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Recent evolution in extent, thickness, and velocity of Haxilegen Glacier No. 51, Kuytun River Basin, eastern Tianshan Mountains

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ABSTRACT

This study focuses on ice thickness distribution and calculation of the area, terminus, and velocity changes of Haxilegen Glacier No. 51 in the Kuytun River Basin of the eastern Tianshan Mountains, during 1964–2010. The ground penetrating radar (GPR) survey indicated that the maximum and the mean thicknesses are 73 m and 39 m for this glacier, respectively. The glacier area decreased from 1.48 km^2 to 1.32 km^2 (10.8%), and its terminus retreated with a rate of 2.3 m a^{-1} between 1964 and 2010. The area change of this glacier is smallest in the eastern Tianshan Mountains, but it experienced a large volume decrease, nearly 30% mass loss during the period 1980s–2010. The ice velocity is within a range of 1.5–3.1 m a^{-1} for the observation period of 2000–2006. The persistent glacier shrinkage is mainly attributed to intensive rise of the local temperature and has an important impact on river runoff.

Introduction

The high concentration of mountain glaciers in Tianshan Mountains preserves abundant water resources, and this area is therefore known as "the water tower of central Asia" (Aizen et al., 2007; Sorg et al., 2012). Variations of these glaciers, therefore, have impacts on regional sustainable development under climate change. Some research show that the annual mean temperature has increased by 1.6–1.8 °C during the past 50 years in northwestern China (Li et al., 2013), and meanwhile the temperature and precipitation in the eastern Tianshan Mountains exhibited remarkable increasing tendencies with rates of 0.34 °C (10a)$^{-1}$ and 11 mm (10a)$^{-1}$ (Wang et al., 2011). Also, continuously extensive shrinkage of glaciers in this region with an accelerated rate in recent decades has been reported (Khromova et al., 2003; Narama et al., 2010; Bolch et al., 2012; Sorg et al., 2012). Glacier meltwater caused by intensified glacier ablation plays an important role in sustaining human habitats and ecosystems within arid and semiarid regions (Hagg et al., 2007; Wang et al., 2014c).

The Kuytun River Basin is in the northern slope of the eastern Tianshan Mountains and located in the southern portion of the Junggar Basin in the Xinjiang Uygur Autonomous Region, China. The glaciers within the Kuytun River Basin are a significant freshwater resource for hydropower generation, irrigation, as well as residential and livestock consumption. Intensified glacier melt has affected the quantity and seasonal distribution of runoff in the Kuytun River Basin. In situ observation is pivotal for accurate evaluation of glacier change and assessment of water supply and can provide valuable information concerning glacier response to climate change. Nevertheless, field observation of the glaciers in the Kuytun River Basin has only been done for a short period of time and only within a small spatial extent. Haxilegen Glacier No. 51 is the only selected one in this basin that has been monitored since 1999. The observation items include glacier thickness, terminus location, ice velocity, and mass balance.

Studies based on satellite imagery showed that glaciers in the Ebinur lake basin supplied by the Kuytun, Sikeshu, Jinghe, Bortala, and Daheyanzi Rivers as well as Sayram Lake have been retreating and losing mass during the past 40 years (1964–2004) (L. Wang et al., 2014). However, detailed analysis of glacial information such as ice thickness and ice velocity, which are essential parameters for the glacial dynamic model, are usually unavailable. To our knowledge, there are only two published papers in Chinese concerning glacier monitoring for Haxilegen Glacier No. 51 (Jing et al., 2002; Jiao et al., 2009) and the data analysis is not sufficiently comprehensive and detailed. In addition, little work has been conducted to examine the impact of topographic factors on glacial-climate interaction. Taking this into account, this study focuses on the analysis of (1) glacier thickness distribution and volume; (2) changes of glacier area, terminus, and velocity; and (3) the response of the glacier to climate change with the aim of providing a better understanding of the influence of climate change and topographic features on glacier variation.

Geographical Setting

The Kuytun River Basin (83°09′33″–85°08′35″E, 43°43′16″–45°52′22″N) is about 220 km west of Urumqi, the capital of Xinjiang Uygur Autonomous Region, China. The total area of this basin is 2.83×10^4 km^2, with the mountainous area covering 1.19×10^4 km^2 (Xu, 2009). The Kuytun River is the second largest river on the northern slope of Chinese Tianshan Mountains. The annual river runoff is approximately 6.63×10^8 m^3 and glacier meltwater accounts for 24.4% of it, which is the main water source for irrigation in Xinjiang. Situated in the hinterland of Eurasia, Kuytun River is under continental climate. The southern river basin is covered by glaciers and snow in the mountainous area (above 3500 m a.s.l.). For the area between 1100 m and 3500 m a.s.l., the annual mean temperature and annual precipitation are approximately 4 °C and 400–500 mm, respectively (Xu, 2009). The Glacier Inventory of China identified 309 glaciers in the Kuytun River Basin. The total estimated glacier area of 201.12 km^2 covers 10.3% of the basin area (Lanzhou Institute of Glaciology and Geocryology, 1986). The Haxilegen Glacier No. 51 (84°24′E, 43°43′N; Fig. 1) at the headwaters of the Kuytun River is classified as a cirque glacier. In 1964, the glacier had an area of 1.48 km^2. The elevation of its top and terminus was 4000 m and 3400 m a.s.l., respectively. It faces toward the northeast with a relatively flat and debris-free surface, and crevasses are not widely distributed. The average ice thickness was estimated to be approximately 49 m in the 1980s from the Glacier Inventory of China (Shi, 2005).

Data and Methods

GPR and GPS Survey

A pulse EKKO Pro penetrating radar system with a center frequency of 100 MHz was employed to survey ice thickness in the area below ~3700 m a.s.l. on Haxilegen Glacier No. 51 (difficult to access above this elevation, see Fig. 1). The field measurement was carried out in September 2010. The transmitting-receiving antennae were arranged at a distance of 4 m and in transverse direction to the survey profile. The handheld approach was used, which is the best choice for complex glacier surface reliefs. Ice thickness measurements were taken along six survey profiles across the glacier tongue (Fig. 1), and tracks were recorded by a real-time kinematic ground positioning system (RTK-GPS). The radar echo signals were processed using the EKKO_View Deluxe software (Professional version). The two-way travel time of return waves from ice bed was determined by inspecting the two-dimensional (2-D) radar image. Assuming a wave velocity in a glacier of 169 m μs^{-1} (Kovacs et al., 1995), ice

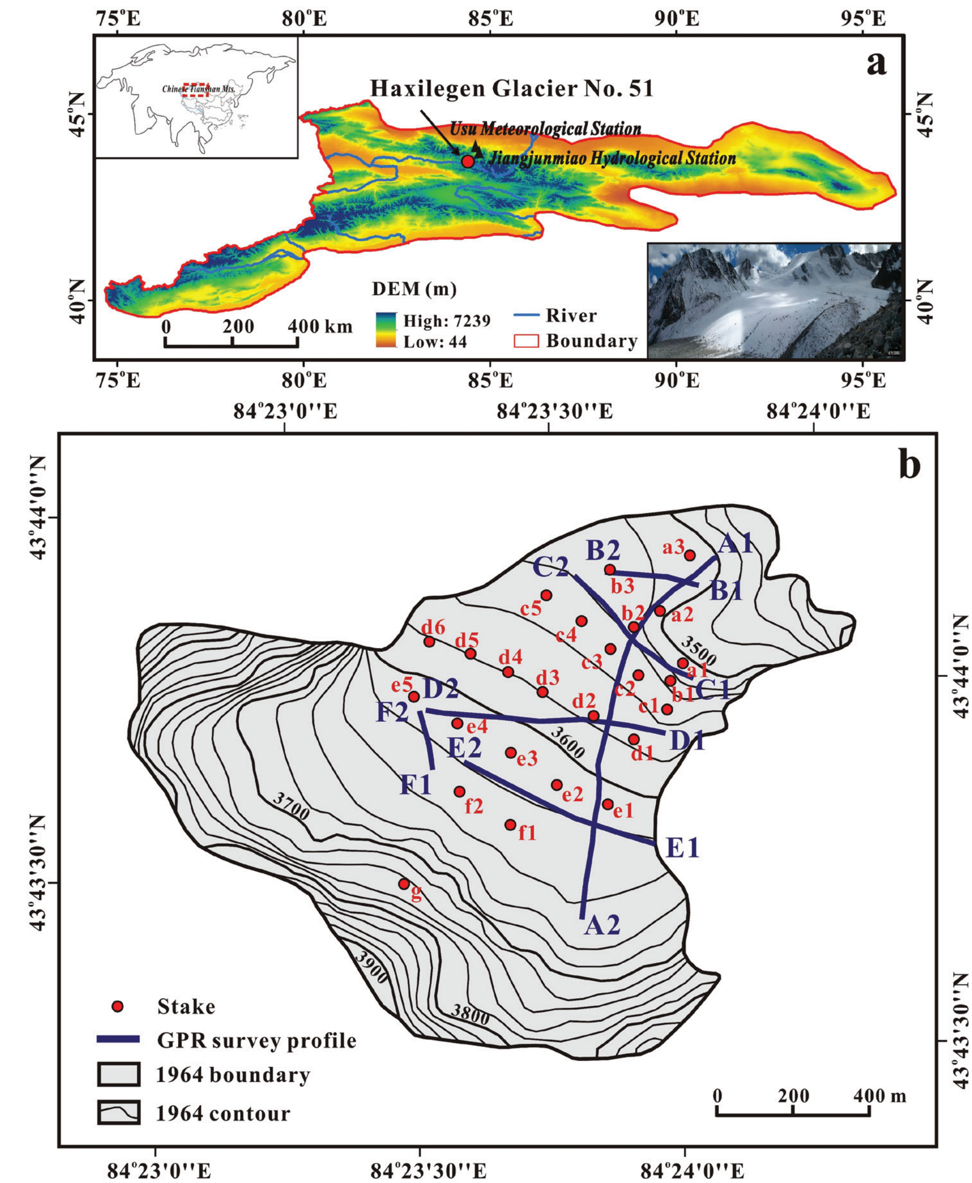

FIGURE 1. (a) Location of Haxilegen Glacier No. 51 in the Kuytun River Basin, eastern Tianshan Mountains. The photo in the bottom-right corner has been published by Jiao et al. (2009). (b) Map of Haxilegen Glacier No. 51 with ice thickness profiles represented by blue bold lines. The red circles are the ice velocity survey stakes, which are distributed at seven different elevations. Contours show surface elevation in 1964 with an interval of 20 m.

thickness can be computed by multiplying the radar wave travel time and velocity. The relative error of radar measurements of ice thickness is estimated to be 1.2% by the equation from Sun et al. (2003).

Ice thickness for the upper part of the glacier, where no measurements were carried out, was derived using the perfect-plasticity assumption for rheology of Nye (1951) and was calculated from the surface slope by the relation (Equation 1) suggested by Paterson (1994), which has been used for many approximations of simple glacier geometries.

$$h = \tau_0 / \rho g \sin \alpha \qquad (1)$$

where h is ice thickness (m); τ_0 is basal shear stress (kPa) (i.e., yield stress of ice); ρ is ice density (910 kg m^{-3}); g is gravitational acceleration (9.81 m s^{-2}); and α is surface slope (°). Assuming a constant value over the whole glacier (Nye, 1952), τ_0 along the main streamlines was calculated using Equation 1 based on the radar measured thickness of the glacier tongue. For the upper part of the glacier, ice thickness can then be calculated from the glacier surface slope. Assuming thickness at the glacier boundary to be zero, the Kriging interpolation can be used. The volume of the glacier was then determined from the interpolated ice thickness distribution.

GPS survey (Unistrong E650) of the glacier terminus and the GPR points was conducted in September 2010. GPS receivers were placed at a fixed base point near the glacier terminus, and other GPS units were used to simultaneously survey the glacier terminus and radar points. RTK differential mode was used, which results in a survey error of ~0.10–0.30 m for geodetic-quality GPS receivers (Rivera et al., 2005). To measure ice flow velocity, a stake network was set up at seven different elevations and the stakes were measured every year during the period of 1999–2006 (Annual Report of Tianshan Glaciological Station, vol. 16–18).

Glacier Area and Terminus Location

Changes in the extent of Haxilegen Glacier No. 51 during the period 1964–2010 were determined via comparisons between a topographic map, satellite images, and GPS data as well as previous study results (Jing et al., 2002; Jiao et al., 2009; Annual Report of Tianshan Glaciological Station, 1999–2006). A topographic map (1:50,000) was derived from an aerial photograph taken by the Chinese Military Geodetic Service in 1964. A Spot-5 (Satellite Pour I'Observation de la Terre-5) image from October 2004 with a resolution of 5 m was also obtained. The satellite image was orthorectified in the ENVI software using the methodology described by Paul et al. (2004). Geocorrection and coregistration were then made, and clearly distinguishable terrain features were selected from the topographic map that could be identified on the satellite image. Thirty ground control points were collected with the root-mean square error (RMSE) limited to less than 0.5 pixels in both the x and y directions. The topographic map, satellite image, and GPS data were projected into the Universal Transverse Mercator (UTM) World Geodetic System 1984 ellipsoidal elevation (WGS84). The terminus and area records of Haxilegen Glacier No. 51 during 1999–2006 were obtained from Jiao et al. (2009) and Jing et al. (2002).

Ice Flow Velocity

The ice flow velocity of Haxilegen Glacier No. 51 was measured by surveying mass balance stakes installed in the glacier. The stakes are in the form of six transects (A, B, C, D, E, F) (Fig. 1) and evenly distributed in different elevations, covering nearly the whole glacier. Forward intersection survey method was used to survey the stakes from the ground control point K1 and K2. The ice velocity was measured using optical theodolite and total station during the period 1999–2002 and 2002–2006, respectively, and it can be obtained by calculating the spatial displacement of the stakes per unit time. The coordinate system is independent and the magnitude of the ice flow velocity (*Uxy*) and the flow direction (α) are determined by the following formulas:

$$U_{xy} = \sqrt{U_x{}^2 + U_y{}^2} \tag{2}$$

$$\alpha = 90 - \arctan\frac{U_y}{U_x} \tag{3}$$

where, *Ux* and *Uy* are the velocity components parallel to the x axis and y axis, respectively and α is degrees relative to north. Generally, the accuracy of *Uxy* is less than 10% of that in the input data and the accuracy of the direction α is $<\pm 2°$ (Annual Report of Tianshan Glaciological Station, 1999–2006).

Temperature and Precipitation

The meteorological data were collected from the two closest stations to the Haxilegen Glacier No. 51, Usu Meteorological Station (84°40′E, 44°26′N; 479 m a.s.l.) and Jiangjunmiao Hydrological Station (84°42′E, 44°03′N; 1270 m a.s.l.). These meteorological data sets were obtained from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn) and previous literature (Jing et al., 2008; Ayinuer and Gao, 2010). Trend analyses were conducted via linear regressions of temperature and precipitation with glacier terminus, area, and velocity to understand the response of this glacier to climate change. The runoff data of the Kuytun River was also collect-

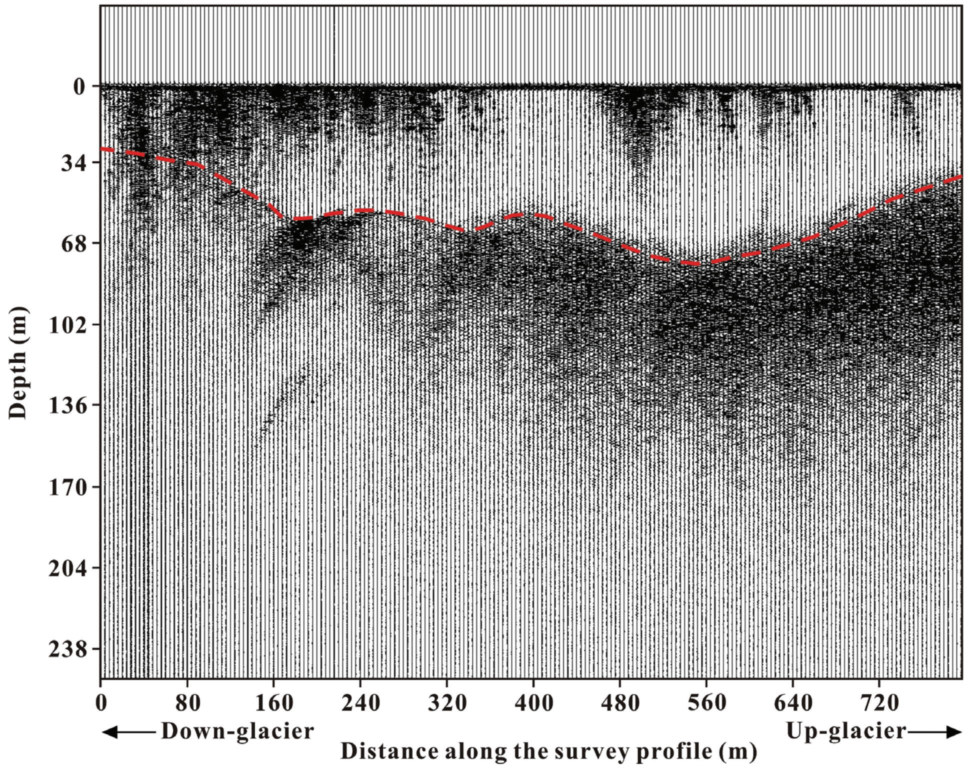

FIGURE 2. A ground penetrating radar image along the survey profile A1–A2. The ice-bed interface is represented by the red dashed line.

ed from the Jiangjunmiao Hydrological Station (Ayinuer and Gao, 2010), which provides essential material for analyzing the impact of glacier changes on river runoff.

Results and Analysis

Ice Thickness and Volume

A sample of the results from the ice thickness measurements across the Haxilegen Glacier No. 51 is presented in Figure 2 (see location of survey profiles in Fig. 1). The ice-bed interface is clearly recognizable in the image. The mean thickness along the profile A1A2 is 53 m and the maximum value of approximately 73 m occurs at an elevation of ~3580 m. The ice thickness map for the whole glacier is shown in Figure 3. It can be seen that the maximum thickness is reached in the central area, showing a typical feature of cirque floor, that is, the deepest bottom is at the cirque center. The glacier area, thickness, and volume in 2010 were computed using the ESRI ArcMap software to be 1.32 km^2, 39 m, and 0.04 km^3, respectively. A comparison with the Glacier Inventory of China (Shi et al., 2005) indicates that the glacier thinned by ~10 m and experienced a volume reduction of ~0.0325 km^3 or ~29% from 1980s to 2010.

Glacier Area, Terminus, and Velocity Change

The area of Haxilegen Glacier No. 51 decreased by 0.16 km^2 (10.8%), from 1.48 km^2 in 1964 to 1.32 km^2 in 2010 (Fig. 4, part a). The APAC (annual percentage of area changes) over the past 46 years is 0.24% a^{-1}, which is smaller than average for the Chinese Tianshan Mountains, 0.31% a^{-1} (Wang et al., 2011). The reduction rate from 1981 to 2010 is 0.0053 km^2 a^{-1}, 50% higher than that (0.0035 km^2 a^{-1}) from 1964 to 2010. The rate increased to 0.0074 km^2 a^{-1} for the period of 2000–2010, more than twice the rate in the period 1964–2010. This strongly indicates that the glacier shrinkage has accelerated since the 1980s, and the acceleration became even more pronounced after 2000.

Cumulative change at the terminus of Haxilegen Glacier No. 51 is illustrated in Figure 4, part

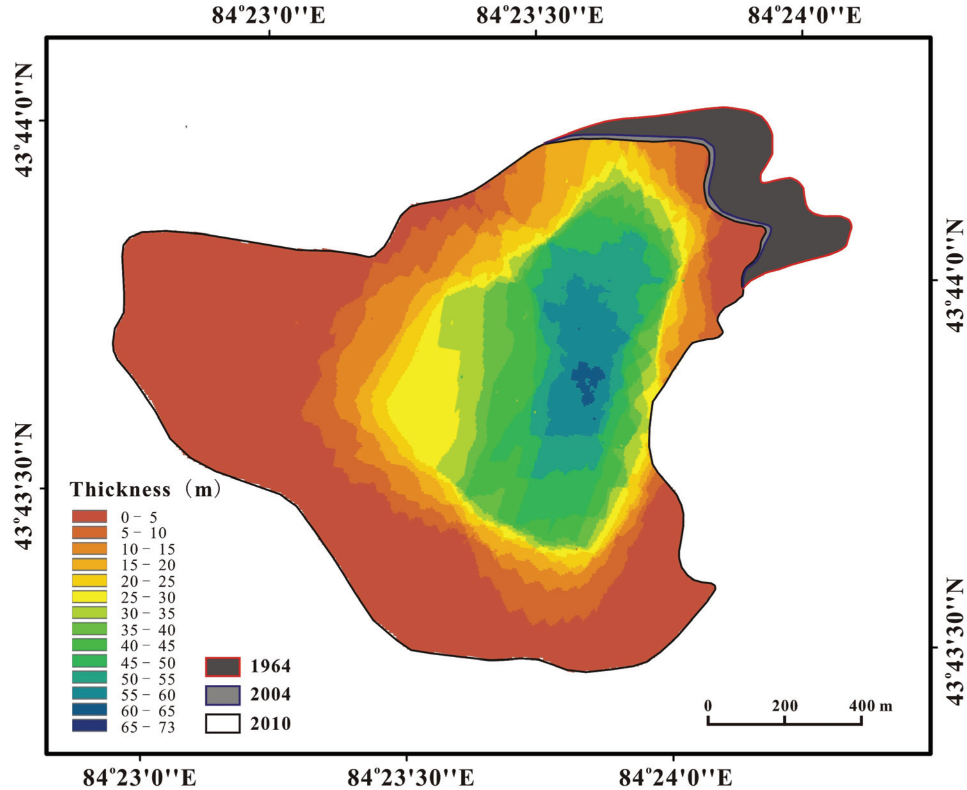

FIGURE 3. Ice thickness distribution of Haxilegen Glacier No. 51 described in graduated color. Glacier termini in 1964, 2004, and 2010 are indicated by different color lines.

b. The total retreat distance of the glacier terminus is approximately 106.8 m, with an average rate of 2.3 m a^{-1}, from 1964 to 2010. During the period from 1964 to 1999, it retreated by 49 m at a rate of 1.4 m a^{-1}, indicating that the glacier was relatively stable before 1999. Since then, however, the terminus retreat accelerated. The retreat rate from 1999 to 2010 is 5.3 m a^{-1}, nearly four times that in the period 1964–1999.

As shown in Figure 5, ice velocity changes are analyzed based on observation during the period of 1999–2006 (Annual Report of Tianshan Glaciological Station, 1999–2006). The velocity is within a range of 1.5–3.1 m a^{-1} for the observation period of 2000–2006, and the maximum occurs at the transect E (~3600 m), approximating to the equilibrium line of the glacier. Down- and upward from this transect, velocity decreases gradually, according to the velocity distribution pattern of mountain glaciers, but below Transect C, it increases toward the glacier terminus. This is understandable because the Transect C is just at the cirque threshold; downward from it the slope increases if we see the glacier morphological feature (see Fig. 1). Although annual change of ice velocity is relatively small, it can still be clearly seen that this glacier movement has slowed down since the first measurement in 1999/2000, especially in the lower altitudes, probably due to thickness decrease.

Discussion

Response of Glacier Change to Climate Change

Shrinkage of Haxilegen Glacier No. 51 over the past 50 years must be attributed mainly to climatic causes. Figure 6 shows meteorological data at Usu Station in the Kuytun River Basin. It can be seen that average annual temperature increased apparently with a very high warming rate of 0.38 °C $(10a)^{-1}$, and the annual precipitation displayed a faint increase trend with very large annual variability during the period of 1954–2013. Therefore, we believe that the increased temperature accounts for primarily the glacier shrinkage

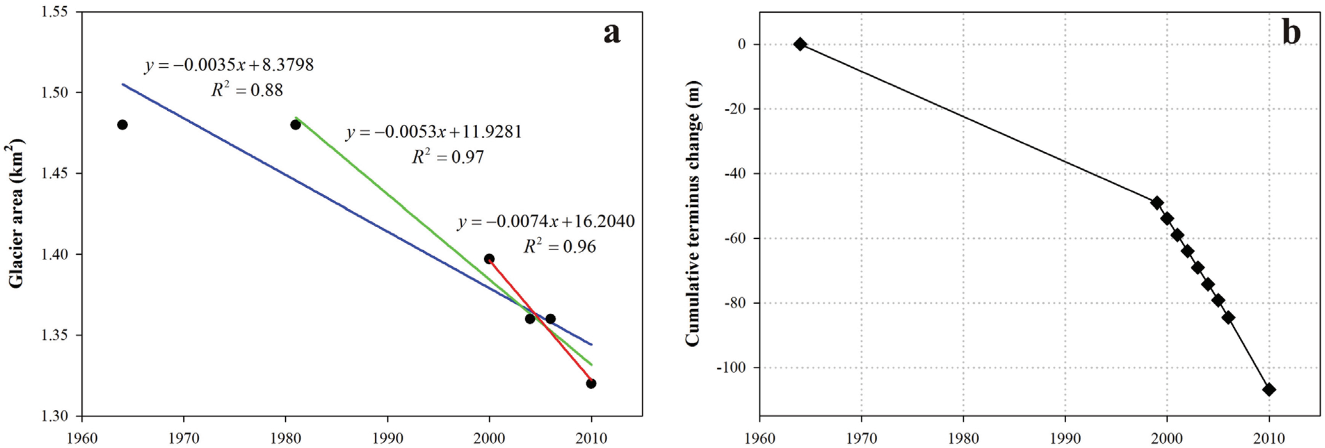

FIGURE 4. Changes of Haxilegen Glacier No. 51. (a) Area change with linear regressions from 1964 to 2010, from 1981 to 2010, and from 2000 to 2010, represented by blue, green, and red lines, respectively; (b) cumulative glacier terminus change from 1964 to 2010.

from the 1960s to the 2000s. Since 2000, temperature has increased continuously and precipitation seemed to decrease somewhat so that glacier recession has accelerated as a result. The monthly runoff at the Jiangjunmiao Hydrological Station exhibits obvious seasonal variation as shown in Figure 7. The runoff from June to September accounted for 75.1% of the annual runoff, which is consistent with the glacier ablation period. Furthermore, the linear trend analysis of runoff shows that the average increase rate of annual runoff is 0.18×10^8 m^3 (10a)$^{-1}$ ($p < 0.05$) during the period 1963–2009. But the rate is 0.68×10^8 m^3 (10a)$^{-1}$ ($p < 0.05$) during 1992–2009, nearly four times of that during 1963–2009 (Ayinuer and Gao, 2010). Analysis of temperature and precipitation for the same periods demonstrates that the increase in runoff should be caused by increased glacial meltwater runoff. Temperature increase has an intensive effect on glacier melting. With temperature increase, glacier melting increases, hence the ablation area enlarges and the glacier albedo decreases (Fujita and Ageta, 2000). And consequently these result in further increase of glacier melting and

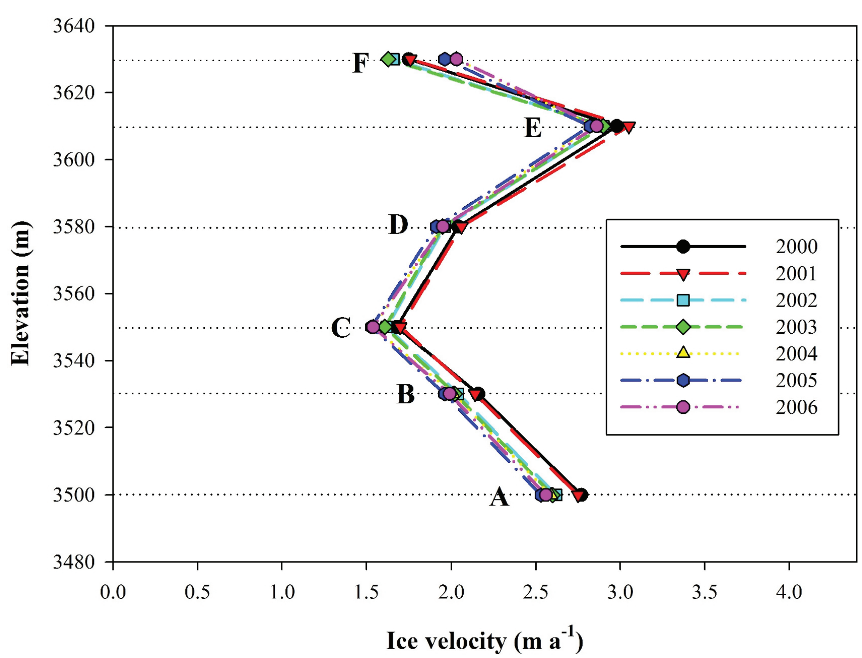

FIGURE 5. Surface ice velocity distribution versus elevation on Haxilegen Glacier No. 51 during 2000–2006.

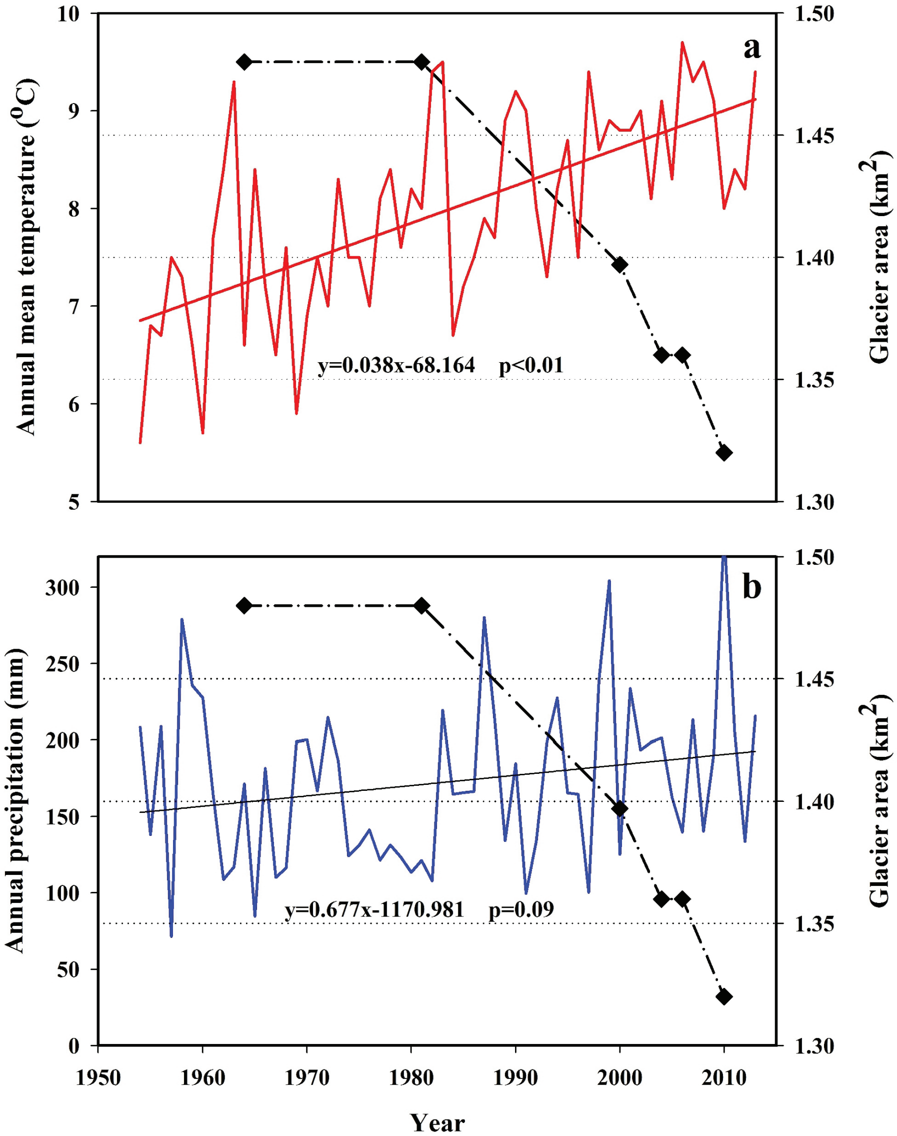

FIGURE 6. Variations of (a) annual mean temperature and (b) annual precipitation at Usu Meteorological Station plotted against the area changes of Haxilegen Glacier No. 51.

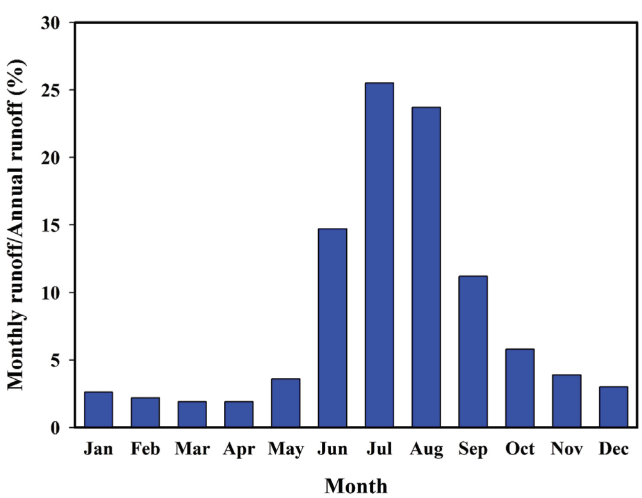

FIGURE 7. Ratios of the monthly runoff to annual runoff at Jiangjunmiao Hydrological Station during 1963–2009.

acceleration of glacier shrinkage. Moreover, temperature increase has also been reflected in an increase of the atmospheric freezing level heights (FLHs), which has a significant influence on glacier change. For example, Wang S. et al. (2014) found that a 10 m rise in summer FLH causes the mass balance of reference glaciers in High Asia to decrease by 7–38 mm water equivalent and ELA to rise by 3.1–9.8 m.

Comparison with Other Studies in the Tianshan Mountains

Ice thickness measurement of glaciers is limited due to labor-intensity and cost. Among 9035 glaciers in the eastern Tianshan Mountains (Shi,

TABLE 1

Comparison of the ice thickness of glaciers in the eastern Tianshan Mountains.

Region	Glacier name	Period	Ice thickness Elevation	m	Method*	Source
			3750 m	185		
			3300 m	73		
Aksu River Basin	Keqikaer Glacier	2004	3170 m	40	RES	Xie et al. (2006)
Kuytun River Basin	Haxilegen Glacier No. 51	2010	below ~3700 m	39	GPR	This study
		1981		55.1	RES	
		2001		51.5	GPR	
Urumqi River Basin	Urumqi Glacier No. 1	2006	—	48.4	RES	Wang, P.Y. et al. (2014a)
			4295 m	68		
			4340 m	66		
		1981	4357 m	59		
			4295 m	62.6		
			4340 m	60.9		
Miaoergou River Basin	Miaoergou Ice Cap	2005	4357 m	54.0	RES	Li et al. (2007)
Sigong River Basin	Sigong River Glacier No. 4	2009	—	27.6	GPR	Wu et al. (2011)

*GPR = ground penetrating radar, RES = radio-echo sounding.

2005), therefore, thickness measurement has been carried out only for several up to present (see Wang et al., 2014a, and Table 1). Although these measurements have been undertaken in different periods by various methods, comparisons between their results can still be made. From Table 1, it can be seen that the average thickness of Haxilegen Glacier is a modest value for glaciers in the eastern Tianshan Mountains and less than that of Urumqi Glacier No. 1 (Wang et al., 2014a), a valley glacier with an almost same area as Haxilegen Glacier No. 51. The collected information of glacier change studies in different regions of the Tianshan Mountains is listed in Table 2. It is shown that glacier shrinkage in the northern Tianshan Mountains is largest, up to an area percentage of ~30%–40% during the second half of the 20th century, and lesser in the eastern Tianshan Mountains. Even since the 1970s, the reduction of glacier area is very small in the central Tianshan Mountains. By contrast, the area shrinkage percentage of Haxilegen Glacier No. 51 (10.8%) is the smallest among the glaciers in the eastern Tianshan Mountains and close to that in the central Tianshan Mountains. The absolute reduction rate of this glacier, 0.004 km^2 a^{-1}, is the smallest for all observed glaciers in the Tianshan Mountains. The reason is that this glacier is a small cirque glacier and its shrinkage is mainly contributed by thickness decrease. Although a less absolute area reduction, the smaller glaciers generally have a larger relative area reduction percentage than larger ones. However, area of cirque glaciers is relatively stable compared with valley glaciers, or in other words, thickness decrease of cirque glaciers is more significant. Therefore, glacial/topographical features have an important impact on glacier change, beside climate causes. For instance, the two branches of Glacier No. 1 in Urumqi River have different shrinkage rates due to differences in slope, aspect, and so on (Xu et al., 2011).

Conclusions

The Haxilegen Glacier No. 51, taken as an only monitoring sample in the Kuytun River Basin , the second largest river on the northern slope of Chinese Tianshan Mountains, has been investigated in detail in order to understand its variation process. Data analysis of ice thickness, terminus location, and area indicates this glacier has been in a persistent shrinkage over past decades. Its area decreased by about 10% during the period 1964–2010, and

TABLE 2

Area changes of glaciers in the Tianshan Mountains.

Region		Studied glaciers	Period	Mean area change %	Mean area change km² a⁻¹	Source
Eastern Tianshan Mountains	Urumqi River Basin	Urumqi Glacier No. 1	1962–2009	16	0.006	Wang, P.Y. et al. (2014b)
	Middle Chinese Tien Shan	70 glaciers	1963–2000	13	0.19	Li et al. (2006)
	Southern Slope of Kalik Mountain	50 glaciers	1972–2005	12.3	0.25	Wang, W. B. et al. (2011)
	Mount Bogda	Sigonghe Glacier No. 4	1962–2009	15.8	0.011	Wang, P.Y. et al. (2012)
	Ebinur lake basin	446 glaciers	1964–2004	14.7	1.34	Wang, L. et al. (2014)
		133 glaciers	1964–2004	15.4	0.33	
	Kuytun River Basin	Haxilegen Glacier No. 51	1964–2010	10.8	0.004	This study
Northern Tianshan Mountains	Tuyksu glacier region	7 glaciers	1958–1998	20.2	0.04	Hagg et al. (2004)
		Central Tuyuksu	1958–1998	15.2	0.01	
	Sokoluk watershed	77 glaciers	1963–2000	28	0.24	Niederer et al. (2008)
	Zailiyskiy and Kungey Alatau	192 glaciers	1955–1999	32.6	1.78	Bolch (2007)
	Malaja Almatinka	12 glaciers	1955–1999	37.6	0.08	
	Bolshaja Almatinka	29 glaciers	1955–1999	34.5	0.20	
	Levyj Talgar	42 glaciers	1955–1999	33.1	0.54	
	Turgen	30 glaciers	1955–1999	36.5	0.30	
	Upper Chon-Kemin	31 glaciers	1955–1999	16.4	0.14	
	Chon-Aksu	48 glaciers	1955–1999	38.2	0.55	
	Ala Archa	48 glaciers	1963–2003	15.2	0.16	Aizen et al. (2006)
Central Tianshan Mountains	Eastern Terskey Ala-Too	335 glaciers	LIA–2003	19	0.55	Kutuzov and Shahgedanova (2009)
	Western Terskey Ala-Too	269 glaciers	1971–2002	8	—	Narama et al. (2006)
	Pskem region	525 glaciers	1970–2000	19	1.43	Narama et al. (2010)
			2000–2007	5	1.19	
	Ili-Kungőy region	735 glaciers	1970–2000	12	2.73	
			2000–2007	4	3.30	
	At-Bashy region	192 glaciers	1970–2000	12	0.46	
			2000–2007	4	0.60	
	SE-Fergana region	306 glaciers	1970–2000	9	0.58	
			2000–2007	0	0.13	
	Akshiirak	178 glaciers	1943–2003	12.5	0.89	Aizen et al. (2007)
	Big Naryn	507 glaciers	1950–2007	23.4	2.52	Hagg et al. (2013)
	Naryn basin	1478 glaciers	1970s to late 1990s	16	—	Kriegel et al. (2013)
			1970s to mid-2000s	23		

the reduction rate became larger and larger, from 0.0035 km^2 a^{-1} in 1964–2010 to 0.0053 km^2 a^{-1} in 1981–2010 and then to 0.0074 km^2 a^{-1} in 2000–2010. The average ice thickness decreased by 10 m from 1980s to 2010, resulting in an ice volume loss of ~29%. The cumulative retreat of the glacier terminus is approximately 106.8 m from 1964 to 2010, and near a half of it (49 m) is accounted for the in last decade (1999–2010). Combining these with analysis of meteorological data and comparison with studies of other glaciers in the Tianshan Mountains, we can conclude that under impact of intensive warming of local climate, the shrinkage of Haxilegen Glacier No. 51 is remarkable, especially with an accelerated shrinkage trend. Although its area reduction is small compared with other glaciers in the Tianshan Mountains, ice thickness and thus volume of it has a large decrease. Impact of the glacier volume decrease on river runoff can be verified by the hydrological data near to the glacier. In view of a glacier melting mechanism, this glacier will continue to shrink in the future even without further climate warming.

Acknowledgments

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