with a reduction rate of 17.2%. For the period 1956–2003, the Shiyi Glacier area reduced by 0.050 km^2 with an annual shrinkage of 0.001 km^2 (Table 1). By comparison, the 7-year area shrinkage during 2003–2010 (0.050 km^2; 0.007 km^2/a) was equal to that during the past 47 years from 1956 to 2003 (0.050 km^2; 0.001 km^2/a). The decrease of Shiyi Glacier area in 2010–2011 reached to 0.010 km^2.

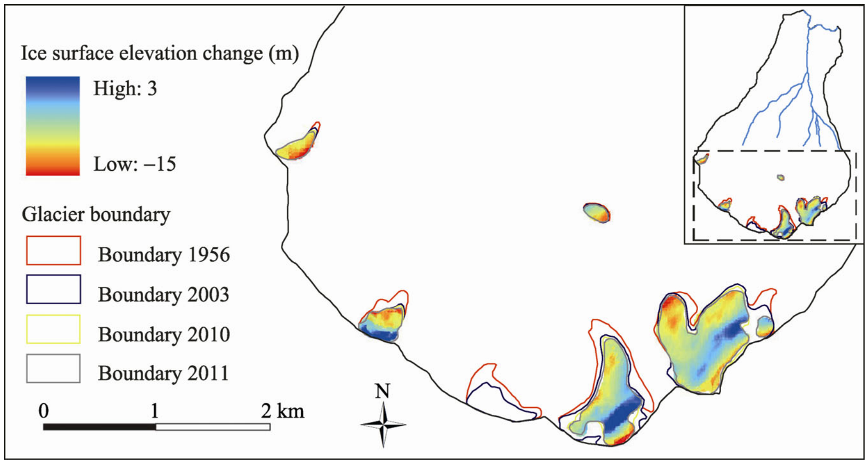

Fig. 2 Glacier changes from 1956 to 2011 and ice surface elevation changes from 1956 to 2000 in the Hulugou Basin of central Qilian Mountains. Ice surface elevation changes from 1956 to 2000 are determined by differencing DEM and SRTM.

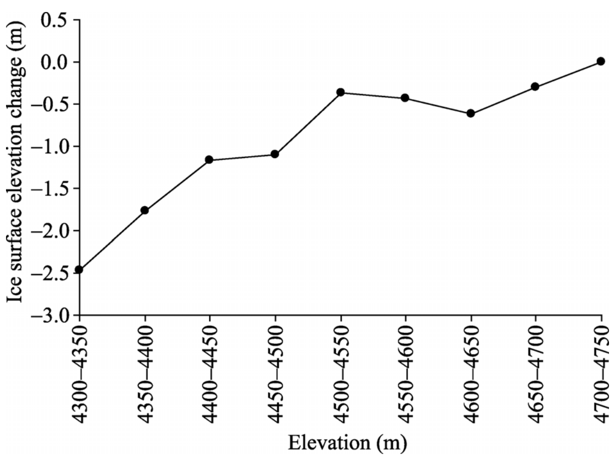

Fig. 3 Ice surface elevation changes of Shiyi Glacier from 4,300–4,750 m at intervals of 50 m

Currently, the Shiyi Glacier has been divided into two individual ones as a result of serious melting.

3.2 Comparison with other studies in the Qilian Mountains

The further comparison between glacier changes in the Hulugou Basin and other regions of Qilian Mountains (Liu et al., 2002; Yang et al., 2007; Wang et al., 2011; Pan et al., 2012; Yan et al., 2012) is shown in Table 2. By comparing aerial photographs, topographic maps and remote sensing images, Wang et al. (2011) found that glaciers in the Heihe River Basin have shrunk by 29.6% in area, equivalent to an annual shrinkage of 0.002 km^2 for an individual glacier. Glacier changes in the Hulugou Basin showed a consistent trend with those in the Heihe River Basin, further confirming the representativeness of this basin selected for intensive monitoring. Comparison with other regions of Qilian Mountains, glacier shrinkage in the Hulugou Basin was more serious. In the Heihe River Basin and Beidahe River Basin, small glaciers are dominant and most of them are hanging glaciers or small cirque-valley glaciers (Wang et al., 1981), which are quite sensitive to climate change (Jóhannesson et al., 1989; Granshaw, 2002). Furthermore, obvious regional differences in glacier changes existed among in the eastern, central and western parts of Qilian Mountains. Little difference was observed for the glacier changes in the central and eastern parts, and the changes were greater in these two parts than in the western part. Although the available studies on glacier changes in the western Qilian Mountains were primarily available form 1956–1990, a qualitative analysis was still possible, even if the rates of glacier change may have varied due to the recent temperature increasing.

Li et al. (2010) showed that Shuiguan River Glacier No. 4 in the eastern Qilian Mountains thinned by 15 m during the period 1972–2007 with an annual thinning speed of 0.42 m (0.38 m/a water equivalent). The area shrinkage of Shuiguan River NO. 4 Glacier for the same period was 0.04 km^2. For Ningchan River Glacier No. 3 in the Lenglongling Range, eastern Qilian Mountains, the terminus retreated by 2.58 m/a with area shrinkage of 0.10 km^2/a and the ice surface elevation decreased by 9.4 m with an annual decrease of 0.25 m during the past 37 years (1972–2009) (Liu et al., 2012). By comparison, the shrinkage of Shiyi

Table 2 Comparisons between glacier changes in the Hulugou Basin and other regions of Qilian Mountains

Region	Period	Number of glaciers	Area change (km^2)	Area change (%)	Reference
Hulugou Basin	1956–2011	6	–0.59	–40.70	This study
Western Qilian Mountains	1956–1990	1,731	–151.90	–10.30	Liu et al., 2002
Yeniugou River Basin	1956–2003	165	–16.22	–25.71	Yang et al., 2007
Heihe River Basin	1950s/1970s–2003	335	–32.41	–29.60	Wang et al., 2011
Lenglongling Mountains	1972–2007	179	–24.40	–28.30	Pan et al., 2012
Beidahe River Basin	1956–2003	372	–32.45	–15.42	Yan et al., 2012

Glacier in the Hulugou Basin was moderate compared to the selected glaciers in the eastern part of Qilian Mountains. Pu et al. (2005) found that the mass balance of Qiyi Glacier in the upper reaches of Heihe River Basin of central Qilian Mountains turned from positive in the 1970s to nearly zero in the 1980s, and then became largely negative in the recent years. The results further stated that glaciers in the Qilian Mountains have shrunk in the recent years.

3.3 Linkage between glacier variation and climate change

The temperature in the Qilian Mountains increased substantially during the mid- and late-1980s and climate warming has been accelerating since the 1990s (Jia et al., 2008), which is essentially consistent with the trends of temperature changes in the western China and showing obvious response to global warming (Jia et al., 2008). Under the background of climate change, all the glaciers in the Qilian Mountains show a considerable shrinking trend. However, regional differences existed due to the differences in regional climate change. Jia et al. (2008) investigated the regional differences of climate change in the Qilian Mountains using 50-year annual temperature and precipitation data from 8 meteorological stations. The results indicated that both the annual mean temperature and summer temperature increased remarkably in the eastern, central and western Qilian Mountains, with the rates of 0.30°C/10a, 0.33°C/10a and 0.27°C/10a for the annual mean temperature; respectively, and 0.27°C/10a, 0.27°C/10a and 0.23°C/10a for the summer temperature, respectively. The increases of annual mean temperature and summer temperature in the eastern part and especially in the central part are larger than those in the western part. The annual precipitation in the Qilian Mountains fluctuated over the minimum value in the 1960s. It increased to the maximum in the 1980s and decreased in the 1990s, and then increased after 2000. The change rates of annual precipitation were 10.0, 12.6 and 12.2 mm/10a for the eastern, central and western parts of Qilian Mountains, respectively (Jia et al., 2008). Changes in temperature can directly influence the glacier melting under the situation of precipitation fluctuation. The pronounced increase in temperature at central Qilian Mountains was a primary reason for the intensive glacier melting in this region. Providing that the increase trend of temperature continues, the snowlines of glaciers in the Hulugou Basin of central Qilian Mountains will increase and glacial melting will intensify, thus directly influence river runoff.

4 Conclusions and outlook

Glacier changes in the Hulugou Basin over the past 50 years were studied by comparing topographic maps, satellite images, digital elevation models and field observation data in the different periods. The total glacier area in the Hulugou Basin decreased by 0.590±0.005 km^2 from 1956 to 2011, which is equivalent to 40.7% of the total glacier area in 1956 and correspondent to an annual decrease of 0.011 km^2. Analyses also showed that the area shrinkage has accelerated during the past five decades. The average glacier thinning was 10±8 m with an annual decrease of 0.23±0.18 m, corresponding to an water equivalent of 0.20±0.15 m/a. The area of Shiyi Glacier reduced from 0.64 km^2 in 1956 to 0.53 km^2 in 2011, with a total reduction rate of 17.2%. Due to severe melting, the Shiyi Glacier has been divided into two individual glaciers. Comparative analysis showed that glacier shrinkage in the Hulugou Basin is more serious than that in the other regions of Qilian Mountains due to climate warming and glacial topographic factors. Glacier melting can directly influence river runoff. However, the impacts of glacier melt water on river runoff have large differences in the various basins. Therefore, the observation to Shiyi Glacier in the Hulugou Basin needs to be strengthened to obtain parameters for glacier dynamic and hydrological models and to make quantitative analysis in the future.

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