Quaternary International 358 (2015) 146–152

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Recent changes of two selected glaciers in Hami Prefecture of eastern Xinjiang and their impact on water resources

Puyu Wang [a,*], Zhongqin Li [a,b], Ping Zhou [a], Wenbin Wang [a], Shuang Jin [a], Huilin Li [a], Feiteng Wang [a], Hongbing Yao [b], Hui Zhang [b], Lin Wang [a]

[a] State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute/Tianshan Glaciological Station, Chinese Academy of Sciences, Donggang West Road 320#, Lanzhou, 730000, China
[b] College of Geography and Environmental Science, Northwest Normal University, Lanzhou, China

ARTICLE INFO

Article history:
Available online 8 July 2014

Keywords:
Glacier change
Water resources
Yushugou Glacier No.6
Miaoergou Ice Cap
Hami Prefecture of eastern Xinjiang

ABSTRACT

It is important to understand and quantify glacier changes and their impact on water resources in Hami Prefecture, an extremely arid region in the eastern Xinjiang of northwestern China. Yushugou Glacier No. 6 and Miaoergou Ice Cap in Hami Prefecture were selected in this study. Results showed that the thickness of Yushugou Glacier No. 6 decreased by 20 m with a rate of 0.51 m y^{-1} from 1972 to 2011 and the terminus retreated by 254 m, or 6.5 m y^{-1} for the same period. The thickness along the main axis of Miaoergou Ice Cap decreased 0–20 m during 1981–2007 and the terminus retreat rate was less than 3.0 m y^{-1} in 2013. The melting rate of Miaoergou Ice Cap was smaller than Yushugou Glacier No. 6, which was directly related to the differences of glacier type and elevation. The impact of glacier changes on water resources would be different in the various drainage basins of Hami Prefecture, depending on the proportion of glacier coverage.

1. Introduction

Glaciers are considered as important source of water augmenting the flow of streams and rivers, and have significant implications for sea-level change. Due to climate warming, observations have identified a general thinning and retreat of glaciers globally (e.g. Li et al., 2006; Bolch, 2007; Vanlooy and Forster, 2008; Kutuzov and Shahgedanova, 2009; Bolch et al., 2012; Wang et al., 2011b; Wang et al., 2014a, 2014b, 2014c). The glacier runoff derived from changes of glaciers is an important source of fresh water to support the sustained development of the ecological environment, industry, and agriculture of downstream counties in arid regions (Fountain and Tangborn, 1985; Braithwaite and Olesen, 1988; Aizen et al., 1995, 1996; Kaser et al., 2010; Immerzeel et al., 2010, 2012; Jacob et al., 2012; Sorg et al., 2012). Glacier changes including area, length, thickness and volume in the Tianshan Mountains and several other regions are known in detail from aerial photographs, topographic maps, remote sensing images, and in-situ observation data (Aizen et al., 2007; Haeberli et al., 2007; Paul et al., 2007; Surzakov et al., 2007; Bolch et al., 2010; Narama et al., 2010; Li et al., 2010; Wang et al., 2011a, 2013, 2014).

Located in eastern Xinjiang of northwestern China, Hami Prefecture is an extremely arid region, and glacier runoff is the main contributor to water resources. A total of 179 glaciers were distributed in Hami Prefecture with combined area of 155.9 km^2 and ice volume of about 8.0 km^3 (LIGG, 1986). Investigations were carried out in the Miaoergou Drainage Basin of Hami Prefecture by Lanzhou Institute of Glaciology and Geocryology (LIGG), Chinese Academy of Sciences (now Cold and Arid Region Environmental and Engineering Research Institute, Chinese Academy of Sciences) in the 1970s, and the thickness of Miaoergou Ice Cap was measured in August 1981. In September 2004, Tianshan Glaciological Station, Chinese Academy of Sciences organized a field survey and selected Miaoergou Ice Cap to be a long-term monitored glacier. Tianshan Glaciological Station and Hami Hydrographical Bureau jointly organized field observations of another typical glacier, Yushugou Glacier No. 6, in 2011 to further strengthen the glacier monitoring and assess the impact on water resources of Hami Prefecture. Gao and Luo (2009) found that the temperature of Hami Prefecture increased since 1957, particularly after 1986. Under climate

* Corresponding author.
E-mail address: wangpuyu@lzb.ac.cn (P. Wang).

http://dx.doi.org/10.1016/j.quaint.2014.05.028
1040-6182/

warming, intensive ablation of glaciers were observed in recent decades (Li et al., 2007, 2010, 2011; Wang et al., 2008; Wang et al., 2011c). However, few of these studies were based on field survey data and focused on the impact on water resources. It is therefore of paramount importance to understand and quantify the glacier changes in Hami Prefecture and their impact on water resources.

The first aim of this study is thus to present recent changes of Yushugou Glacier No. 6 and Miaoergou Ice Cap. Secondly, the impact of glacier changes on water resources under the background of climate warming is discussed. Study can not only accumulate observation data for the study of glacier changes, but also make possible analysis of the relationship between changes in glacier properties and runoff variability.

2. Study area

In the Hami Prefecture (40°53′-45°06'N, 91°07′-96°23'E), the main mountain range is the eastern section of the Tianshan Mountains, including the Harlik and Barkol Ranges from east to west. The Harlik Range contains a total of 122 glaciers with an area of 125.9 km^2, covering nine drainage basins, including Yushugou and Miaoergou. A total of 57 glaciers with a combined area of 30.0 km^2 are distributed in the Barkol Range, discharging to the Turpan-Hami Basin and Junggar Basin on the northern and southern slopes (LIGG, 1986). Hami Prefecture is particularly characterized by high temperature and evaporation. The precipitation is low in the piedmont, with more than 200 mm above 2000 m a.s.l. and about 25–40 mm on the plains. The amounts of evaporation in Hami City and Naomaohu Gobi reach 2800 and 4418 mm, 80 and 300 times local precipitation, respectively (http://www.hami.gov.cn/; Wang et al., 2011c).

The area of Yushugou Drainage Basin is 308 km^2. Nine glaciers with a total area of about 22.85 km^2 and ice volume of 1.59 km^3 are distributed in this basin, accounting for 14.7% of glacier area and 20% of ice volume, the drainage basin with the largest glacier area and volume in Hami Prefecture (LIGG, 1986; Luo et al., 2002; Gao and Luo, 2009; Ma and Luo, 2009). Located in the upstream of Yushugou Drainage Basin, Yushugou Glacier No. 6 (43°05'N, 94°19'E) is a valley glacier facing towards the west, covering an area of 4.06 km^2 and ranging from 4744 m to 3610 m a.s.l. (LIGG, 1986, Fig. 1). Miaoergou Drainage Basin with an area of 372 km^2 is to the east of the Yushugou Drainage Basin. Seven glaciers with a total area of 18.43 km^2 and ice volume of 1.27 km^3 are distributed in this drainage. According to the Glacier Inventory of China (LIGG, 1986), Miaoergou Ice Cap (43°03'N, 94°19'E) covers an area of 3.45 km^2 with a total length of 2.4 km. It ranges from 4512 to 3840 m a.s.l. with southwest aspect (Fig. 1).

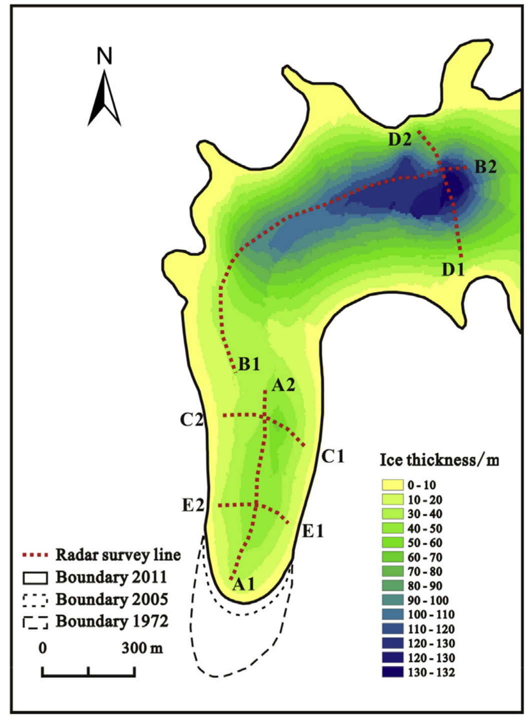

Fig. 2. Radar survey lines on the tongue of Yushugou Glacier No. 6, the ice thickness distribution and the glacier terminus changes. The radar survey lines are indicated by the dotted lines. Various line styles represent glacier terminus in the different periods.

3. Data and methods

Topographic maps, remote sensing images, GPS survey and ice thickness data used for Yushugou Glacier No. 6 and Miaoergou Ice Cap in this study are shown in Table 1. For Yushugou Glacier No. 6, the ice thickness was measured by An SSI (Sensor Software Inc., Canada) Pulse EKKO-PRO Ground Penetrating Radar (GPR). Five profiles, including two longitudinal profiles (A1–A2 and B1–B2) and three transverse profiles (C1–C2, D1–D2 and E1–E2), were surveyed with a total of 498 points (Fig. 2) to calculate the ice thickness distribution of the glacier tongue accurately. The

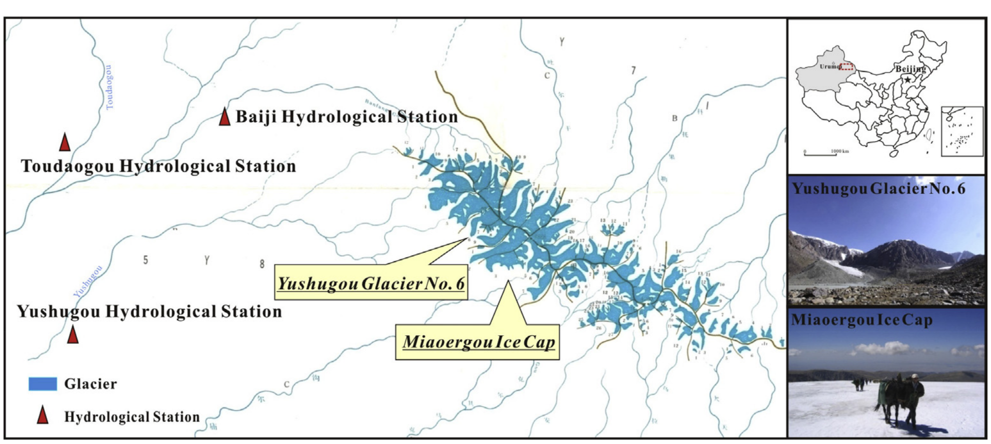

Fig. 1. Location of Yushugou Glacier No. 6 and Miaoergou Ice Cap in the Hami Prefecture of Xinjiang, China. Photographs of the two glaciers were taken by Zhongqin Li in 2011 and 2007, respectively.

locations of the GPR survey lines were dependent on the glacier surface topography. A common-offset geometry with point measuring mode was used in the survey with antenna set at 100 MHz. The transmitting and receiving antennae were arranged parallel at a distance of 4 m and transverse to the profile direction. The propagation velocity was assumed to be 169 m μs^{-1}. The ice thickness can be obtained using EKKO_View Deluxe software (professional version). Through evaluation, the relative error of radar thickness was 1.18%. Concurrent with GPR surveying, the position of GPR points were surveyed using a Real Time Kinematic-Global Position System (RTK-GPS) (Unistrong E650) with the relative accuracy of ±2 cm. The terminus position of Yushugou Glacier No. 6 was also surveyed using RTK-GPS. The GPR survey profiles after elevation-calibration are shown in Fig. 3. The ice thickness distribution in the glacier tongue can be then obtained by Kriging interpolation method based on the GPR survey data.

For Miaoergou Ice Cap, independent campaigns measuring ice thickness were carried out in August 1981, August 2005, and August 2007. The first measurement was made with a B-1 radar-sounding system, operated at 300 MHz central frequency, with theoretical error less than 3 m within measuring range of 150 m, designed at the former Lanzhou Institute of Glaciology and Geocryology (LIGG), Chinese Academy of Sciences. The ice thickness was surveyed from the glacier terminus to the elevation of 4380 m along the main axis at a distance of 50 m. Both the second and the third measurements were taken using the improved B-1 radar-sounding system. Compared with the original B-1 radar-sounding system, it was more portable and flexible and had higher precision. Seven points at different elevations were surveyed in the second measurement. However, only three points met the accuracy requirement for studying the thickness changes. For the third measurement, the ice thickness of the main axis and two transversal profiles were measured. Changes of ice thickness, terminus, and area for Miaoergou Ice Cap are analyzed systematically in this study, combined with previous studies (Li et al., 2007, 2010; Wang et al., 2011c).

Previous information of Yushugou Glacier No. 6 and Miaoergou Ice Cap were determined from 1:50,000 topographic maps prepared in 1972 and a SPOT5 remote sensing image taken in 2005 with the resolution of 5 m. The systematic error of the topographic map was <±11 m over slopes <15° and <±19 m over slopes >25° (State Bureau of Surveying and Mapping (2007)). The topographic map was scanned at 600 dpi, and geometrically corrected to a precision of less than one pixel. Then, the remote sensing image was co-registered and orthorectified using the corrected topographic map. Clearly distinguishable terrain features were selected as ground control points. Numerous ground control points were taken from the topographic map for co-registration and orthorectification of the SPOT5 remote sensing image. The registration error was limited to less than one pixel for both images by overlaying the remote sensing image and topographic map. Glacier boundaries in the different periods were mapped manually and processed using ArcGIS software.

4. Results and analyses

4.1. Changes of Yushugou Glacier No. 6

The elevation of ice-bed interface and glacier surface for the different radar survey profiles of Yushugou Glacier No. 6 are shown in Fig. 3, reflecting the ice thickness distribution and the subglacial valley. The longitudinal profile A1–A2 indicated that the maximum ice thickness was 33 m, and the average value was 26 m along the direction of the main line from the terminus to an elevation of about 3800 m. The average ice thickness reached 64 m, with the maximum of 101 m between 3840 m and 4000 m for the longitudinal profile B1–B2. As a whole, the ice was thin at the terminus and thickened gradually from the elevation of about 3900 m along the main axis of the glacier tongue. It reached to the maximum at the elevation of about 3975 m, where a clear overdeepening was formed in the bedrock topography. Both transversal profiles C1–C2 and D1–D2 showed the non-symmetric subglacial valley with maximum ice thickness of 132 m.

The ice thickness distribution and recent terminus changes of Yushugou Glacier No. 6 can be seen from Fig. 2. Graduations show the variation range of the ice thickness, with the darkest area indicating the location where the ice flow direction changed, the maximum ice thickness. The average ice thickness of the glacier tongue was estimated to be about 50 m in 2011. Field investigation found that it was flat in the upper area of the glacier and the overall slope was relatively even (~14°). Therefore, it could be concluded that the average thickness of the whole glacier was more than 50 m. By comparison of the survey data with the Glacier Inventory of China (LIGG, 1986), the average ice thickness of Yushugou Glacier No. 6 decreased by about 20 m with an annual reduction rate of 0.51 m y^{-1} from 1972 to 2011. The glacier terminus retreated by 254 m at the rate of 6.5 m y^{-1} for the same period, and showed accelerated retreat of 6.4 m y^{-1} and 7.0 m y^{-1} for 1972–2005 and 2005–2011, respectively (Table 2). Furthermore, due to serious ablation, surface streams were common on the glacier tongue and a large moraine-dammed glacial lake was formed at the glacier terminus (Fig. 4). The lower part of the glacier tongue was debris covered and dust particles were deposited in the exposed part. Previous studies (Takeuchi and Li, 2008) indicated that the glacier albedo was significantly reduced by the surface dust, which was an important aspect accentuating the glacier ablation.

Table 1
Information of the data for Yushugou Glacier No. 6 and Miaoergou Ice Cap used in this study.

Glacier name	Data			
	Topographic map	Remote sensing image	RTK-GPS survey data	Ice thickness data
Yushugou Glacier No. 6	1972 (1:50,000)	August 2005 SPOT5 (5 m resolution)	August 2011 (Glacier terminus and GPR positioning data)	August 2011 (Two longitudinal and three transverse profiles)
Miaoergou ice cap			–	August 1981 (main axis) August 2005 (seven points at different elevation) August 2007 (main axis)

Table 2
Changes of Yushugou Glacier No. 6 and Miaoergou Ice Cap.

Glacier name	Terminus change		Thickness change		Source
	Period	Annual change (m a^{-1})	Period	Annual change (m a^{-1})	
Yushugou Glacier No. 6	1972–2005	6.4	1972–2011	0.51	This study
	2005–2011	7.0			
	1972–2011	6.5			
Miaoergou ice cap	1972–2005	2.3	1981–2005	0.21 (4295–4357 m a.s.l.)	Li et al., 2007
	2005–2009	2.7	1981–2007	0–0.77	This study

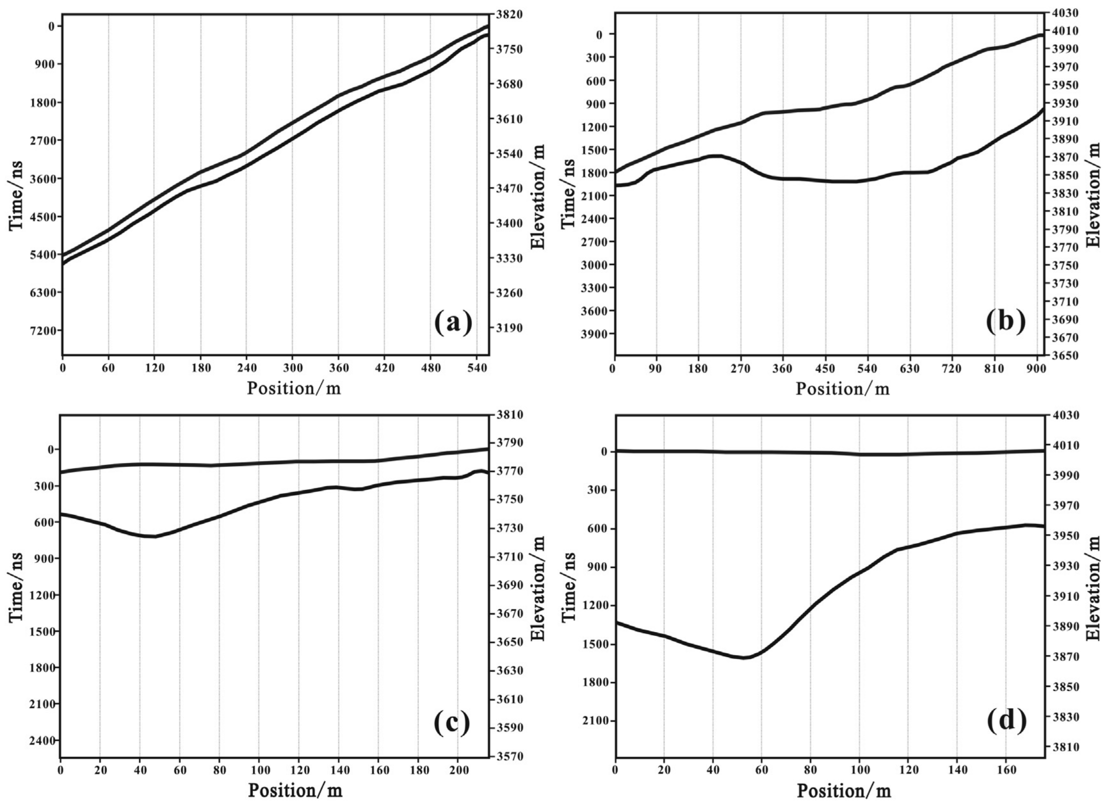

Fig. 3. The elevation of ice-bed interface and glacier surface for the longitudinal profiles ((a) A1–A2 and (b) B1–B2) and transversal profiles ((c) C1–C2, (d) D1–D2) of Yushugou Glacier No. 6, reflecting the ice thickness distribution and the subglacial valley. The ice-bed interface and glacier surface are indicated by black and blue curves, respectively. The *x*-axis is the distance from the starting point of the radar survey and the *y*-axis shows the elevation.

4.2. Changes of Miaoergou Ice Cap

As shown in Fig. 5, the ice thickness along the main axis of Miaoergou Ice Cap decreased by 0–20 m during 1981–2007, mainly in the lower part of the ice cap. The largest thinning existed near the narrowest part of the glacier (~4300 m a.s.l.), probably influenced by the regional glacier terrain. During the period 1981–2005, the ice thicknesses of Miaoergou Ice Cap decreased by about 5 m from 4295 to 4357 m a.s.l. Glacier melting was accelerated in the most recent 20–30 years, indicated by the ice core data analysis (Li et al., 2007). The glacier area was reduced by 0.360 km^2 or 9.9%, from 3.64 km^2 in 1972 to 3.28 km^2 in 2005 (Table 2). The largest average terminus retreat was 2.3 m y^{-1}, increasing to 2.7 m y^{-1} in 2005–2009. Field observation found that the terminus retreat was less than 3.0 m y^{-1} in 2013. The ablation rate of Miaoergou Ice Cap (ice cap; 3840 m a.s.l.) was smaller than Yushugou Glacier No. 6 (valley glacier; 3610 m a.s.l.) due to the differences of glacier type and elevation. Generally, ice caps with higher terminus elevation respond much more slowly to climate than do valley glaciers (Kuhn, 1985).

5. Discussion

Glacier changes in the Yushugou Drainage Basin and Miaoergou Drainage Basin during the past four decades were studied by Wang et al. (2008). Glacier areas in the Yushugou Drainage Basin decreased by 2.5 km^2, accounting for 11.3% of the value in 1959/1961 and glacier volume declined by about 10.3% for the same period. For the Miaoergou Drainage Basin, the total glacier area reduced by 3.10 km^2 with areal shrinkage of 15.0% and volume loss of 18.3% during the past 40 years. Glaciers in both drainage basins are sensitive to climate change, and a slight increase of temperature will cause significant glacier melting. Glacier shrinkage in the Miaoergou Drainage Basin was significantly larger than in the Yushugou Drainage Basin, although the ablation rate of Miaoergou Ice Cap was smaller than Yushugou Glacier No. 6, probably because of the larger glacier average area in the Miaoergou Drainage Basin. Generally, the relative changes of small glaciers were usually higher than those of large ones, which exhibit larger absolute loss (Li et al., 2010; Narama et al., 2010; Wang et al., 2011a).

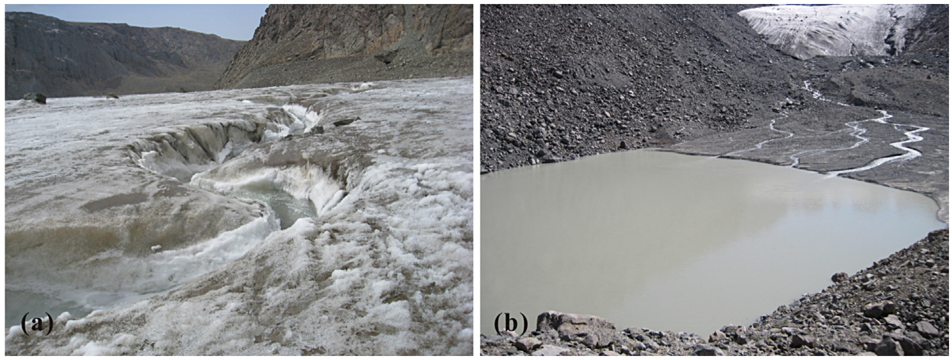

Fig. 4. Intensive ablation of Yushugou Glacier No. 6. (a) Streams in the glacier surface, and (b) a moraine-dammed glacial lake in 2011.

Under the background of climate warming, glacier melting will experience three stages in terms of runoff production: (1) runoff increases caused by the shrinkage of glaciers; (2) runoff then reaches its peak (i.e. reaching a 'turning point'); and (3) runoff decreases due to loss of ice volume and reduction of ice-covered area. The evolution of precipitation and runoff during the periods of the year was analyzed to show the relationship between glacier shrinkage and runoff trends. Therefore, annual precipitation and runoff data from the three hydrological stations in the Toudaogou Drainage Basin, Guxiang Drainage Basin, and Yushugou Drainage Basin with a long period of observations were used (Table 3). All the data used were from 1979 to 2007 and provided by the Hami Hydrological Bureau. Guxiang Drainage Basin is covered by small glaciers and Yushugou Drainage Basin is mainly supplied by glacier melt. Toudaogou Drainage Basin, without glacier coverage, is mainly dependent on precipitation and ground water.

Table 3
Hydrological stations used in this study (locations are shown in Fig. 1).

Hydrological station	Altitude (m)	Basin	Glacier coverage	Observation period
Toudaogou	1430	Toudaogou drainage basin	No	1979–2007
Baiji	1500	Guxiang drainage basin	Yes	1979–2007
Yushugou	1670	Yushugou drainage basin	Yes	1979–2007

An average of the annual runoff anomalies from 29 years (1979–2007), as well as annual precipitation, was analyzed over the same time period from the three hydrological stations in Table 3. Fig. 6 shows the trends in annual precipitation and runoff over the period 1979–2007 through linear trend analysis. The annual runoff variation of Guxiang Drainage Basin and Yushugou Drainage Basin with glacier coverage was small. However, the runoff indicated from Toudaogou Hydrological Station fluctuated and increased yearly for the Toudaogou Drainage Basin. Due to strong glacier melting in the past several decades, the released runoff will be gradually reduced for the Guxiang Drainage Basin, along with the coverage of small glaciers. For Yushugou Drainage Basin, the river runoff is from the snow/glacier melting water and precipitation in the mountainous region. Hence, the runoff variation is the reflection of temperature and precipitation in the drainage basin. Intensive glacier ablation causes an initial increase of runoff, decreasing when ablation reaches a critical extent (Hock et al., 2005). By comparison, runoff is controlled by precipitation for drainage basins with glacier coverage, but is controlled by energy for the glacier-free drainage basin. Glaciers release most water resources in the arid dry periods, a direct response to climate warming.

Many studies concluded that climate change was the principal reason for the variation of glaciers and runoff (Wang et al., 2011a; Shahgedanova et al., 2012). In addition, disturbances from anthropogenic activities can also be a main reason (Liu and Yan, 2002). Glacier recession can result in the development of glacial lakes, which have increased the potential risk for glacial lake outburst floods (GLOFs) (Quincey et al., 2007; Wang et al., 2012). Observation of the glacial lake at the terminus of Yushugou Glacier No. 6 found it was formed by the increase of glacier meltwater and had the potential to burst. Outburst would eventually result in flooding and debris flow, necessitating special attention and precautions.

6. Conclusions and outlook

Taking Yushugou Glacier No. 6 and Miaoergou Ice Cap as representative, this study focused on a comprehensive analysis of recent glacier changes in Hami Prefecture of Xinjiang and their impact on water resources. The average ice thickness of the tongue of Yushugou Glacier No. 6 was about 50 m in 2011, and it thinned by 20 m at the rate of about 0.51 m y^{-1} from 1972 to 2011. The terminus retreated by 254 m with an average annual retreat of 6.5 m. Due to significant ablation, the surface meltwater runoff of Yushugou Glacier No. 6 was obvious and a moraine-dammed lake was

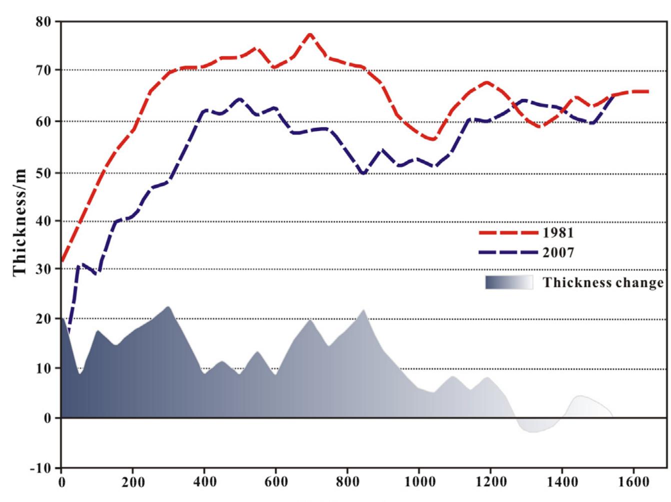

Fig. 5. Ice thickness changes along the main axis of Miaoergou Ice Cap during 1981–2007. The *x*-axis is the distance from the starting point of the radar survey and the *y*-axis is the ice thickness. The ice thickness changes are calculated by the comparison of ice thickness in 1981 and 2007, indicated by the polygon.

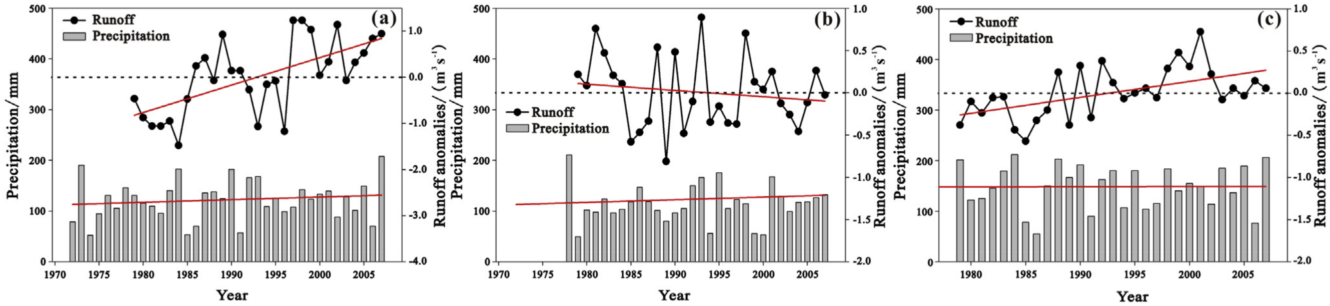

Fig. 6. Annual precipitation and runoff anomalies of (a) Toudaogou, (b) Baiji and (c) Yushugou Hydrological Station during the period 1979–2007. The three hydrological stations are located in the Toudaogou Drainage Basin, Guxiang Drainage Basin, and Yushugou Drainage Basin, respectively.

formed at the glacier terminus. For Miaoergou Ice Cap, the thickness along the main axis decreased 0–20 m during 1981–2007. The area was reduced by 0.36 km^2 (9.9%) from 3.64 km^2 to 3.28 km^2, with a terminus retreat rate of 2.3 m y^{-1} during the period 1972–2005. The largest average terminus retreat was 2.3 m y^{-1} and then increased to 2.7 m y^{-1} in 2005–2009. The observed terminus retreat was less than 3.0 m a^{-1} in 2013. The ablation of Miaoergou Ice Cap was more serious than Yushugou Glacier No. 6 due to the differences of glacier type and elevation. By analyzing the observation data of Toudaogou, Baiji, and Yushugou Hydrological Stations, the impact of glacier changes on water resources showed regional differences in Hami Prefecture depending on the proportion of glacier coverage in the drainage basins. The annual river runoff variation was relatively large for the drainage basin without glacier coverage (Toudaogou), whilst it was small for the drainage basins with glacier coverage (Guxiang and Yushugou). However, the impact of glacier changes on the runoff is still limited to qualitative or semi-quantitative analysis, which causes uncertainty in the prediction of future glacier meltwater change in the different regions of Hami Prefecture. An observation system of glaciers of different types and sizes and continuous hydrological monitoring should be established to make further predictions of the evolution of glaciers and glacial water resources.

Acknowledgements

We greatly appreciate suggestions from Professor Zhaodong (Jordan) Feng (Guest Editor) and two anonymous referees for the improvement of our paper. This research was jointly supported by the Funds for Creative Research Groups of China (41121001), the National Natural Science Foundation of China (41301069), the West Light Program for Talent Cultivation of Chinese Academy of Sciences and the Postdoctoral Science Foundation of China (2013M540779).

References

Aizen, V.B., Aizen, E.M., Melack, J., 1995. Climate, snow cover, glaciers, and runoff in the Tien-Shan, Central Asia. Water Resources Bulletin 31 (6), 1113–1129.
Aizen, V.B., Aizen, E.M., Melack, J.M., 1996. Precipitation, melt and runoff in the northern Tien Shan. Journal of Hydrology 186 (1–4), 229–251.
Aizen, V.B., Kuzmichenok, V.A., Surazakov, A.B., Aizen, E.M., 2007. Glacier changes in the Tien Shan as determined from topographic and remotely sensed data. Global and Planetary Change 56, 328–340.
Bolch, T., 2007. Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. Global and Planetary Change 56, 1–12.
Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., Bajracharya, S., Stoffel, M., 2012. The state and fate of Himalayan glaciers. Science 336, 310–314.
Bolch, T., Menounos, B., Wheate, R., 2010. Landsat-based inventory of glaciers in western Canada, 1985-2005. Remote Sensing of Environment 114 (1), 127–137.
Braithwaite, R.J., Olesen, O.B., 1988. Effect of glaciers on annual run-off, Johan Dahl Land, South Greenland. Journal of Glaciology 34 (117), 200–207.
Fountain, A.G., Tangborn, W.V., 1985. The effect of glaciers on streamflow variations. Water Resources Research 21 (4), 579–586.
Gao, J., Luo, G., 2009. Analysis of the impact of climate changes on river's runoff in Hami Prefecture, Xinjiang. Journal of Glaciology and Geocryology 31 (4), 748–758 (in Chinese).
Haeberli, W., Hoelzle, M., Paul, F., Zemp, M., 2007. Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps. Annals of Glaciology 46, 150–160.
Hock, R., Jansson, P., Braun, L.N., 2005. Modelling the response of mountain glacier discharge to climate warming. In: Huber, U.M., Bugmann, HKM, Reasoner, M.A. (Eds.), Global Change and Mountain Regions (A State of Knowledge Overview). Springer, Dordrecht.
Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate change will affect the Asian water towers. Science 328, 1382–1385.
Immerzeel, W.W., van Beek, L.P.H., Konz, M., Shrestha, A.B., Bierkens, M.F.P., 2012. Hydrological response to climate change in a glacierized catchment in the Himalayas. Climatic Change 110, 721–736.
Jacob, T., Wahr, J., Pfeffer, W.T., Swenson, S., 2012. Recent contributions of glaciers and ice caps to sea level rise. Nature 482, 514–518.
Kaser, G., Grosshauser, M., Marzeion, B., 2010. Contribution potential of glaciers to water availability in different climate regimes. Proceedings of the National Academy of Sciences of the United States of America 107, 20223–20227.
Kuhn, M., 1985. Fluctuations of climate and mass balance: different responses of two adjacent glaciers. Zeitschrift für Gletscherkunde und Glazialgeologie 21, 409–416.
Kutuzov, S., Shahgedanova, M., 2009. Glacier retreat and climatic variability in the eastern Terskey-Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century. Global and Planetary Change 69, 59–70.
Lanzhou Institute of Glaciology and Geocryology (LIGG), Chinese Academy of Science, 1986. Glacier Inventory of China (III) (Tianshan Mountains: Interior Drainage Area of Scattered Flow in East). Science Press, Beijing (in Chinese).
Li, B., Zhu, A., Zhang, Y., Pei, T., Qin, C., Zhou, C., 2006. Glacier change over the past four decades in the middle Chinese Tien Shan. Journal of Glaciology 52, 425–432.
Li, K., Li, Z., Gao, W., Wang, L., 2011. Recent glacial retreat and its effect on water resources in eastern Xinjiang. Chinese Science Bulletin 56 (33), 3596–3604.
Li, Z., Li, K., Wang, L., 2010. Study on recent glacier changes and their impact on water resources in Xinjiang, North Western China. Quaternary Sciences 30, 96–106 (in Chinese).
Li, Z., Wang, F., Zhu, G., Li, H., 2007. Basic features of the Miaoergou flat-topped glacier in east Tianshan Mountains and its thickness change over the past 24 years. Journal of Glaciology and Geocryology 29, 61–65 (in Chinese).
Liu, D., Yan, S., 2002. Sustainable utilization and management of tourism resources in No. 1 Glacier in Xinjiang Tianshan Mountains. Areal Research and Development 21 (2), 72–75 (in Chinese).
Luo, G., Ai, L., Qi, X., Xu, L., Li, B., 2002. Hydrological characteristics of the Yushugou valley. Xinjiang Meteorology 37, 19–20 (in Chinese).
Ma, X., Luo, G., 2009. Impacts of climate change on the streamflow in the Yushugou River Basin. China Water Transport 9 (10), 190–193 (in Chinese).
Narama, C., Kääb, A., Duishonakunov, M., Abdrakhmatov, K., 2010. Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~ 1970), Landsat (~ 2000), and ALOS (~ 2007) satellite data. Global and Planetary Change 71, 42–54.
Paul, F., Kääb, A., Haeberli, W., 2007. Recent glacier changes in the Alps observed by satellite: consequences for future monitoring strategies. Global and Planetary Change 56, 111–122.
Quincey, D.J., Richardson, S.D., Luckman, A., Lucas, R.M., Reynolds, J.M., Hambrey, M.J., Glasser, N.F., 2007. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. Global and Planetary Change 56, 137–152.
Shahgedanova, M., Nosenko, G., Bushueva, I., Ivanov, M., 2012. Changes in area and geodetic mass balance of small glaciers, Polar Urals, Russia, 1959-2008. Journal of Glaciology 58, 953–964.

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M., 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Climate Change 2 (10), 725–731.
State Bureau of Surveying and Mapping, 2007. Technical Rules for Producing Digital Products of 1:10000 1:50000 Fundamental Geographic Information. Part 1: Digital Line Graphs (DLG). CH/T 1015. 1–2007.
Surzakov, A.B., Aizen, V.B., Aizen, E.M., Nikitin, S.A., 2007. Glacier changes in the Siberian Altai Mountains, Ob river basin, (1952-2006) estimated with high resolution imagery. Environmental Research Letters 2 (4), 045017.
Takeuchi, N., Li, Z.Q., 2008. Characteristics of surface dust on Urumqi glacier No. 1 in the Tien Shan mountains, China. Arctic, Antarctic, and Alpine Research 40, 744–750.
Vanlooy, J.A., Forster, R.R., 2008. Glacial changes of five southwest British Columbia ice fields, Canada, mid-1980s to 1999. Journal of Glaciology 54, 469–478.
Wang, L., Li, Z., Wang, F., Ross, E., 2014a. Glacier shrinkage in the Ebinur lake basin, Tien Shan, China, during the past 40 years. Journal of Glaciology 60 (220), 245–254.
Wang, P., Li, Z., Gao, W., 2011a. Rapid shrinking of glaciers in the middle Qilian Mt. Region of Northwest China, during the last ~50 years. Journal of Earth Science 22 (4), 539–548.
Wang, P., Li, Z., Li, H., Wang, W., Yao, H., 2014b. Comparison of glaciological and geodetic mass balance at Urumqi glacier No. 1, Tian Shan, Central Asia. Global and Planetary Change 114, 14–22.
Wang, P., Li, Z., Wang, W., Li, H., Zhou, P., Jin, S., 2013. Changes of six selected glaciers in the Tomor region, Tian Shan, Central Asia, over the past ~50 years, using high-resolution remote sensing images and field surveying. Quaternary International 311, 123–131.
Wang, S., Zhang, M., Li, Z., Wang, F., Li, H., Li, Y., Huang, X., 2011b. Glacier area variation and climate change in the Chinese Tian shan Mountains since 1960. Journal of Geographical Sciences 21 (2), 263–273.
Wang, S., Zhang, M., Pepin, N., Li, Z., Sun, M., Huang, X., Wang, Q., 2014c. Recent changes in freezing level heights in High Asia and their impact on glacier changes. Journal of Geophysical Research: Atmospheres 119. http://dx.doi.org/10.1002/2013JD020490.
Wang, W., Li, K., Gao, J., 2011c. Monitoring glacier shrinkage using remote sensing and site-observation method on southern slope of Kalik Mountain, eastern Tian Shan, China. Journal of Earth Sciences 22 (4), 503–514.
Wang, X., Liu, S.Y., Guo, W.Q., Yao, X.J., Jiang, Z.L., Han, H.D., 2012. Using remote sensing data to quantify changes in glacial lakes in the Chinese Himalaya. Mountain Research and Development 32, 203–212.
Wang, Y., Hou, S., Lu, A., Liu, Y., 2008. Response of glacier variations in the eastern Tianshan Mountains to climate change, during the last 40 years. Arid Land Geography 31 (6), 813–821 (in Chinese).