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Five decades of changes in the glaciers on the Friendship Peak in the Altai Mountains, China: Changes in area and ice surface elevation

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ABSTRACT

Mountain glaciers are indicators of climate change and of current water resources. They are important ecological systems and can be used to support sustainable development of industry and agriculture. However, due to climate warming, most glaciers are in a state of rapid retreat. Using topographic maps in 1959, ASTER remote sensing data in 2008 and ASTER digital elevation models (DEMs), area, ice surface elevation, and volume changes of glaciers on the Friendship Peak in the Chinese Altai Mountains were analyzed. Results showed that the collective area of all 201 glaciers investigated was reduced by 30.4% from 1959 to 2008. Fifty-five glaciers disappeared entirely. The average rates of reduction in area of glaciers with sizes <0.5, 0.5–1, 1–4, 4–10, and >10 km^2 were 25.9%, 30.8%, 30.9%, 35.9%, and 27.4%, respectively. From 1959 to 2008, the elevation of the glacier surface decreased by 20 m at an average rate of 0.4 m a^{-1}. For the Kanas Glacier, the changes in ice surface elevation ranged from −101 to +38 m. Results showed that glaciers at lower altitudes and smaller sizes experienced more extensive changes in elevation. The intensive glacier ablation over the Friendship Peak in the Altai Mountains was found to be caused by increases in the regional temperature, which occurred at an average rate of 0.52 °C per decade.

1. Introduction

The Altai Mountains, located on the border of China, Russia, and Mongolia, are the highest latitude glaciated region in China, and they provide important water resources for local residents and economic development. The region is affected by the westerlies and there is plentiful ice and snow during the winter. Glaciers and snow melt are the main sources of the Irtysh River (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982; Shi, 2008). This area is the only representative of the Siberian taiga ecosystem in China. At present, the government of the Xinjiang Uygur Autonomous Region has paid significant attention to forestry, wildlife protection, and development of tourism resources in the area. However, work related to glacier and snow monitoring and local hydrometeorology is still limited. Research into changes in the glaciers is urgently needed because the glaciers in the Chinese Altai Mountains are extremely sensitive to climate change due to their relatively small individual area (average of approximately 0.82 km^2; Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982). Conducting glacier change research in the Altai Mountains has considerable practical significance given the predicted effects of global climate change.

Research into changes in glaciers in China has mainly focused on the Tianshan Mountains, Kunlun Mountains, Qilian Mountains, and Hengduan Mountains. However, glacier research in the Chinese Altai Mountains has been sparse. The glacier inventory in the Altai Mountains was completed from 1978 to 1980 using aerial photographs and topographic maps (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982). In 1980, a field survey was conducted for the Kanas Glacier, the largest valley glacier in the Altai Mountains, which included glacier ablation, temperature, and glacier velocity. Results indicated that the maximum terminus retreat reached 424 m at an annual rate of 20 m a^{-1} from 1959 to 1980 (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982). Wang et al. (2011a) found that glaciers in the Altai Mountains were in a state of retreat from 1959 to 2000 based on topographic maps and Landsat ETM images. During this period, the glacier shrinkage in the Chinese Altai Mountains was more severe than that in the Russian

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part of the mountain range. In the Burjin River Basin, 100 glaciers disappeared entirely. The annual shrinkage rate was 29.94% by area, and the total area of the Kanas Glacier decreased by 4.21% with an annual rate of 0.0011 $km^2\ a^{-1}$. In order to study changes in the glaciers in the Chinese Altai Mountains in greater depth, an expedition was jointly organized by the Tianshan Glaciological Station, the Chinese Academy of Sciences, and the government of Xinjiang Uygur Autonomous Region. The survey quantified glaciological, ecological, and hydrological conditions on Friendship Peak of the Altai Mountains during August 2009. In 2011, Kanas Station (Altai Mountains) was established to monitor the glaciers, snow, and ecology of this region.

The elevation of the glacier surface was determined through repeated measurement by global positioning system (GPS) surveys (e.g. Jezek, 2012; Nuimura et al., 2012; Rivera et al., 2005; Wang et al., 2012, 2014). However, this method can be costly and labor intensive. Several studies have utilized satellite images and DEMs for calculation of changes in glacier area, elevation, and volume by comparison to earlier topographic maps and aerial photographs (e.g. Aizen et al., 2006; Herzfeld and Wallin, 2014; Larsen et al., 2007; Rignot et al., 2003; Sauber et al., 2005; Schiefer et al., 2007; Surazakov and Aizen, 2006; Vanlooy and Forster, 2011). Herein, multi-temporal remote-sensing images and digital elevation models were used to calculate glacier area, surface elevation, and spatial variability of a sample of 201 glaciers on the Friendship Peak of Altai Mountains. The interactions between climate change and glacier variation are discussed.

2. Study area

The Altai Mountains are a mountain range in East-Central Asia on the borders of Russia, China, Mongolia, and Kazakhstan. These mountains contain the headwaters from the Irtysh River and the Ob River. Friendship Peak (4374 m a.s.l.) is the highest peak in the Chinese Altai Mountains and the Friendship Peak Region (48.67°–49.17° N, 87°–88° E) is the highest latitude glaciated region in China. The Burqin River is a branch of the Irtysh River that is supplied by glaciers in the region. Glacier meltwater does not account for a large amount of river runoff; however, seasonal snowmelt accounts for 45–50% and is the main source of the rivers in this region (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982). The river runoff in the Altai Mountains is $12.611 \times 10^9\ m^3$ and accounts for 16% of the total river runoff in Xinjiang Uygur Autonomous Region. This is the second highest level in China after Yili Prefecture. The local climate is controlled by westerlies and polar air masses. In the Altai Mountains, the annual mean temperature is below 4.7 °C and the annual temperature range is relatively large. The annual precipitation is usually above 150 mm, which is more plentiful than the nearby Junggar Basin and precipitation is relatively evenly distributed across the year. Both the temperature and precipitation decrease gradually from west to east along the mountains (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982).

According to the Glacier Inventory of China, there are 416 glaciers in the Altai Mountains, with a collective area of 293.20 km^2 and an average individual area of 0.70 km^2 (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982). Glaciers on the Friendship Peak account for 72.6%, 84.4%, and 89.7% of the number, area, and total volume, respectively, of all the glaciers in the Altai Mountains. The average area of glaciers on this peak is 0.82 km^2 and the average glacier terminus is approximately 2600 m (Wang et al., 1983). The largest glacier in this area is the Kanas Glacier, which had an area of 30.13 km^2 and length of 10.8 km in 1959. It is a compound valley glacier with a northwest aspect. It is the glacier with the lowest terminus elevation in China, approximately 2416 m a.s.l. (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982). Kanas glacier tongue terminates on a very low altitude of around 2400 m a.s.l. in comparison with the other glacier terminus. It is even surrounded with a rich plant cover depending on certain environmental factors such as the availability of soil moisture, air temperature and light which are indicating a moderate summer climate (Fig. 1).

3. Data and methods

3.1. Data and processing

Topographic maps, satellite images, and digital elevation models (DEMs) from different periods were used to assess changes in the glaciers on the Friendship Peak in the Altai Mountains. The Glacier Inventory of China for the Altai Mountains was also included to investigate the glacier distribution (Lanzhou Institute of Glaciology and

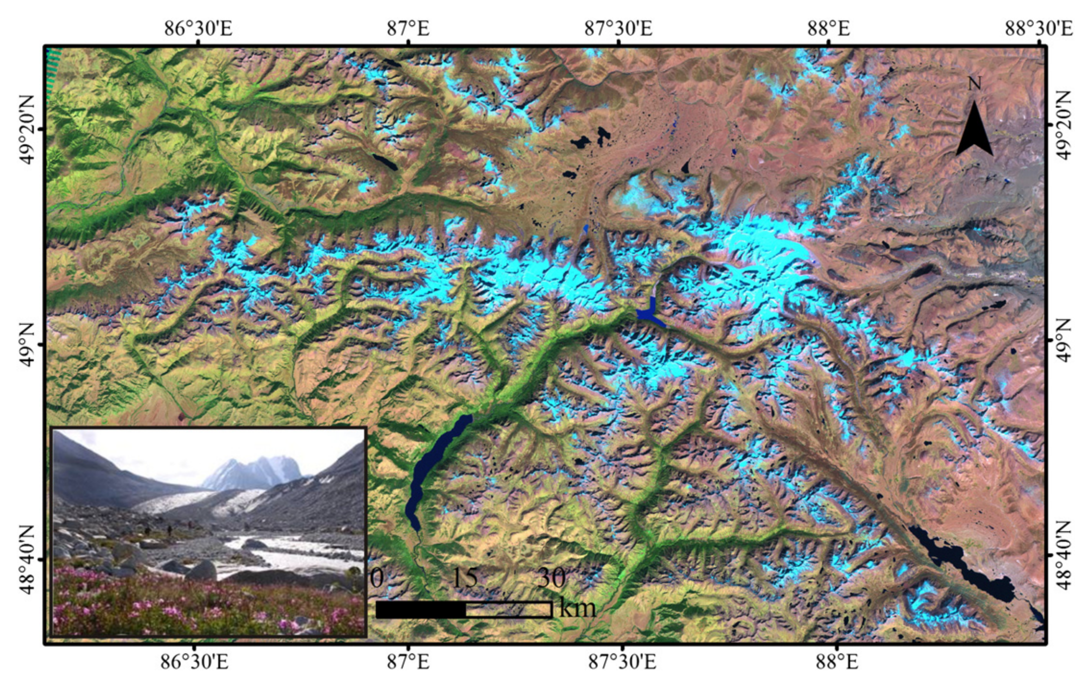

Fig. 1. Locations of glaciers on the Friendship Peak in the Altai Mountains. The photo in the lower-left corner was taken in 2009 by Zhongqin Li.

Geocryology, Chinese Academy of Sciences, 1982). Topographic maps with the scale of 1:50,000 (derived from aerial photographs) from the Chinese Military Geodetic Service. The systematic error of the topographic map was $< \pm 11$ m over slopes $< 15°$ and $< \pm 19$ m over slopes $> 25°$ (State Bureau of Surveying and Mapping, 2007). To establish a 1959 DEM, the topographic maps were firstly scanned at a resolution of 300 dpi and rectified geometrically so that the error was less than 1 pixel. The 20 m interval contours of the topographic maps from 1959 were then digitized and the contours were interpolated to a raster with a cell size of 5 m × 5 m. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) level 1B image was acquired on August 2008 with a resolution of 15 m. The satellite image processing was conducted using ENVI software and the images were orthorectified using methodologies described by Paul et al. (2004). Geocorrection and co-registration were then conducted. The co-registration used was feature-based registering the ASTER images to align with the topographic maps. Clearly distinguishable terrain features that could also be identified on the satellite images were selected from the topographic map. In total, 40 ground control points (GCPs) were collected with the root-mean square error (RMSE) < 1 pixel in both the x and y directions. These points were spread in the non-glaciated area over the scenes and then the satellite images and topographic maps were warped. The polynomial method and the resampling as nearest neighbor were adopted.

For generating the 2008 DEM, the VNIR nadir and backward images (3N and 3B) of ASTER level 1B data were used. Using the DEM Extraction Wizard module in the ENVI software, the images were matched automatically through a comparison of the respective gray values of the image which generates a DEM. In addition to the 40 GCPs, 49 tie points (TPs) were collected for obvious features at the different altitudes (e.g. peak, valley). The 2008 DEM was then generated at a 30 m resolution with the highest possible level of detail, and small holes were filled by automated interpolation.

The climate data were from the Habahe Meteorological Station (48° 03′ N, 86° 24′ E) which is the station nearest to the study area. The data was provided by the meteorological data sharing service system of China (http://cdc.cma.gov.cn). Linear analyses were performed to study the response of glacier changes to atmospheric warming.

3.2. Changes in glacier area and surface elevation

Assessments of changes in glacier area are dependent on the delineation of the glaciers. The glacier boundaries were mapped manually based on the topographic map, satellite images, and DEM using ArcGIS software. The manual interpretation method was used to obtain for the glacier boundaries. This method remains the best tool for extracting higher-level glacier boundary information from satellite images, especially for debris-covered glaciers (Paul et al., 2004). Here, 201 glaciers were identified. Changes in area were then assessed using coverage in 1959 and 2008.

Glacier elevation changes were obtained by the comparison of the 1959 DEM and the 2008 ASTER DEM. Changes in elevation were then used to determine changes in volume by multiplication by the entire glacier area (i.e., the 201 glaciers were considered one large glacier) and changes in mass were calculated by multiplying change in surface elevation and glacier density (850 ± 60 kg m^{-3}). Huss (2013) reported that assuming a value of 850 ± 60 kg m^{-3} to convert changes in volume to changes in mass is appropriate for a wide range of conditions.

3.3. Uncertainty analysis

Uncertainties of our derivation of glacier area come from the following respects. Firstly, satellite image selection is an important part. Although we intended to choose satellite images with high-resolution (e.g. SPOT-5), the period and quality requirement (e.g. cloud-free and minimal snow cover) limited the choices for the images. Therefore, ASTER image obtained in (nearly) cloud-free conditions during a period with minimal snow cover was used despite of its less desirable resolution. The uncertainty is related to the spatial resolution of the satellite image and uncertainties due to errors in imagery registration. These components can be evaluated by the formula (Ye et al., 2006):

$$U_A = 2\left(\sqrt{\sum \lambda^2} + \sqrt{\sum \lambda \varepsilon^2}\right)\sqrt{\sum \lambda^2} + \sqrt{\lambda \varepsilon^2}.$$

Here, U_A is the uncertainty in glacier area for an individual glacier, λ is the resolution of each image, and ε is the registration error of each image to the topographic map. The resulting uncertainty for the individual glacier area caused by the spatial resolution of the satellite image and imagery registration was < 0.0024 km^2 and the total uncertainty of glacier area was less than 0.3504 km^2.

The other part derives mainly from the uncertainty of glacier boundary delineation. Although it is difficult to estimate the delineation associated error, there are two ways to reduce potential uncertainty. One way is to perform field verification and a field survey has been carried out on Friendship Peak of the Altai Mountains in 2009. The other requires rich glaciological experiences, which an interpreter uses to determine the boundaries of the glacier. For example, experience is required to identify the placement of the boundary in accumulation zones (e.g. flow divides) or the ablation zones (e.g. where debris-covered glacier is adjacent to non-glacier morainal material). The interpreter of this region is glaciological experienced and has already joined in the expedition of Friendship Peak, Altai Mountains.

The sources of error for the DEM derived from the topographic map include the preexisting error in the topographic maps, manual digitizing error, coordinate conversation error, and interpolation error. The accuracy of this process was estimated by the method described by Binh and Thuy (2008). This method indicated the maximum error to be approximately 14.2 m. This meets the accuracy requirements of the 1:50,000 DEMs of the State Bureau of Surveying and Mapping (SBSM). For the ASTER DEM, the accuracy was estimated using the checkpoint method (Tan and Xu, 2014). Here, 60 corresponding points of elevation in both the ASTER DEM and the topographic map were compared. This analysis showed the maximum error to be 13.5 m for the ASTER DEM.

4. Results

4.1. Changes in glacier area from 1959 to 2008

Two hundred and one glaciers were identified on the Friendship Peak in the Altai Mountains. They had an average area of 1.06 km^2. The distribution of glacier coverage is presented in Table 1 and Fig. 2 according to five area classes (<0.5, 0.5–1, 1–4, 4–10 and >10 km^2). Approximately 57% of all glaciers (114 glaciers) were smaller than 0.5 km^2 in 1959 and these accounted for 10.1% of the total glacier area. Roughly 18% of the glaciers (36 glaciers) were 0.5–1 km^2 in 1959 and these accounted for 12.3% to the total glacier area. In addition, approximately 20% of the glaciers (41 glaciers) were 1–4 km^2, and these accounted for the most total area of any group, 34.8%. Only 10 glaciers

Table 1
Changes in number and area of glaciers in different sizes categories.

Glacier size (km^2)	1959		2008		Glacier changes		
	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Relative change in area (%)
<0.5	114	21.70	87	16.08	27	5.62	25.9
0.5–1	36	26.33	27	18.22	9	8.11	30.8
1–4	41	74.54	26	51.51	15	23.03	30.9
4–10	7	38.60	4	24.75	3	13.85	35.9
>10	3	52.87	2	38.38	1	14.49	27.4
Total	201	214.04	146	148.94	55	65.10	30.4

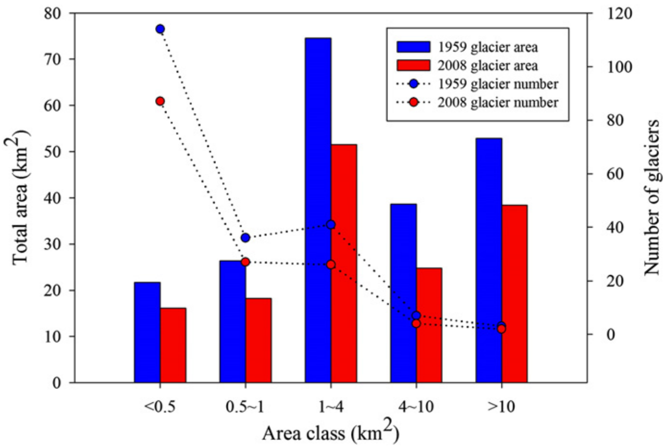

Fig. 2. Glacier area, number of glaciers, and decreases in both for glaciers on the Friendship Peak from 1959 to 2008.

were 4–10 km^2 and >10 km^2 in size. These two groups accounted for 42.7% of the total area, even though they only made up 5% of the total number of glaciers.

During the period from 1959 to 2008, the total glacier area decreased by 65.10 km^2 (30.4%) from 214.04 km^2 to 148.94 km^2 with an average reduction in area per glacier of 0.32 km^2. Fifty-five glaciers had disappeared completely by 1998 and nearly half of these were smaller than 0.5 km^2. The shrinkage rate varied for glaciers in different size classes. The largest relative change in area was for glaciers 4–10 km^2 which decreased by 35.9% from 38.60 km^2 to 24.75 km^2. The shrinkage rates for 0.5–1 km^2 (30.8%) and 1–4 km^2 (30.9%) glaciers were similar. The total area of glaciers <0.5 km^2 decreased by 5.62 km^2 (25.9%), while the total area of glaciers >10 km^2 decreased by 14.49 km^2 (27.4%) (Table 2).

4.2. Changes in glacier surface elevation from 1959 to 2008

As shown in Fig. 3, the glacier surface elevation decreased by 20 m on average at an average rate of 0.4 m a^{-1} from 1959 to 2008. The surface lowering was mostly existed in the glacier ablation area. There was also some decrease in glacier surface elevation in the steep ridges of the glacier accumulation area. It was probably caused by an avalanche. The maximum value of thinning at the glacier terminus was more than 100 m over the past five decades. Glaciers in this region display sensitive responses to atmospheric warming due to the low altitude of glacier terminus.

The first investigation of Kanas Glacier, the largest glacier near Friendship Peak, was carried out in 1980 (Wang et al., 1983). In August 2009, another field study was conducted. The firn in the accumulation area of the Kanas Glacier was found to have thinned significantly and the elevation of the snow line to have increased by at least 30 m since 1980. Several caves and a large hole formed at the lower part of the glacier, and with melt water flowed from both. Comparing with the previous topographic maps, the glacier area was here found to have decreased from 30.13 km^2 in 1959 to 28.80 km^2 in 2008 with an area loss of 4.4%. The terminus retreated at a rate of 16.4 m a^{-1}. As shown in Fig. 4, changes in the elevation of glacier surface ranged from −101 to 38 m. The level of ablation decreased as elevation increased. This pattern is likely related to the correlation between temperature and elevation. However, the glacier terminus is covered by thick debris that becomes thinner higher up on the glacier, and this can obscure the glacier's boundaries and introduce bias to the results. A 2009 field observation showed that the moraine on the outlet of glacier meltwater runoff had collapsed.

4.3. Changes in glacier surface elevation vs. changes in glacier elevation or size

The changes in ice surface elevation are roughly correlated with altitude for the 10 selected glaciers larger than 3 km^2 (Fig. 5). The changes in elevation were more pronounced at lower altitudes, a maximum decrease of more than 60 m. The changes in surface elevation at regions above 3400 m were small, within 0 to −40 m. However, the changes in ice surface elevation fluctuated at higher elevations. This is related to the error of the DEM as derived from ASTER. Generally, the ablation for glaciers at the lower elevations was greater than at high elevations. The higher the glacier terminus altitude is, the less intensive ablation is and more delayed the response to climate change is. Ablation was nonetheless intense for some glaciers at high elevations, due primarily to their small size. The relative changes of small glaciers were usually higher than those large ones (Narama et al., 2010) and Xu et al. (2011) suggests that the larger the glacier area, the slower the absorbed heat can be transferred into the ice center. This also supports the view that larger glaciers respond slowly to atmospheric warming (Kutuzov and Shahgedanova, 2009).

Fig. 6 shows changes in ice surface elevation by glacier size for the 201 investigated glaciers. Changes in ice surface elevation changes for 105 glaciers smaller than 1 km^2 were within the range of −20 to −10 m with an average value of −15.25 m. For 48 glaciers larger than 1 km^2 and smaller than 10 km^2, the changes in ice surface elevation ranged from −30 to −20 m with a mean value of −20.68 m. For the 3 glaciers larger than 10 km^2, the changes in ice surface elevation were relatively large with a mean value of −23.48 m.

5. Discussion

Climate change is one of the crucial factors driving changes in glaciers. Summer temperature and annual precipitation determine glacier

Table 2
Glacier reduction in the Altai Mountains and other parts of China.

Location	Period	Reduction in area km^2	Reduction in area %	Source
South slope of the Altai Mountains (China)	1959–2000	87.38	31.3	Wang et al. (2011a)
North slope of the Altai Mountains (Russia and Kazakhstan)	1952–1998	56.89	7.1	
Friendship Peak in the Altai Mountains (China)	1959–2008	65.1	30.4	This study
Tianshan Mountains	1960–2000	–	11.5	Wang et al. (2011b)
Middle Chinese Tianshan Mountains	1963–2000	7	13	Li et al. (2006)
Tibetan Plateau interior area	1970s–2009	766.7	9.5	Wei et al. (2014)
East Pamirs	1962/66–1999	66.02	7.9	Shangguan et al. (2006)
Tuanjiefeng Peak of the Qilian Mountains	1966–2010	16.1	9.9	Xu et al. (2013)
Geladandong	1969–2000	14.91	1.7	Yang et al. (2003)
China	1960s/1970s–2000s	2089	10.1	Zhang et al. (2011)

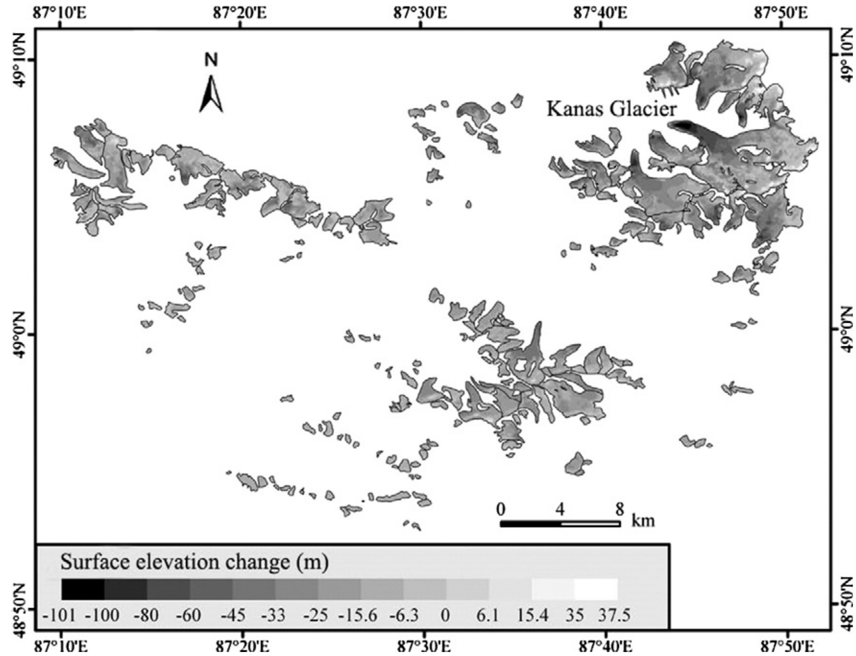

Fig. 3. Changes in the surface elevation of glaciers on the Friendship Peak from 1959 to 2008.

ablation and accumulation, respectively. The investigation found that the ablation period is from June to August and the accumulation period is from November to March. In order to analyze the influence of changes in temperature and precipitation on changes in glaciers, climatic data from the Habahe Meteorological Station was used in this study. The air temperature at the altitude of the glaciers was calculated using the lapse-rate of 0.65 °C/100 m according to the previous studies (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982). The annual mean temperature increased 2.65 °C at a rate of 0.52 °C per decade from 1958 to 2009. This is higher than the rate of 0.34 °C per decade in the Tianshan Mountains (Wang et al., 2011b) and 0.22 °C per decade average across China (Liu et al., 2009). The linear analyses indicated that the average temperature in both the ablation (0.33 °C per decade) and accumulation periods (0.67 °C per decade) underwent an increasing trend, particularly since the late 1980s. The increase of temperature in the ablation period was more obvious. The increase in the air temperature in the summer intensified the glacier ablation, and the increase in temperature during the accumulation period led to earlier and longer thawing periods. These combined effects eventually resulted in significant ablation (Fig. 7).

According to the previous studies (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1982), the precipitation gradient was 19–22 mm/100 m and the annual precipitation was more than 350 mm in the glaciated area in the Chinese Altai Mountains. Therefore, the precipitation in the glaciated area was calculated using the average value of 20.5 mm/100 m as precipitation gradient. The precipitation displayed an increasing tendency during 1959–2008 with a rate of 9.8 mm per decade. The increase in precipitation in this area has become more obvious since the late 20th century. The increasing tendency of temperature and precipitation is consistent with the results of Shi et al. (2003) showing that the climate in Xinjiang is changing from warm–dry to warm–wet. By analyzing the equilibrium line altitude

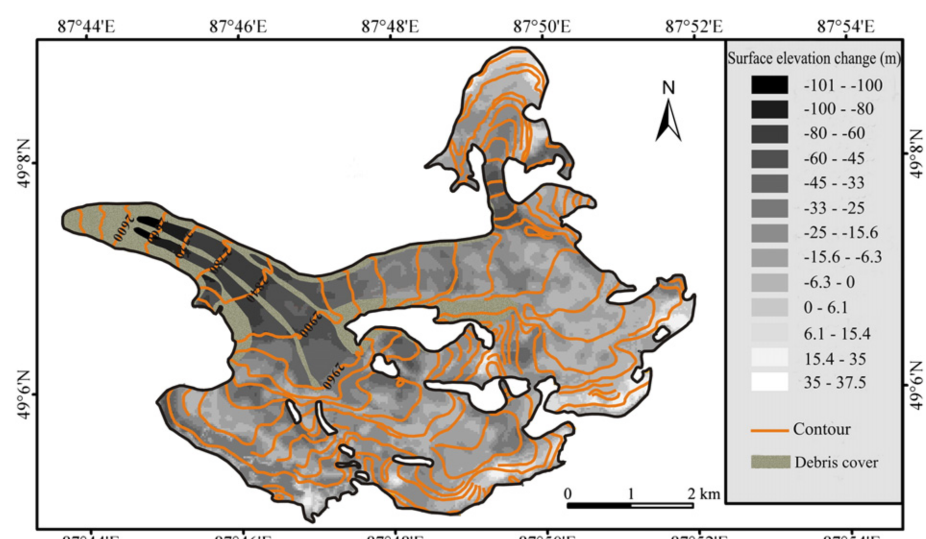

Fig. 4. Changes in the surface elevation of the Kanas Glacier from 1959 to 2008. The glacier boundary is based on topographic maps and Glacier Inventory of China from 1959. The contour interval is 60 m.

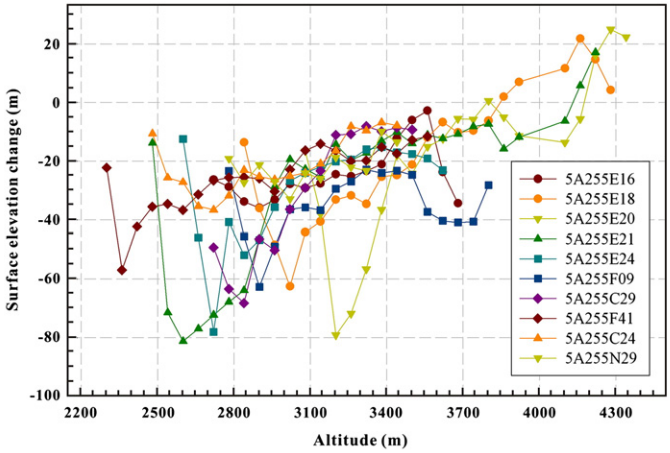

Fig. 5. Changes in ice surface elevation of ten glaciers larger than 3 km^2 at different elevations during the period from 1959 to 2008. All these glaciers were covered by debris.

(ELA) of twelve glaciers and the relation with summer temperature, Kang (1996) found that the altitude of the equilibrium will rise 100–160 m when the mean summer temperature increases by 1 °C. In order to keep the altitude of the equilibrium line remain unchanged, the precipitation increase needs to reach 40% or even doubled. Obviously, increased precipitation usually benefits ice accumulation. However, the increase cannot offset the accelerated glacier retreat. The intensive glacier retreat in the Altai Mountains is mainly resulted from a strong temperature effect (Fig. 8).

Changes in glacier area as assessed in this study (30.4%) were consistent with previous research. Wang et al. (2011a) reported that glaciers on the south slope of the Altai Mountains (in China) decreased in area by 31.3% during 1959–2000 while glaciers on the north slope (in Russia and Kazakhstan) decreased by 7.1% during 1952–1998. This discrepancy with the current study is likely due to the different climate warming rates from 1959 to 2000. Zhang et al. (2011) showed that glacier area in China decreased from 23,982 km^2 in the 1960s/1970s to 21,893 km^2 in the 2000s with an area-weighted shrinkage rate of 10.1%. Over the course of 37 years (1963–2000), the total glacier area in the middle of the Chinese Tianshan Mountains decreased by 13%, from 55 km^2 to 48 km^2 (Li et al., 2006). Continuous glacier retreat was observed in the interior of the Tibetan Plateau and glacier area decreased by 9.5%, or approximately 766.7 km^2 from the 1970s to 2009 (Wei et al., 2014). Glacier area has decreased significantly between 1962/66 and 1999, with a total area loss of 66.02 km^2 (7.9% of the original area in the 1960s) (Shangguan et al., 2006). Yang et al. (2003) found that glacier areas in the Geladandong decreased by 14.91 km^2 (1.7%) from 1969 to 2000. Xu et al. (2013) found that the total area of glaciers on Tuanjiefeng Peak of the Qilian Mountains decreased by 16.1 ± 6.34 km^2 (9.9 ± 3.9%) from 1966 to 2010. They also found that the average change in glacier thickness was −7.3 ± 1.5 m (−0.21 ± 0.04 m a^{-1}) from 1966 to 1999. Glaciers in the Altai Mountains and China are in the state of shrinkage and thinning due to global climate change. However, regional glacier changes have varied as a function of the regional climate conditions, elevation, and glacier-size distribution. Glacier shrinkage over the Friendship Peak in the Altai Mountains is more serious than the other regions. The average temperatures in both winter and summer over the Friendship Peak in the Altai Mountains showed an obvious increasing trend. Moreover, the rate of increase in summer temperatures is relatively large and glacier surface temperature has increased accordingly. Winter accumulation cannot compensate for the loss of mass caused by increasing temperature, and this has caused glacier ablation to accelerate. In addition, the altitude of the snow lines in this region is the lowest in China and the areas of the glaciers are relatively small (Li et al., 2010). These are additional reasons for the serious glacier changes in area and obvious glacier thinning.

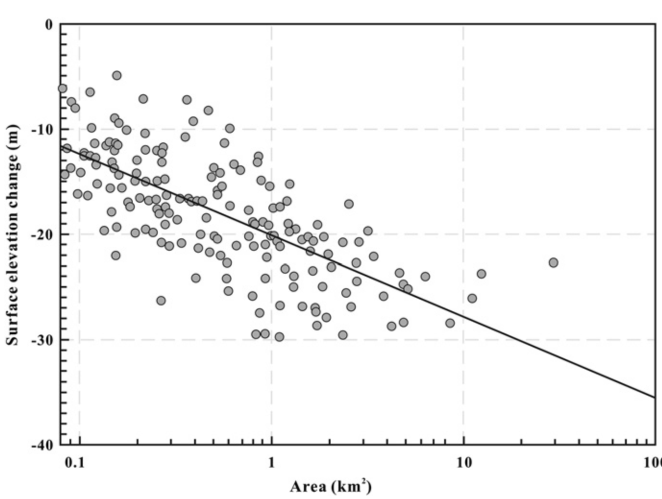

Fig. 6. Changes in ice surface elevation for glaciers with the different sizes from 1959 to 2008.

The impact of changes in glaciers on water resources and local ecology merits special attention. Although glacier meltwater does not account for a substantial proportion of total water resources, the runoff caused by glacier melting can increase over a relatively short period. The rapid retreat will increase the instability of rivers supplied by glacier meltwater. These rivers and especially their small and medium-sized branches will face the threat of running dry. Generally, river runoff increases as glaciers shrink and eventually peaks (i.e. reaches a turning point). Then the runoff decreases due to the loss of ice volume. If the current rate of glacier loss continues, future river runoff will be affected.

6. Conclusion and future research

Topographic maps, ASTER images, and ASTER DEM were used to study glacier area and changes in surface elevation of glaciers over Friendship Peak in the Altai Mountains. The area of the 201 glaciers investigated here decreased by 30.4% from 214.04 km^2 in 1959 to 148.94 km^2 in 2008. Fifty-five glaciers disappeared during the same period. Half of these were classified as small (<0.5 km^2) and their size made them more sensitive to climate warming. The average change in surface elevation for the glaciers on the Friendship Peak in the Altai Mountains was 20 m (0.4 m a^{-1}) from 1959 to 2008. The thinning in surface elevation took place mostly in the glacier ablation zone with some in the steep ridges of the glacier accumulation zone. For the Kanas Glacier, the changes in ice surface elevation ranged from −101 to 38 m and the area decreased in size by 4.4% from 1959 to 2008. Changes in glacier surface elevation were found to be related to both elevation and glacier size. The changes in elevation of small glaciers at lower altitudes were found to be more sensitive to climate change than that of either larger glaciers or glaciers at higher altitudes. The annual mean temperature increased by 2.65 °C at a rate of 0.52 °C per decade from 1959 to 2008. The rate was 0.33 °C per decade and 0.67 °C per decade for the ablation period and accumulation period, respectively. The meteorological data suggests that increasing temperatures in the region were responsible for the glacier shrinkage from 1959 to 2008. Glacier shrinkage on the Friendship Peak in the Altai Mountains is more serious than in other glaciated regions in China. The regional differences in glacier changes may have been affected by several different factors, such as regional climate conditions, glacier elevation, and glacier size.

The current analysis of the area and changes in surface elevation of glaciers over the Friendship Peak in the Altai Mountains was found to be limited by the estimation of accuracy. There is still a dearth of field survey data for this region, and more observation work is needed. This

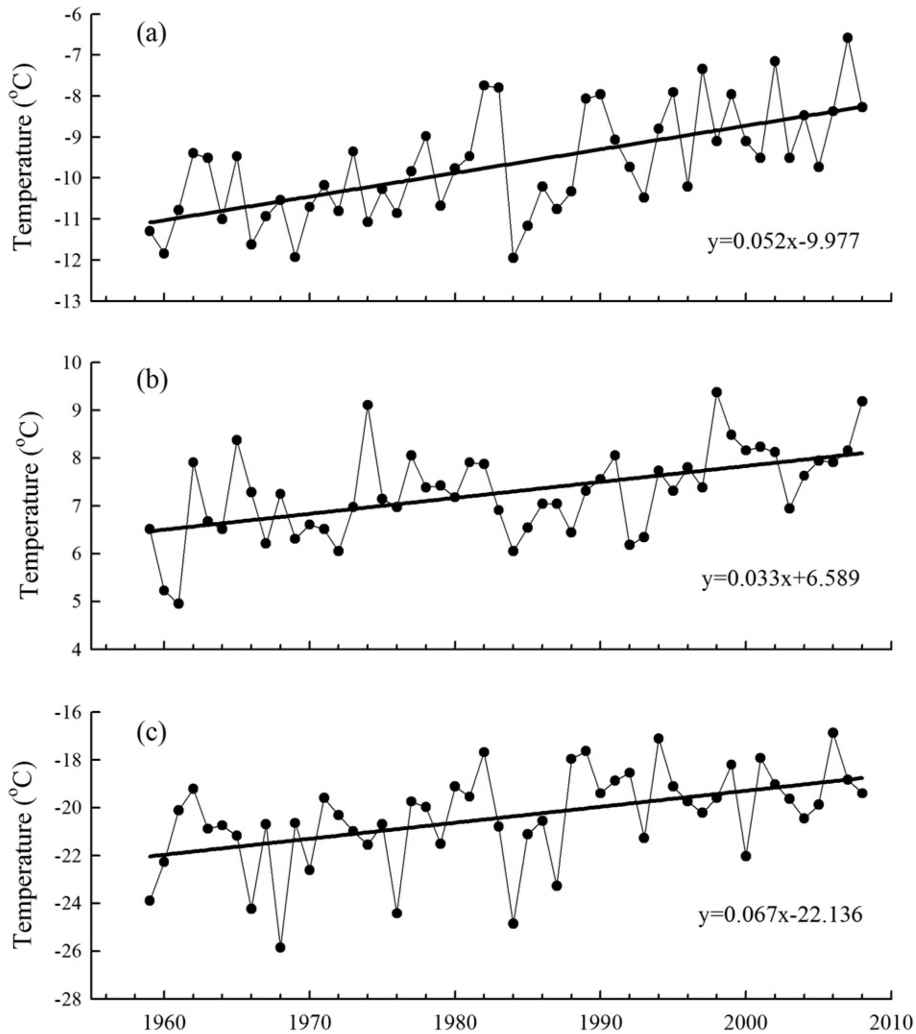

Fig. 7. (a) Annual mean temperature, (b) mean temperature during the ablation period, and (c) accumulation period at the altitude of the glaciers calculated from the Habahe Meteorological Station between 1959 and 2008 using the lapse-rate of 0.65 °C/100 m.

would include measurements of ice thickness measurement and GPS surveys. A monitoring system for glaciers of different sizes and types is needed and should be based on a combination of remote sensing and detailed field survey.

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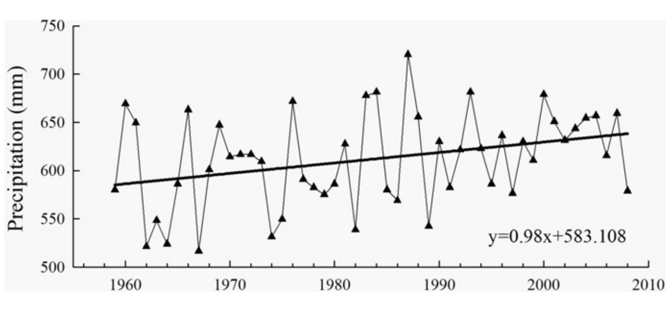

Fig. 8. Annual precipitation at the altitude of the glaciers calculated from the Habahe Meteorological Station from 1959 to 2008 using the precipitation gradient of 20.5 mm/100 m.

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