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Monitoring Glacial Shrinkage Using Remote Sensing and Site-Observation Method on Southern Slope of Kalik Mountain, Eastern Tian Shan, China

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ABSTRACT: Currently, one of the effective means in monitoring glacier change in regional scale is remote sensing and site-observation method. In this article, we present a study of comparing glacier area in 2005 derived from SPOT5 satellite image with area in 1972 derived from topographic maps. Moreover, Miaoergou (庙儿沟) flat-summit glacier is site observed to verify glacial change in regional scale. During the study period, glaciers located in the southern slope of Kalik (喀尔里克) Mountain reduced their area by 12.3%. The high individual change indicates that the wastage corresponding to area changes has been the dominant process of glacier mass loss in this region. Glaciers smaller than the mean size (1.3 km^2), especially those <0.5 km^2, lost more of their area with high variability and yielding two glaciers vanished. It is suggested that small glaciers are prone to disappear under such climate conditions in future years. With the difference supplied by upstream glaciers, there appears great disparity trend of river runoff recently. Seen from decade-scale, the discharge, the lower glacier-covered catchment, is decreased because of strong consumption of small glaciers during the past decades. Owing to the rivers that are supplied by more meltwater from medium and larger glaciers mainly, the trend of the river runoff increase is still going on. Trends of river runoff of three different glacier-covered catchments exhibit distinctive results. This implies that retreating glaciers will reduce the ability to regulate the water circulation.

KEY WORDS: glacier change, Kalik Mountain, remote sensing, runoff, water resource.

INTRODUCTION

Water, as the most widely scattered substance on our planet, plays a critical role in surrounding environment and in human survival (Shiklomanov, 1999). This is especially important to arid area of northwest-

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ern parts of China where precipitations are few and biased. Snow cover and ice on mountain region are the overriding water-stored bodies and form reliable freshwater supplies to consume for downstream populations who heavily rely on their meltwater. With increasing demands for water by the growing population, agriculture, and industry, the problem regarding the lack of water would influence the sustainable development of China. In most regions, the limited water provided by Alpine glaciers and rich precipitation in mountain regions are not permanent. Most of the earth's glacier mass had suffered an enhanced wastage over last two to three decades, which is mainly a result of climatic warming (Barry, 2006; Zemp et al., 2006; Oerlemans, 2005). The ablation is even occurring at high elevation sites (Kehrwald et al., 2008). Alpine glaciers are in retreat in almost all of the world's mountain regions (Howat et al., 2008; Zemp et al., 2006; Dyurgerov and Meier, 2000). Many of the smallest Alpine glaciers and those in marginal environments will be likely to disappear (Meier et al., 2003). The glacial runoff affected by its covering will reach the maximum and then decrease in the next two decades (Milner et al., 2009; Xie et al., 2006). Over the past half-century, the availability and quality of solid water have increasingly become a global concern, particularly in light of the growing demographic pressures and the projected climate change. This suggests that glaciers are constantly changing with time and it can profoundly affect the river runoff and hydrological cycle system of glacier-dominated regions. Hami is located in extremely arid region. As a result of shortage of water resources and small quantity of Alpine glaciers in this region, we need to know the high solid reservoir well by long-term monitoring and in-situ observation. Moreover, the mass balance of the glacier was measured, aimed to detect the ablation of this region.

There are 9 035 glaciers in the Chinese Tian Shan Mountains, with an area of 9 225 km^2 and a volume of 1 011 km^3 (Shi et al., 2008). Glacier variation has been noticed since the early comprehensive field survey on glaciers in 1958 (Ren, 1988) in China, but the long-term observation on glacier variation has been limited, except for those on Glacier No. 1 at the headwaters of Urumqi River (Li et al., 2003). With the development of geographic information system (GIS) and remote sensing (RS), many scientists have focused on regional glacier variation and climate change based on high-resolution remote sensing images (e.g., Li Z Q et al., 2010; Shangguan et al., 2009; Li B L et al., 2006), but these data are not sufficient to explain the asynchronous degradation of the glaciation in different parts of the mountains. In the Kalik Mountain (Mt. Kalik), glacier and snow-melt is especially an important source of water into the Yiwu River in northern slope and Miaoergou basin in southern slope. Its significant role is providing dry season runoff for major rivers. Knowing the past change and future evolution in glacial extent is important to this special location, because it influences the river runoff pattern and socioeconomic development of the basins on both sides. However, the glacial study is less documented, although it has played a prominent role in nourishing the oases and in improving environmental conditioning. One of the simple and efficient methods to monitor past evolution in glacial extent is with the aid of high-quality remote sensing imagery. In this article, an attempt has been made to calculate the glacier area change in regional scale during 1972 to 2005. Extensive field investigation and mass balance measurement on Miaoergou flat-summit glacier can provide us with the information of mass wastage and debris distribution, which can improve the quality of data from satellite imagery. Some research works have been conducted. Items of observation mainly include mass balance and sampling of chemistry as well as temperature distribution of glacier by drilling ice-core in 2005 (Liu et al., 2006). Results show that the glacial borehole temperature was around -7 ℃ at 10 m depth and -8.3 ℃ at 60 m of the bottom. The thickness changed about -5 m in an altitude of 4 295–4 375 m during 1981–2005, and the accumulation rate is about 200 $mm\cdot a^{-1}$ based on the records of ice-core (Li et al., 2007a).

STUDY AREA

Hami District, with an area of 15.3×10^4 km^2, or 9% of whole Xinjiang, is separated into two closed basins by eastern Tian Shan where distinct climate conditions are formed between the south and the north. The Kalik Mountains (42º50'N–43º35'N, 93º41'E–

95º07'E) are located at the eastern boundary of the Tian Shan Mountains of western China, and major glaciers in this region are distributed in the mountain. It has unique geographical features, being surrounded by the vast barren sand of the Gobe desert, where dust storms occurred more frequently (Wang et al., 2004; Qian et al., 2002). The geographical location of this mountain range is very important in terms of its atmospheric circulation. The area is on a boundary between two major sources of water vapor: monsoon vapor from the eastern Pacific or Indian Oceans and westerly vapor from the Arctic or Atlantic Oceans (Tian et al., 2007). The investigated region is also one of the places with greatest distance from oceans (~2 000 km to the Pacific or Indian Ocean and ~3 000 km to the Arctic Ocean) and the farthest distance of moisture sources from Atlantic Ocean (~7 000 km) in the world. The mountain range extends from northwest to southeast, and the highest peak is Tomort Peak with an altitude of 4 886 m a.s.l.. The investigated glaciers are in the southern slope of Mt. Kalik, which are located in the north of Hami City in the Xinjiang Uygur Autonomous Region of China (Fig. 1). According to Glacier Inventory of China (III) (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1986), there are totally 122 glaciers covering 125.89 km^2, distributed between southern slope and northern slope of the mountain. Hanging glaciers are more extensive in Mt. Kalik. Among the mountain glaciers, there are 73 glaciers distributed in southern slope, which function as water storage and water supply for the oasis existence with great importance.

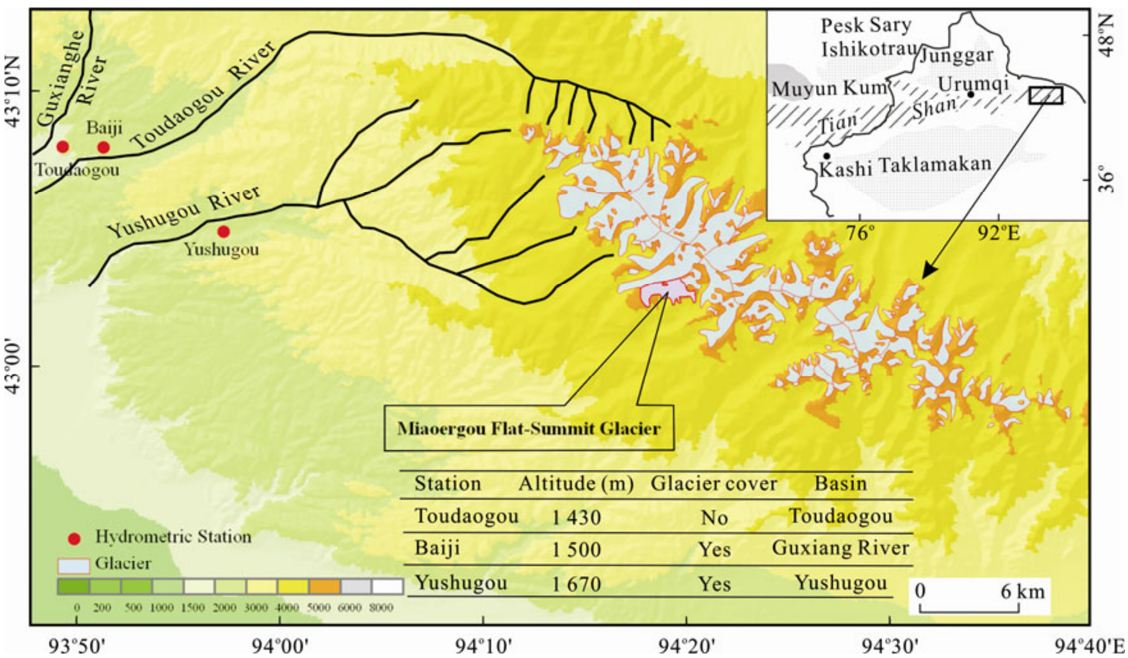

Figure 1. The location of investigated region.

The southern Hami City has an area of about 60% of the whole district with more than 70% of total population, while the northern region has a population of barely 30%. However, there are no large rivers, and rivers and streams are all seasonal flow depending on precipitation and melting water mostly originating from Mt. Kalik. Thus, the water supply is the particular case in the existence and development of oases. Due to climate warming and glacier wastage, the number of Karze decreased from 437 in 1950s to 292 in 1990. This region is particularly characterized by high temperature and evaporation, low precipitation in piedmont, which can reach above 200 mm above 2 000 m a.s.l. but only 25–40 mm on the plains. The mounts of evaporation in Hami City and Naomaohu Gobi attain 2 799.8 and 4 417.8 mm, which is 80 and 300 times of local precipitation, respectively (http://www.hami.gov.cn/).

DATA AND METHODS

Topographic Maps

The glacier outlines for 1972 were digitized manually on screen depending on topographic maps. As reference data set, the topographic maps from the 1 : 50 000 scale series were photogrammetrically compiled based on air photos taken in midsummer of 1972 and published by Bureau of Surveying and Mapping of People's Liberation Army. The topographic map includes glacier outlines and contour lines, and they were orthorectified in ArcGIS 8.0 software. The official map provided us with outlines and lengths of former glacier information, which is extracted under the geographic information system. Before the data arising from the digitized topographic maps are analyzed, the factors affecting glacier shape are considered (e.g., debris cover and snow) and glacier identified refers to the ID of (III) (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1986).

Satellite Imagery from SPOT5

The present glacier cover and boundaries were determined from Satellite Pour l'Observation de la Terre (SPOT5) images acquired on August 24, 2005. The SPOT High-Resolution Geometric (HRG) data offer a higher spatial resolution of 5 m in panchromatic mode. The carefully picked image is clear of clouds and exposes the glacier surface near the end of the ablation period when glacier outlines are most visible. Typical challenges connected to glaciers in cast shadow or debris cover (Raup et al., 2007; Bolch and Kamp, 2006; Paul, 2001) did not cause problems in our study. Shadowed areas were mostly found in the high-altitude accumulation areas but not on the low-lying glacier forelands. Moreover, there were only few glaciers partially debris-covered and the mapping of outlines on the glacier foreland was not affected by it. The raw SPOT image was orthorectified with ArcView software manual. The ground control points (GCPs) have been selected from the topographic maps and identified on the image, which were used for the orthorectification of the satellite scene and the validation of the digital elevation data. The DEM data come from SRTM with 15 m vertical precision and 90 m horizontal precision. The clear boundary and excellent image ensure the maximum accuracy of the glacier boundary determination.

The rectification of satellite image used orbital parameters method, which is developed by Toutin (1995). The inputs for the model were orbital parameters gathered from header files and image coordinates (pixel, line) corresponding to the coordinates (x, y, z) of investigated regions. The rectification process using PCI's OrthoEngine software was based on a co-linearity transformation model between the image and ground space. The rectified image was transformed and re-sampled to create epipolar geometry to ensure that image was offset only in the horizontal direction. Image matching was performed to match the corresponding pixel with the reference image. This involved moving a template window in the search area of the epipolar image until the best digital number match was obtained. All 24 GCPs were used in the rectification either as controls or checkpoints. The horizontal root-mean-square error ($RMSE_{x,y}$) with respect to 24 GCPs of the image was <0.5 pixel, or 2.5 m, which is considered appropriate as it is half of the SPOT5 image pixel size. Then, we extract glacier outline through manual work.

Observed Data

From 1972 to 2005, the annual temperature, precipitation, and runoff data about three hydrological stations, Toudaogou River, Guxiang River, and Yushugou River, were provided by the Hami Hydrological Bureau. Three stations are located around the southwestern side of Mt. Kalik. The investigated region provided us as a great good place to know well how Alpine glacial melting water affects the river runoff (Fig. 1). The potential runoff may be affected by the size and type of glacier, the season of precipitation occurrence, and the location on the glacier of initial precipitation deposition. Thus, the release of water from storage greatly affects the local hydrological cycle by means of contributing to streamflow in otherwise low flow periods. Toudaogou River is mainly dependent on precipitation and ground water with no glacial meltwater supplying upstream; Guxiang River is supplied only by some small glaciers, while the Yushugou is the river that is mainly supplied by glaciers. We evaluated the statistical significance of temperature, precipitation, and runoff trends and their relationships through the trend analysis. This would help us understand these effects on basin runoff with both theoretical and practical importance.

RESULTS

Area Change during 1972 to 2005

The SPOT5 satellite images in 2005 yielded 48 glaciers in southern slope of Mt. Kalik with an area of 58.1 km^2. Compared with the past states, 50 glaciers covering 66.3 km^2 existed in 1972. In all, two small glaciers disappeared in investigated region with all size smaller than 0.1 km^2. The SPOT-derived glaciers range from 0.038 to 6.19 km^2, with a mean size of 1.163 km^2. There is a clear trend that a large quantity of glaciers smaller than the mean size of 1.33 km^2 have a high relative area change, ranging from -100% to 14.3% (glaciers in the left side of vertical line in Fig. 2). All glaciers reduced their areas by 12.3%. As shown in Fig. 2, glaciers larger than 1.33 km^2 (glaciers in the right side of vertical line) lost their areas nearly in this mean value, or centered on the dashed horizontal line, 12.3%. It is suggested that glaciers larger than this mean value essentially decide the level of area loss of Miaoergou basin.

Figure 3 shows an incommensurability of glacier area distribution according to the size class. The strongly increasing column is moving towards the class of 2–5 km^2 with a heavy area loss or that of 3.768 km^2, which is 46% of total area loss during 1972 to 2005. Glaciers smaller than 0.1 km^2 reduce their areas by 0.187 km^2, only contributing to 2% of the total loss in this period. This implies that the larger glaciers are still the major contributors to the river runoff despite their limited number and lower relative area changes. Small glacier systems, ranging from minor advance to complete disappearance, have rapid response time to climate perturbations, and these systems exhibit instability with highly individual area changes. The wastage corresponding area changes have been the dominant process of glacier mass loss in the entire region under the similar climate conditions. Having already entered an ablation-dominated mode, it might seem hard for glacier advancement. Thus, the confusion associated with the stable or advancing glacier may be understood in terms of ice dynamics such as glacier surging or mistakes made by topographic maps. To larger glacier systems, as their dynamical response time can be many decades (Bahr et al., 1998), the ices in colder regions with higher altitude are less sensitive to climate change.

Glacier recession in regional scale is affected by local climatic conditions (e.g., Narama et al., 2010). However, glacier distribution (Brenning and Trombotto, 2006; Evans, 2006), as well as area change of individual glacier (Li et al., 2011; Debeer and Sharp, 2009), is influenced by their local topographic settings and climatic conditions in regional scales. Small glaciers located in lower altitude lost more of their area or even completely disappeared. This is partly caused

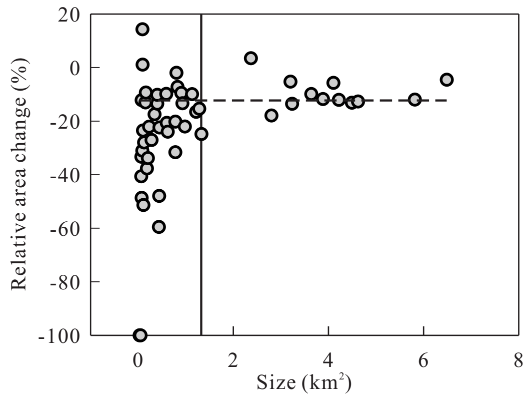

Figure 2. Scatter plot showing a clear trend that glaciers smaller than the mean value (1.33 km^2) lost more of their area with high variability. The horizontal short line represents the mean area change, and the vertical solid line represents the mean size of investigated glaciers.

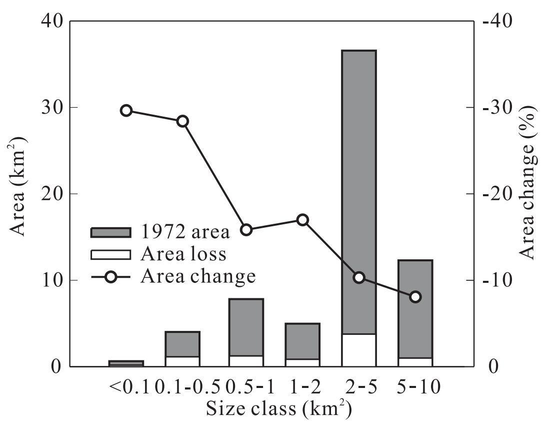

Figure 3. Area distribution of 50 glaciers according to their size class (in km^2: <0.1, 0.1–0.5, 0.5–1, 1–2, 2–5, and 5–10).

by their surrounding topography as well as their locations. For example, glaciers <0.1 km^2 locate in a lower elevation, which are all below 4 600 m a.s.l. with mean slope of 32.4º (Table 1). Glacier in such height will expose most of their ice into ablation area or accumulating little in winter. These conditions with low winter accumulation and high summer ablation overlap, producing conditions favorable for negative annual mass balance and the start of glacial strong retreat. The case that leads to the mass input cannot compensate the ice deficit because of the rise of air temperature but thus results in an accelerating wastage. Moreover, the mean slope of glacier tends to decrease with the growth in size in this region, while the mean elevation is increased significantly with the increase in dimension. Glaciers larger than 2 km^2 account for 76% of the whole glacier area in 2005 but only 24% in total number. It is suggested that these glaciers with favorable conditions in avoiding strong present retreat are likely to be the subject of the extensive melting water and the main contributor to river runoff in the future.

Table 1 The basic information of investigated glaciers

Class (km^2)	Number	Total area (km^2)	Mean elevation (m a.s.l.)	Maximum elevation (m a.s.l.)	Mean slope (º)	Mean length (m)
<0.1	9	0.631	4 344	4 600	32.4	456
0.1–0.5	15	4.015	4 322	4 680	28.9	770
0.5–1	10	7.821	4 379	4 528	24.0	1 370
1–2	4	4.968	4 537	4 602	23.4	1 519
2–5	10	36.566	4 643	4 880	13.7	3 880
5–10	2	12.302	4 814	4 888	11.7	5 717
Total	50	66.303	4 438	4 888	24.4	1 713

Table 2 Summary of glacier area change in sub-basins

Sub-basins	Area (km^2)		Average area (km^2)	Area change (%) (1972–2005)	Area change (%) (1972–2002)*
	1972	2005			
5Y822A	13.82	11.89	1.15	-14.0	-7.5
5Y822B	22.97	20.28	2.55	-11.7	-6.1
5Y822C	18.54	16.43	2.65	-11.4	-6.4
5Y822D	10.98	9.54	0.50	-13.1	-3.7
Total	66.30	58.14	1.33	-12.3	-6.0

*Data of the column from Wang et al. (2009), which use the ASTER and Landsat ETM+ imagery.

The glacier length and shrinking are in agreement with their area. The length of the glaciers varied between 316 and 6 554 m with a mean of 1 713 m (Table 1). The mean length was reduced by 7.3% from 1972 (1 713 m) to 2005 (1 589 m). The largest relative reduction that occurred in the interval <0.1 km^2 decreased from the mean length of 456 to 342 m and reduced by 25%. However, the largest absolute reduction happened to be the interval 5 to 10 km^2, which is shortened by 368 m (or -6.4%), from the mean value of 5 717 to 5 349 m. The relative number of glacier length shorter than the mean (1 713 m) is 74%, with dimension smaller than 1.33 km^2. Only seven glaciers had a length exceeding 4.0 km.

Based on Glacier Inventory of China (III) (Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1987), there were 73 glaciers distributed on the southern slope of Mt. Kalik in 1972. In this study, 50 glaciers are scattered on four sub-basins, representing 68% of the total number or about 87% of the total covering. The relative area loss is in connection to their mean size, such as glacier area in the sub-basins 5Y822B and 5Y822C, reduced by 11.7% and 11.4% from 1972 to 2005, respectively (Table 2). Although the differences between this study and the investigation conducted by Wang et al. (2009) may be caused by different time scale, different resolutions of different satellite images (Paul et al., 2002a, b), and different operators, the trends of glacier shrinkage are obvious during the past three decades.

Observed Changes

The Miaoergou flat-summit glacier (5Y822C3) is the only observed one in Miaoergou basin with an altitude of snowline about 4 100 m. The area (3.64 km^2) was reduced by 9.9% and the length (2.4 km) was shortened by 77 m during 1972 to 2005.

The direct action of climate variability on glacier dynamics is observable through annual net mass balance, which results from the difference between accumulation and ablation (Paterson, 1994). Fluctuations in the annual net mass balance lead to variations in the glacier profile, which modify the ice flow pattern inside the glacier and even modify the glacier length and the position of the glacier terminus. Ablation of the glacier strengthened during past two decades. The surface mass balance that was obtained during the period of 2005 to 2009 can provide us with more detailed information to know the ice wastage in this region. Here, the comparison with Urumqi River Glacier No. 1 (UG1), a typical valley glacier with long-term observation data and exhaustive research (e.g., Li et al., 2007b; Ye et al., 2005), can help us understand the melting process further. Although the field data are limited, the comparison between UG1 and Miaoergou flat-summit glacier put up marked differences as well. The strong negative mass balance was shown in ablation zone of UG1, and the whole glacier expressed higher gradient in an altitude of 3 700–4 200 m. The annual mass balance even attained to 3 m w.e. in terminus. However, the mass loss of Miaoergou flat-summit glacier was slightly decreased with the altitude increasing from 4 200 to 4 500 m. Moreover, there was no strong melting process in terminus as UG1, partly because the flat-summit glacier is located in the higher place and less sensitive to climate warming.

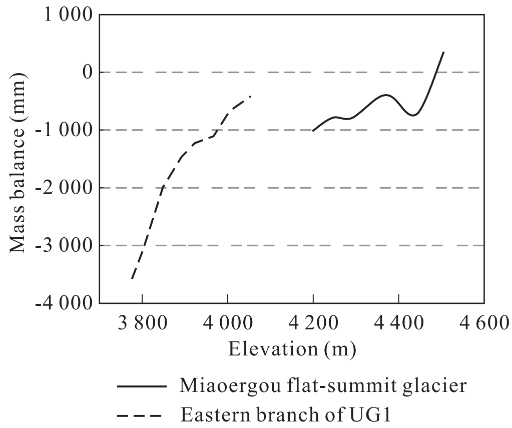

Figure 4. Comparison between the mass balance profile of Urumqi Glacier No. 1 (UG1) and that of Miaoergou flat-summit glacier (C3).

DISCUSSION

Force to Glacier Melting

The glacier retreat was firstly influenced by climate-related factors in regional scale, such as the temperature rise and the change of precipitation allocation between summer and winter. The climate in northwest China has been changed to warmth and wetness since 1980s (Shi et al., 2007); the precipitation and air temperature have increased continuously during the recent decades in Mt. Kalik as well (Wang et al., 2009; Li et al., 2007a). The rising temperature will increase the equilibrium line altitude (ELA) and expose more ice into ablation area. A sensitivity study shows that a change in regional climatic steady-state equilibrium line altitude of ±100 m is caused by a temperature change of ±1 ℃ or a precipitation decrease of 20% and increase of 27% in the European Alps (Zemp et al., 2007). However, the relationship between glaciers and the climate is complex, and the mass balance sensitivity to the temperature or precipitation changes varies with the seasonal timing of change (Oerlemans and Reichert, 2000). An increase in winter temperature that does not bring the surface temperature above the melting point of ice might still affect partitioning of rain and snow in the atmosphere and alter the winter balance. Conversely, precipitation increase would have a negative effect on glacier mass balance if they occur only during summer in the form of rain. Generally, changes in summer temperature appear to drive the increased rates of mass loss of glaciers (e.g., Ye et al., 2005), while the increase of the winter temperature and its contribution to glacier melt should be considered (e.g., Bolch, 2007; Beniston, 2006). Although winter warming would cause an increase in the winter freezing levels height and have little or no effect on the glacier mass balance (Arendt et al., 2009), the increased temperature could reduce the cold reserve of glaciers and thus increase the sensitivity of the glacier to air temperature rise (Li et al., 2007b).

Impact on Water Resources

Alpine glaciers can modulate the river runoff and keep hydrological cycle balanced. The common sense is that glaciers are considered that they can delay the runoff by preventing precipitation from running off directly. Such storage occurs in summer with snow accumulation and melted on the glacier, and it seems moderate when encountered with heavy rains. Thus, the water is stored as snow and ice in glaciers and is melted depending on climate (e.g., Fountain and Tangborn, 1985; Østrem, 1973). For glacier-free basins, such as Toudaogou Hydrological Station, the annual variability of runoff is great. However, for the glacier-covered basin, such as Baiji and Yushugou, although the retreat of glaciers has caused variability of runoff, the effect is relatively small (Fig. 5). Seen from the decade-scale, for the lower glacier-covered catchment, such as Baiji, the discharge is decreased because of the strong consumption of small glaciers during the past decades. For the catchment of Yushugou, the runoff tends to increase owing to the existence of the larger glaciers. However, the increase of runoff is subject to the constraints. The enhanced glacier melting will produce increased river runoff and then start to decrease after reaching a critical glacier size (Hock et al., 2005). Glacier cover is likely to govern the year-to-year variability of runoff and the variability is the lowest at moderate percentage of glacier cover (about 40%) and increases as the glacier cover both decreases and increases (Chen and Ohmura, 1990; Braithwaite and Olesen, 1988; Fountain and Tangborn, 1985).

The main difference between glaciered and glacier-free catchments is that runoff from glacier-free is dominated by precipitation, whereas glaciered basins are energy dominated (Chen and Ohmura, 1990). It highlights the importance of glaciers since they produce most water during hot and dry periods when the precipitation is lacked. Figure 6 gives us an illustration that temperature is rising at the studied region (Fig. 6a) and the precipitation in Toudaogou is slightly increased (Fig. 6b), while the other is nearly kept to hold the line (Figs. 6c and 6d). This may partly explain why the runoff of Toudaogou expresses the increase with high variability. Increasing air temperature appears to account for recent glacier shrinkage; thus, the strong mass loss leads to increasing the interannual variability of river runoff. The discrete events such as the sudden release of water may cause a rise in the level of glacier lake outburst flood (GLOF) (Shen et al., 2006). In the coming decades, a continuous increase in glacial runoff can reasonably be expected in response to warming, especially in spring and early summer (Liu et al., 2009; Barnett et al., 2005).

CONCLUSION

In this article, we report local glacier changes on southern slope of Miaoergou basin in easternmost of Tian Shan. The investigated glaciers witnessed climate warming during the past four decades and

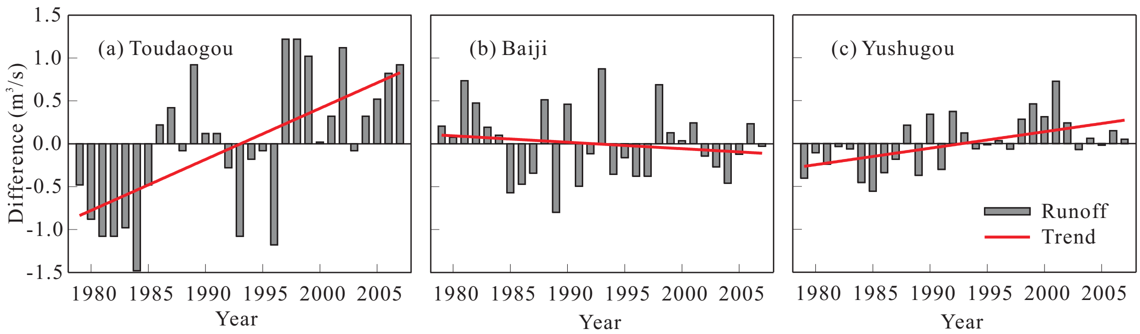

Figure 5. Time series of runoff deviation from the average during 1979 to 2007 of Toudaogou, Baiji, and Yushugou hydrological stations.

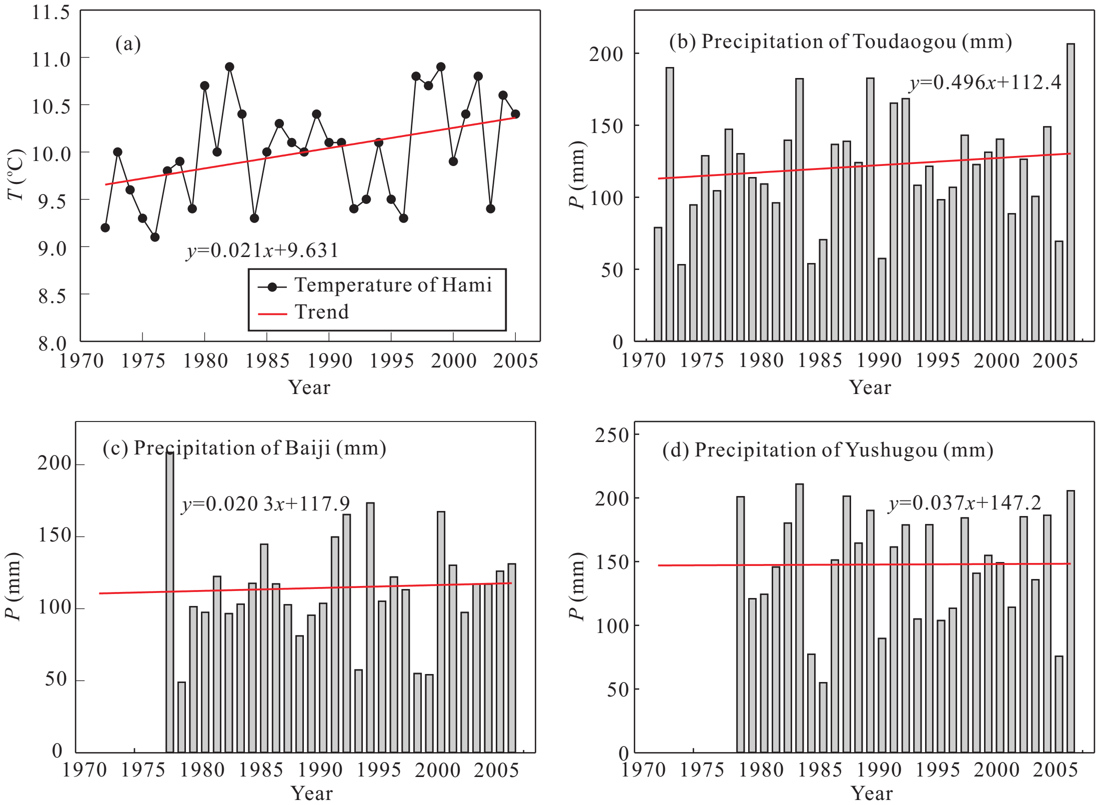

Figure 6. Time series of temperature of Hami and precipitation of Toudaogou, Baiji, and Yushugou hydrological stations during the period 1979 to 2007.

reduced their area by 8.17 km^2 or relative change by -12.3%. Moreover, two glaciers vanished completely during the periods of 1972 to 2005. A large quantity of glaciers smaller than the mean size (1.33 km^2) lost more of their areas in combination with high variability. The larger glaciers reduced their areas gently but mainly contributed to river runoff. We also extend our investigation beyond the size. Topographic factors of elevation and slope correspond to glacial erosion. Such patterns are more pronounced in places where glacial extents were fewer. It is suggested that small glaciers are efficiently influenced by their topographic settings.

The area of Miaoergou flat-summit glacier is reduced by 9.9%, the length (2.4 km) shortened by 77 m, -2.3 m/a, and it is markedly thinning during 1972 to 2005. The mass loss of Miaoergou flat-summit glacier was slightly decreased with altitude increasing from 4 200 to 4 500 m. Moreover, there was no strong melting process in terminus as UG1, partly because the flat-summit glacier is located in the higher place and less sensitive to climate warming.

The basin of Miaoergou is a glacier-dependent region where the melting water is indispensable for local economic development and ecological system. Glaciers in the upper stream of river play an important role in collecting solid water in winter and releasing itself in the form of water. Even a low fraction of glacier covered within a basin has tremendous impact on hydrology (Jansson et al., 2003). The marked influence is the decreased runoff when glacier tends to become smaller or be vanished. In those regions where larger glaciers (>1.33 km^2) are distributed, the runoff may be met with the increased runoff in the future with present climate warming.

With the different supplies of upstream glaciers, there appears a great disparity trend of river runoff recently. For glacier-free basins, such as Toudaogou hydrological station, the annual variability of runoff is great. While for the glacier-covered basin, such as Baiji and Yushugou, although the retreat of glaciers causes the variability of runoff, the effect is relatively small. Seen from decade-scale, the lower glacier-covered catchment, such as Baiji, the discharge is decreased because of the strong consumption of small glaciers during the past decades. For the catchment of

Yushugou, the runoff tends to increase owing to the existence of larger glaciers.

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