Effect of topography on the changes of Urumqi Glacier No. 1 in the Chinese Tianshan Mountains Post-print

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Abstract

Topography plays an important role in determining glacier changes, yet it has often been oversimplified in glaciological studies. No systematic studies have evaluated the relationship between glacier changes and topographic features. This study provides detailed insights into changes in the two branches (east and west) of Urumqi Glacier No. 1 in the Chinese Tianshan Mountains since 1993 and systematically discusses the effect of topography on glacier parameters. We analyzed comprehensive recently observed data (from 1992/1993 to 2018/2019), including mass balance, ice thickness, surface elevation, ice velocity, terminus position, and area, to determine differences in changes between the two branches and explore topographic effects. We also applied a topographic solar radiation model to analyze the influence of topography on incoming shortwave radiation (SWin) across the entire glacier, focusing on differences between the branches. The glacier mass balance of the east branch was more negative than that of the west branch from 1992/1993 to 2018/2019, mainly attributed to its lower average altitude. Compared with the west branch, the decrease rate of ice velocity was lower in the east branch owing to its relatively increased slope. The narrow shape of the west branch and its southeast aspect in the earlier period resulted in larger terminus retreat. The spatial variability of SWin across the glacier surface became much larger with increasing altitude. The SWin received by the east branch was slightly larger than that received by the west branch, and northern aspects could receive more SWin, leading to enhanced glacier melting.

Full Text

Preamble

Effect of Topography on the Changes of Urumqi Glacier No. 1 in the Chinese Tianshan Mountains

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Abstract: Topography plays an important role in determining glacier changes, yet it has often been oversimplified in glaciological studies. No systematic studies have evaluated the relationship between glacier changes and topographic features. This study provides detailed insights into changes in the two branches (east and west) of Urumqi Glacier No. 1 in the Chinese Tianshan Mountains since 1993 and systematically discusses the effect of topography on glacier parameters. We analyzed comprehensive recently observed data (from 1992/1993 to 2018/2019), including mass balance, ice thickness, surface elevation, ice velocity, terminus position, and area, to determine differences in changes between the two branches and explore topographic effects. We also applied a topographic solar radiation model to analyze the influence of topography on incoming shortwave radiation (SWin) across the entire glacier, focusing on differences between the branches. The glacier mass balance of the east branch was more negative than that of the west branch from 1992/1993 to 2018/2019, mainly attributed to its lower average altitude. Compared with the west branch, the decrease rate of ice velocity was lower in the east branch owing to its relatively increased slope. The narrow shape of the west branch and its southeast aspect in the earlier period resulted in larger terminus retreat. The spatial variability of SWin across the glacier surface became much larger with increasing altitude. The SWin received by the east branch was slightly larger than that received by the west branch, and northern aspects could receive more SWin, leading to enhanced glacier melting.

In the future, differences in glacier changes between the two branches will persist due to their topographic differences. This work is fundamental to understanding how topographic features affect glacier changes and provides information for

building different types of relationships between glacier area and ice volume to promote further studies on basin-scale glacier classification.

Keywords: glacier changes; topography; solar radiation; glacier terminus retreat; climate warming; Urumqi Glacier No. 1; Chinese Tianshan Mountains

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1. Introduction

As large solid reservoirs, mountain glaciers have a vital impact on regional water resources, ecosystems, and economic societies (Zemp et al., 2015; RGI Consortium, 2017; IPCC, 2019). Over the last 50 years, climate warming has caused most glaciers to shrink globally, with this shrinkage accelerating since the end of the last century (Vaughan et al., 2013; Farinotti et al., 2015; Zemp et al., 2015). Glacier mass loss in the Tianshan Mountains is mostly unsustainable, and ice volume in this region will reduce by at least 30.00% by 2100 (Miles et al., 2021). Nevertheless, glacier changes are not homogeneous worldwide (Yao et al., 2012; Vaughan et al., 2013; Zemp et al., 2015, 2019), and even within the same region under identical regional climate conditions, glaciers may differ in their responses due to variations in dimensions, shape types, and topographic characteristics (Wang et al., 2020). For example, detailed investigations of glaciers in the Tomor Peak of the Tianshan Mountains have demonstrated quite different shrinkage rates, with one terminus even becoming almost stable due to differences in topography and debris coverage. Therefore, understanding the effect of topography on glacier changes is crucial.

The surface topographic settings where most small glaciers ($<$0.400 km^2) are located can result in very limited glacier area, suggesting that topographic settings protect glaciers from direct solar radiation and create favorable conditions for glacier preservation (DeBeer and Sharp, 2007). Additionally, some glaciers with relatively high altitudes caused by topographic settings do not extend to low altitudes, which reduces glacier mass loss and benefits glacier preservation (DeBeer and Sharp, 2007, 2009). Thus, the local surface topographic settings of small glaciers have a significant effect on their responses to climate change. Basal topography also influences glacier retreat rates. For instance, basal topography strongly modulates the Humboldt Glacier in northern Greenland, producing substantial variations in retreat rate at seasonal to decadal timescales (Carr et al., 2015). Topography significantly alters the incoming shortwave radiation (SWin) received at the surface of valley glaciers in High Mountain Asia; during summer months (May–August), net shortwave radiation is one of the main components of the surface energy balance, usually accounting for 84.00% or more of available energy on the surface (Wang et al., 2020). Thus, changes in SWin amount can alter overall radiation and consequently have a significant influence on surface energy balance. The intensity of SWin received on a glacier surface is primarily a function of latitude and time of year, with components such as topographic shading, slope, and aspect controlling radiation distribution at local scales. Therefore, SWin is an important factor not only contributing to surface energy balance but also influencing glacier response and mass balance estimates (Olson and Rupper, 2019).

In the middle part of the Chinese Tianshan Mountains, Glacier No. 1 at the head of the Urumqi River (Urumqi Glacier No. 1) has been monitored since 1959 and completely separated into two branches in 1993. Observation results showed that the two branches exhibit different behaviors in their changes. Although many studies have reported observations and results for this glacier (Han et al., 2006; Jing et al., 2006; Li et al., 2010; Xu et al., 2019), the effect of topography on its changes has not been addressed in depth (Wang et al., 2018). Therefore, this study presents comprehensive recently observed data (including mass balance, ice thickness, surface elevation, ice velocity, terminus, and area) to discuss the effect of topography on Urumqi Glacier No. 1 based on differences between the two branches. Importantly, the spatial heterogeneity of SWin across topography, aspect, and slope was also assessed to accurately discuss the distribution of point-source SWin observations across the entire glacier. This study evaluated the impact of topographic features on glacier changes in combination with climate change to provide a more comprehensive understanding of glacier change processes.

2. Study Area

Urumqi Glacier No. 1 (43°07′N, 86°49′E), located in the central region of the Chinese Tianshan Mountains in Central Asia, is a cirque-valley glacier with two branches (Fig. 1 [Figure 1: see original paper]). This glacier was first investigated in 1959 and has been continuously monitored by the Tianshan Glaciological Station. Its area and length were 1.910 km^2 and 2.20 km, respectively, in the early 1960s based on the first mapping in 1962. Since then, it has experienced continuous shrinkage and was completely separated into two independent branches in 1993, presently covering an area of 1.521 km^2, of which the east and west branches occupied 0.970 and 0.551 km^2, respectively, based on observations in 2018.

The glacier region is mainly controlled by three dynamic factors: a westerly jet in the upper troposphere, Siberian anticyclonic circulation, and westerly cyclonic disturbance. According to observation data from the Daxigou Meteorological Station (3539 m a.s.l.), located 3 km southeast of Urumqi Glacier No. 1, the mean annual temperature was approximately –4.9°C and annual precipitation was 473.0 mm during 1959–2019. Mean annual temperature increased at a rate of 0.24°C/10a, and annual precipitation increased gradually at a rate of 21.8

mm/10a, based on linear analyses shown in Figure 2 [Figure 2: see original paper]. The main ablation period is from May to August, and precipitation mainly originates from water vapor carried by westerly winds. Precipitation from May to August accounts for 78.00% of the annual total amount, with main types being solid fall such as snow, hail, and sleet.

3. Observation Data and Processing Method

The two branches of Urumqi Glacier No. 1 were observed in terms of mass balance, ice thickness, surface elevation, ice velocity, terminus position, and area. Table 1 provides all observation items and their data. As Urumqi Glacier No. 1 separated in 1993, we extended some data items, such as terminus position, before 1993 to compare situations before and after separation. This paper briefly introduces the observations, data processing, and related uncertainties in recent years.

3.1.1 Mass Balance

The mass balance of Urumqi Glacier No. 1 has been conventionally observed using the stake/snow pit method during the ablation season from 1 May to 31 August since 1959. The mass balance from 1993 to 2019 was used for subsequent analyses. The number of stakes differed across years, with 42 or 43 stakes distributed across the entire glacier in recent years (Fig. 1b). Observation items for each mass balance stake included the vertical height of stakes over the glacier surface and stratigraphy of snow pits, including thickness and density of the firn layer and thickness of superimposed ice. The density of superimposed ice was assumed to be 900 kg/m^3 due to difficulty of in situ measurements (Xu et al., 2019).

3.1.2 Ice Thickness

Integrated observations using ground-penetrating radar (GPR) equipment were carried out to determine ice thickness in 2001, 2006, and 2012. The GPR equipment comprised an enhancement radar system (pulse EKKOPRO 100 A, Sensors and Software Inc., Mississauga, Canada) equipped with 100 MHz resistively loaded dipole antennae. The field survey was conducted with antennae oriented perpendicular to survey lines, ensuring maximum power transmission in-line. Reflections from offline were minimal, although high-conductivity surface features could produce reflections (e.g., survey poles and data loggers) (Sensors and Software Inc., 1994; Murray et al., 1997). GPR survey point positions were concurrently determined using Real-Time Kinematic (RTK) Global Positioning System (GPS) (Unistrong E650, Beijing UniStrong Science and Technology Co. Ltd., Beijing, China). GPR measurement paths included seven transverse profiles along stake rows and one longitudinal profile along center lines in both east and west branches. GPR data were processed using EKKO View Deluxe software (professional version developed by Sensors and Software Inc., Mississauga, Canada) to obtain corresponding two-dimensional radar images of survey paths.

3.1.3 Surface Elevation

Surface elevation was obtained using a theodolite in 2001, total station in 2006, and RTK GPS in 2009 and 2012. Specifically, the Unistrong E650 GPS (produced by Beijing UniStrong Science and Technology Co. Ltd., Beijing, China) was used in 2009 and 2012. Digital elevation models (DEMs) with 1 m resolution were established by interpolating GPS survey data. A map from the terrestrial stereo-photographic survey of 1994 was also used to derive the DEM. From 2015 to 2017, a terrestrial laser scanning system, Riegal VZ®-6000 (Riegal Company, Horn, Austria), was used to survey glacier surface elevation from four scan positions at the glacier terminus every year (Xu et al., 2019). An unmanned aerial vehicle (UAV; MATRICE 200, DJ-Innovations, Shenzhen, China) survey was conducted at the end of August 2018, covering nearly the entire Urumqi Glacier No. 1. We then used Pix4Dmapper software (Pix4D S.A., Prilly, Switzerland) to generate a glacier DEM in 2018 with 1 m spatial resolution, according to the method of Li et al. (2022). DEMs were resampled to the same spatial resolution. We further compared DEMs from different periods to determine glacier surface elevation changes over respective time periods. According to Nuth and Kaab (2011), it is necessary to co-register DEMs before extracting glacier surface elevation changes.

3.1.4 Ice Velocity

Traditionally, ice velocity is obtained by installing a network of stakes and surveying position changes on the glacier surface. Ablation stakes were also used for ice velocity measurements. Previously, theodolite and total station instruments were used, whereas GPS was not employed until 2007. GPS was then used to measure stake positions after 2007. Measurement methods varied by year, as explained by Wang et al. (2018). The GPS survey method was described in Section 3.1.3. We calculated displacement vectors in the X and Y directions of ablation stakes based on two measurements within a certain period. Stake displacement was considered as ice velocity at the corresponding stake position. Similar to other glacier observation items, ice velocity change during 1994–2019 was analyzed.

3.1.5 Terminus Position and Glacier Area

Changes in the terminal position of Urumqi Glacier No. 1 were determined using both GPS survey and tape measurements. Several sites around the terminus edge were measured using GPS at the beginning (1 May) and end (31 August) of the ablation season, and the distance of each site to a stationary landmark was simultaneously measured using a tape measure. These actions were taken for both east and west branches.

Glacier area was determined by terrestrial stereo-photographic mapping in 1994 and 2000, theodolite in 2001, total station in 2006, and RTK GPS in 2009 and 2012. Measurement procedures using theodolite and total station instruments have been introduced in previous studies (Dahl-Jensen et al., 1986; Wang et al., 2014). Since 2015, laser-scanning systems have been used to determine glacier area (Xu et al., 2019). In 2018, glacier area was surveyed using a UAV.

3.1.6 Topographic Characteristics

To analyze the effect of topography on glacier changes, we derived topographic characteristics including surface elevation distribution, slope, and aspect from DEMs in 1994 and 2018, processed using 3D Analyst Tools in ArcMap 10.3 software (Environment System Research Institute, ESRI, Redlands, USA). Subglacial topography was constructed by subtracting ice thickness surveyed in 2012 from glacier surface elevation during the same period. Basal topography was analyzed by assuming subglacial topography remained unchanged during these periods.

3.1.7 Incoming Shortwave Radiation (SWin)

To investigate SWin distribution across the entire glacier, we observed point-source SWin at an automatic weather station (4025 m a.s.l.) deployed on Urumqi Glacier No. 1 from 30 April 2018 to 30 April 2019.

3.2 Data Processing Methods

3.2.1 Mass Balance Change

The mass balance of a single point (b) can be calculated using the method of Paterson (1994) as follows:

$$b = b_s + b_{gi} + b_{si}$$

where b_s, b_{gi}, and b_{si} are the mass balances of snow, glacier ice, and superimposed ice, respectively, with units of m w.e. (meter water equivalent).

Based on point observations, specific mass balance can be calculated using one of two methods. The first method interpolates point mass balance by drawing equal mass-balance contour lines. Specific mass balance (b_n) is obtained as follows:

$$b_n = \frac{1}{s}\sum_{i=1}^{n} b_i s_i$$

where s is total glacier area (km^2), s_i refers to area between two contour lines (km^2), and b_i is corresponding mass balance (m w.e.).

The second method is based on repeated point measurements at different altitudes. Specific mass balance (b_n) can be calculated by extrapolating point mass balance to the entire glacier as a linear function of altitude:

$$b_n = \sum_{i=1}^{n} b'_i s'_i$$

where n is total number of altitude bands, s'_i is area of altitude band (km^2), and b'_i is corresponding mass balance (m w.e.).

3.2.2 Ice Thickness Change

Ice thickness (h; m) can be calculated using two-way travel time (t_s, with unit of ns (nanosecond)) of radar wave from vertical axis and velocity of radar signal in glacier (v; m/ns), as shown in Equation 4:

$$h = \frac{t_s v}{2}$$

Radar signal velocity in mountain glaciers ranges from 0.167–0.171 m/ns (Glen and Paren, 1975; Robin, 1975; Narod and Clarke, 1994). In this study, we set velocity at 0.169 m/ns based on field tests.

3.2.3 Surface Elevation Changes

To determine glacier surface elevation changes over respective time periods, we compared DEMs of Urumqi Glacier No. 1 at different periods, as mentioned in Section 3.1.3. It is necessary to co-register DEMs before extracting glacier surface elevation changes (Nuth and Kaab, 2011). DEM uncertainties are usually estimated in two ways: (1) comparing DEM values with an independent set of GPS points in non-glaciated areas; and (2) simultaneously rectifying horizontal displacements and vertical biases based on cosinusoidal relationship between surface elevation difference and topographical parameters (slope and aspect).

To analyze ice thickness change during 1994–2018, we synthesized data from different sources, including thickness and surface elevation changes. Finally, the relationship between ice thickness change and surface elevation changes during 2001–2006 and 2006–2012 was established.

3.2.4 Solar Radiation Modelling

SWin is an important factor affecting glacier melting. Spatial distribution of SWin on glacier surface may result in differences in glacier melting. Therefore, we used a solar radiation model to explore spatial variation of SWin in Urumqi Glacier No. 1 (Kumar et al., 1997) and analyzed SWin of east and west branches. The solar radiation model included effects of terrain shading and cloud cover.

It can compute clear-sky direct and diffuse shortwave radiation in response to geographical position, altitude, slope, and aspect of the glacier (Kumar et al., 1997). Forcing data comprised latitude, spatial resolution of DEM, and ground reflectance, with default of 0.2. Potential SWin was computed and then corrected for cloud cover through SWin measured at an automatic weather station (4025 m a.s.l.) deployed on Urumqi Glacier No. 1 from 30 April 2018 to 30 April 2019. The $r_{ix,y}$ is ratio of potential SWin to measured SWin. Spatially distributed SWin ($Q_{corrx,y}$) can be expressed as measured SWin multiplied by $r_{ix,y}$ (ratio of potential SWin to measured SWin). In our study, UAV-DEM was derived from UAV in 2018 (see Section 3.1.3). To improve computer operation efficiency, we resampled UAV-DEM to 30 m resolution, then carried out coordinate normalization using WGS84 datum (EPSG: 4326) and UTM 45N projection and applied data to obtain spatially distributed SWin.

3.2.5 Statistical Analysis

In this study, statistical analysis of annual average temperature and annual precipitation was carried out using linear fitting method. Origin 2018 (OriginLab, Northampton, United States) and ArcMap v.10.3 (Environment System Research Institute, ESRI, Redlands, USA) were used for figure preparation.

4.1 Changes in the Two Branches

Figure 3a [Figure 3: see original paper] shows annual mass balance changes in east and west branches from 1992/1993 to 2018/2019. Results indicate that after separation of Urumqi Glacier No. 1, mass balance of east branch became more negative than west branch from 1992/1993 to 2018/2019, except for 1996/1997 and 2003/2004. Both branches experienced overall decreasing trends in mass balance with large inter-annual variability, but west branch changed less than east branch. The period 1997–2008 appeared to be a stage of continuous decrease, with an abnormally low value occurring between 2009 and 2010. Afterwards, a four-year increase stage occurred, followed by a relatively steady stage after 2015, but highest increase occurred again in 2019. We checked meteorological data in years with abnormally high and low mass balance values and found that summer (June–August) temperature was the most important factor, followed by annual average temperature and annual precipitation, consistent with previous discussions of relative importance of meteorological parameters (Wang et al., 2016). For instance, summer temperature was usually higher than 4.2°C during the study period (except for 2009, 2014, and 2019, with values of 3.0°C, 3.2°C, and 3.3°C, respectively), corresponding to extremely high mass balance values in these years.

Maximum ice velocity series from 1992/1993 to 2018/2019 is shown in Figure 3b, illustrating ice velocity changes after separation and differences between west and east branches. Patterns of average and minimum ice velocities were similar to maximum ice velocity. Ice velocities of both branches were in continuously decreasing state, with decreasing rate of west branch being larger than east branch overall until 2010/2011, after which they became almost the same for both branches. Higher decreasing rate of ice velocity in west branch was attributed to higher slope (Wang et al., 2016).

Figure 3c shows changes in glacier terminus position since 1980. Generally, glacier terminus retreat was larger after separation than before. Glacier terminus retreated at rate of 4.0 m/a from 1980 to 1993 (before separation), and retreat rates of east and west branches were 5.0 and 5.8 m/a, respectively, from 1994 to 2020 (after separation). Glacier terminus change process can be roughly divided into three stages: period before 1993, period of 1994–2011, and period after 2011. In first stage (before 1993), terminus retreat rate remained steady and low, with value of approximately 3.60 m/a from 1983 to 1988, while fluctuating significantly in other years. In second stage (1994–2011), east branch had lower terminus retreat rate between 3.1 and 3.7 m/a, whereas west branch had much higher retreat rate with stepped fluctuation between 4.7 and 7.0 m/a. In third stage (after 2011), pattern of terminus retreat rate in east and west branches reversed compared to previous stage. Terminus retreat rate in east branch sped up suddenly in 2011/2012 and remained at nearly 8.0 m/a in other years; in contrast, terminus retreat rate in west branch slowed to less than 4.0 m/a. In recent years, glacier terminus retreat has become increasingly complex.

Ice thickness change trends in different periods are shown in Figure 4 [Figure 4: see original paper]. Thinning rate of entire glacier was calculated using area-weighted average of two branches. Specifically, thinning rate of east branch was larger than west branch on average, but both remained almost same in early years following separation. Since 2006, thinning rate of east branch remained clearly larger than west branch, but difference between east and west branches seemed to have decreased in recent years.

Photographs of Urumqi Glacier No. 1 in different years (Fig. 5 [Figure 5: see original paper]) visually show glacier shrinkage process. Table 2 presents glacier area change values of east and west branches from 1994 to 2018. These values demonstrate that east branch area reduced from 1.115 to 0.983 km^2 at rate of 5.740$\times10^{-3}$ km^2/a, while west branch reduced from 0.627 to 0.559 km^2 at rate of 2.960$\times10^{-3}$ km^2/a. Relative change rates were –0.006 km^2/a for east branch and –0.003 km^2/a for west branch, indicating large difference between branches. However, shrinkage of west branch was larger than east branch before 2009 but decreased thereafter. Main reason is that narrow shape and southeast- and south-dominated aspects of west branch tongue in earlier period were beneficial for terminus melting and retreat. Glacier area shrinkage rate was much larger after separation (0.009 km^2/a) than in previous period from 1962 to 1992 (0.002 km^2/a).

4.2 Topographic Differences of the Two Branches

Combined with glacier area, terminus (or length), hypsometry, and accumulation area ratio, topographic characteristics of east and west branches can be elucidated by maps of altitude, slope, aspect, and subglacial topography, as shown in Figures 6 and 7. Altitude of Urumqi Glacier No. 1 ranged from 3740 to 4478 m a.s.l., where average altitudes of east and west branches were 3994 and 4127 m a.s.l. in 2018, respectively. In comparison, average altitudes were 3985 and 4123 m a.s.l. for east and west branches in 1994, respectively. Both average and terminus altitudes of east branch were lower than those of west branch.

Average slope angles of east and west branches were approximately 22° and 24° in 2018, and about 21° and 22°, respectively, in 1994. In contrast, both slope distribution and average slope value show that slope angle of east branch was lower than west branch. Aspect maps show that west branch faced east, whereas east branch mainly faced north. Additionally, subglacial topography, as shown in Figure 7 [Figure 7: see original paper], indicates that basal topography of east branch was more undulating than west branch and that ice thickness of east branch was larger than west branch.

Our results further demonstrate that shrinkage of west branch was larger than east branch before 2009, and narrow shape and southeast- and south-dominated aspects of west branch tongue during same period were beneficial for terminus melting and retreat. Therefore, slope and aspect of glacier strongly influenced glacier area reduction. In addition, glacier shape directly affected ice dynamics. Urumqi Glacier No. 1 exhibited wide cross-sections in firn basins and narrow cross-sections in ablation zones (Fig. 6 [Figure 6: see original paper]). Ice velocity, an ice dynamic element, was also related to ice thickness, and distribution pattern of ice thickness was similar to that of ice velocity (Fig. 3) (Wang et al., 2018).

4.3 Impact of Incoming Shortwave Radiation (SWin) on Glacier Changes

During period from 30 April 2018 to 30 April 2019, spatial variability of SWin across glacier surface became much larger as altitude increased, based on UAV-DEM shown in Figure 8 [Figure 8: see original paper]. Mean change of SWin calculated by UAV-DEM for all combined topographic components was greatest at lower altitudes ($<$3886 m a.s.l.) and then began to decrease with altitude increase; however, at higher altitudes ($>$4300 m a.s.l.), it exhibited slightly increasing trend. Mean changes of SWin in west and east branches were 143 and 150 W/m^2, respectively. SWin in east branch was slightly larger than in west branch, which may be due to lower altitude of east branch (Fig. 9 [Figure 9: see original paper]). Additionally, estimated result of UAV-DEM indicates that northern aspect could receive more SWin, as shown in Figures 6f and 8. Such variations would surely have significant effect on heat budget of different sites, thus influencing glacier surface melting.

5.1 Uncertainties of Individual Glacier Parameters

Glacier mass balance within a budget year can be obtained using stakes or snow pits. In this study, we aimed to analyze difference in mass balance of two branches before and after 1993 (separation of Urumqi Glacier No. 1) to potentially reflect impact of topography on glacier changes. Uncertainties of in situ mass balance can usually be categorized into three terms. First, according to Fountain and Vecchia (1999) and Kuhn (1999), value of $±$0.10 m w.e./a is usually adopted for field measurement. Second, Hock and Jensen (1999) demonstrated that error introduced by Kriging interpolation method is approximately $±$0.10 m w.e./a for single point mass balance. Third, glacier retreat could result in overestimation of mass loss of $±$0.02 m w.e./a for Urumqi Glacier No. 1 (Xu et al., 2019). Additionally, internal accumulation and ablation cannot be quantified. We recognized that internal accumulation and ablation could lead to small but significant systematic cumulative errors. By considering factors mentioned above, annual uncertainty of in situ mass balance was therefore $±$0.14 m w.e./a without taking into account systematic uncertainties. Cumulative uncertainty of mass balance was $±$0.73 m w.e. during period of 1993–2019.

To determine glacier surface elevation changes over respective time periods, we compared DEMs of two branches at different periods, as mentioned in Section 3.1.3. According to Wang et al. (2014), relative error of DEMs during 1994–2009 was less than $±$0.30 m based on GPS points in non-glaciated area. For DEMs between 2012 and 2015, ten independent GPS points in non-glaciated area were selected to perform uncertainty analysis of DEMs with $±$0.33 m, and after co-registration, mean surface elevation difference in non-glaciated area was $±$0.41 m (Li et al., 2022). For DEMs between 2015 and 2017, standard error was estimated by calculating surface elevation changes from terrestrial laser scanning system over non-glaciated area with 0.23 m in 2015–2016 and 0.16 m in 2016–2017 (Xu et al., 2019). Surface elevation difference in non-glaciated area during 2017–2018 was 0.68 m. It was concluded that surface elevation difference in non-glaciated area had stabilized, making processed DEM difference suitable for estimating glacier surface elevation changes.

Glacier terminus position data were input into same coordinate system, and terminus change was obtained by comparing data from various periods. Tape measurement error was very small and mainly determined by manual operation. Glacier area change can be derived from comparison of topographic maps for different periods. After integrated evaluation, overall uncertainty in glacier area change during 1994–2018 was approximately 0.01 km^2 according to Williams et al. (1997), Hall et al. (2003), and Silverio and Jaquet (2005).

Accuracy of ice thickness estimation depended on accuracy of measurement system and properties of ice and bedrock. Relative error of measurement system was approximately 1.18%. Combined with survey points and measurement path differences for different surveys, ice thickness distribution for each survey caused errors when using different interpolation methods. Properties of ice and bedrock (e.g., crevasses and bedrock roughness) had significant influence on ice thickness estimation, though this is difficult to determine. Error caused by neglecting firn layers was estimated at approximately 5.00% according to Haeberli et al. (1982).

Relationship between ice thickness and surface elevation changes was compared in this section. Comparison results show that correlation coefficient was 0.75 and root mean square error was 3.40 m. Difference was within 10.00%, indicating good agreement between ice thickness and surface elevation changes. Therefore, ice thickness change trend can be demonstrated in more detailed time intervals over long-term period.

Estimated error of ice velocity at each point was <10.00% of ice velocity components in X and Y axis directions (Wang et al., 2018). Uncertainty of ice velocity and its changes also depended on interpolation method and glacier surface characteristics, such as ice thickness and slope.

5.2.1 Glacier Mass Balance and Ice Thickness

If adjacent glaciers or branches of a glacier have same topography, their mass balance should be close because they are in same regional climate conditions. However, differences in topography (see Fig. 6) can result in differences in mass balance between them. Affected by altitude, slope and aspect of glacier, energy received by glacier is different, which eventually leads to difference in glacier mass balance.

First, because average altitude of east branch is lower than west branch, increase of SWin will inevitably lead to greater amount of glacier melting on surface of east branch than on surface of west branch (Fig. 9). Second, we calculated accumulation area ratio of two branches annually and found that accumulation area ratio of east branch was generally lower than west branch, as shown in Figure 10a [Figure 10: see original paper]; therefore, larger ablation area ratio of east branch resulted in higher glacier mass loss rate. Third, both east and south aspects influenced amount of solar radiation received. Figure 6 shows that lower section of west branch faced east and south more than east branch, suggesting more intensive glacier melting in west branch than east branch. However, large part of upper section in east branch facing northwest was beneficial for receiving strong solar radiation in afternoon, whereas upper section of west branch faced mainly northeast and north, meaning it received less solar radiation (Fig. 9). According to study of Yue et al. (2017), on average, albedo did not have apparent difference between east and west branches, although it was slightly less for west branch. Therefore, it can be concluded that lower altitude and accumulation area ratio are main factors leading to more negative glacier mass balance in east branch. Influence of topography on solar radiation is complex due to complicated surface features and aspect changes in lower section of branches over time. For example, area of west branch tongue facing south shrank as glacier terminus retreated. Albedo was closely related to both surface impurity concentration and topographic shield.

Topographic difference between east and west branches led to similar trend in ice thickness and glacier mass balance changes, that is, thinning rate of east branch was larger than west branch on average. This is reasonable because ice thickness change is determined mostly by glacier mass balance (Huang et al., 2018), so higher glacier mass loss will cause greater thinning in east branch than west branch.

5.2.2 Ice Velocity

Because accumulated glacier mass in upper section of two branches is transported down to ablation area through ice movement, ice velocity is one of significant factors controlling surface and dimensional changes of Urumqi Glacier No. 1. Slope influences ice velocity and mass balance, and may also impact snow accumulation rate through its effect on avalanche transport of snow on glacier surface. Figure 3b shows that ice velocity of west branch was always higher than east branch, but difference decreased, particularly after 2010. Previous studies, such as Li et al. (2011), concluded that Urumqi Glacier No. 1 was predominantly cold-based, with basal sliding occurring only close to its snout. It is well known that ice velocity caused by creep deformation mainly depends on ice thickness and slope (Paterson, 1994). After analyzing effects of ice thickness and slope using basic dynamic principle, Wang et al. (2018) found that ice velocity is more sensitive to slope compared to ice thickness, and larger slope will lead to higher ice velocity in west branch than east branch. Figure 6 shows that slope was higher in west branch than east branch. Calculated average slope indicates that difference in slope between west and east branches declined to some extent, as mentioned above. This coincides with change trend of maximum ice velocity, as shown in Figure 3b; that is, ice velocity was higher in west branch than east branch, gradually becoming closer under current slope changes. Because average ice thickness in early 2000s was larger in east branch (approximately 59.0 m) than west branch (approximately 45.0 m), contribution of ice thickness to ice velocity was larger in east branch than west branch. However, measured ice velocity in east branch was lower than west branch, indicating that effect of ice thickness was less than that of slope.

From Figure 7 we can conclude that compared with west branch, more undulant basal topography of east branch has retardative effect on ice movement. Therefore, difference in ice velocity between west and east branches is result of comprehensive effects of slope, ice thickness, and basal topography.

5.2.3 Glacier Terminus

Changes in terminus of a glacier are mainly controlled by glacier mass balance and ice velocity near terminus. Results of this study mentioned above indicate that glacier mass balance of east branch was more negative, and ice velocity of east branch was lower than west branch, which makes mass supply in terminus of east branch slow. Combination of these two factors led to larger glacier terminus retreat for east branch than west branch. However, before 2012, measured glacier terminus retreat was lower for east branch than west branch (Wang et al., 2016; Li et al., 2022).

Comparing ice thickness and shape of east branch with west branch, west branch tongue was much narrower with pointed terminus, making absolute ice thickness thinner than east branch. Another factor is that southeast aspect of west branch tongue in earlier period benefitted more from solar radiation for glacier melting; therefore, glacier melting rate of west branch was stronger (Wang et al., 2016). This feature must have led to larger terminus retreat rate in west branch compared with east branch if differences in glacier melting rate and ice velocity between east and west branches were not too large. From observation data in Figure 10b and c, glacier melting rate did not show systematic differences at stakes closest to terminus of east or west branch, while ice velocity at stake of west branch was much higher than east branch before 2007, but difference gradually decreased thereafter. Thus, glacier terminus retreat was influenced by combined effects of tongue shape, melting rate, and ice velocity.

Since 2011/2012, difference in glacier terminus retreat between west and east branches seemed to have become more complex. West branch retreated more than east branch in some years but less in other years, with frequent alternation after 2015. In view of small difference in ice velocity between west and east branches after 2010, glacier melting rate and topography were main causes of difference in terminus retreat. In particular, difference in glacier melting was more important because topography changed little from year to year.

5.3 Changes of East and West Branches in Response to Climate Change

It is widely accepted that glaciers in High Mountain Asia will continue to shrink under background of climate warming or even cessation of warming due to lag of glacier responses to climate change (Li et al., 2011; Yao et al., 2012; Farinotti et al., 2015; Zemp et al., 2015, 2019; IPCC, 2019), as is case for Urumqi Glacier No. 1 (Li et al., 2011; Xu et al., 2011; Wang et al., 2016). However, it still needs to be explored whether this glacier retreat will accelerate, although some studies have indicated that glacier retreat in Tianshan Mountains, including Urumqi Glacier No. 1 specifically, has accelerated in recent decades and will continue to do so in near future (Pieczonka et al., 2013, 2015; Brun et al., 2017). Observational data suggest that glacier shrinkage became more rapid after 1990s than before, but observed glacier mass balance did not appear to have become more negative since 2012, based on comparison between mean values of 2012–2019 and 1997–2011 (Fig. 3a). Average glacier mass balance was –0.8 m w.e. during 1997–2011 and –0.7 m w.e. during 2012–2019 in east branch, whereas it was –0.6 and –0.4 m w.e. during 1997–2011 and 2012–2019 in west branch, respectively. If current climate conditions are maintained in future, negative glacier mass balance and terminus retreat will undoubtedly continue, but terminus retreat will slow gradually when terminus positions of east and west branches retreat to higher altitudes.

Owing to topographic differences, changes in glacier mass balance, ice velocity, and terminus retreat will inevitably differ between east and west branches despite same climate conditions. As mentioned above, glacier mass balance was more negative for east branch than west branch because of lower average altitude and accumulation area ratio in east branch. Ice velocity of both branches will continue to decrease in future, but velocity of east branch may catch up and even exceed that of west branch because east branch is thicker on average and slope difference between west and east branches diminishes gradually. Difference in terminus retreat is complicated because it depends not only on glacier melting rate and ice velocity at terminus but also on shape of glacier snout. In addition, shape and size of glacier are important factors controlling glacier dynamics. It was previously found that small glaciers lost more area than large glaciers because small glaciers such as Urumqi Glacier No. 1 are generally more sensitive to climate change (Oerlemans, 1989). Response time of glacier to climate change can be roughly estimated from simplest formula introduced by Paterson (1994), which is based on ideal assumption. According to Wang et al. (2016), actual response time is likely to be shorter than estimated value, perhaps around 10 years. This suggests that Urumqi Glacier No. 1 will continue to shrink in coming decade even without further climate warming due to time required to respond to previous climate warming. Nevertheless, it can be imagined that when east and west branches shrink, terminus retreat of east branch will be faster than west branch, as lower altitude and western-facing direction of east branch would lead to more ice loss compared to west branch.

6. Conclusions

Under background of climate warming, Urumqi Glacier No. 1 has experienced continuous mass loss and dimensional shrinkage in recent decades; however, after separation into two branches, no obvious accelerated trend was identified in recent years. Observation data show that differences existed between east and west branches in terms of glacier mass balance and dimensional changes, such as terminus retreat, thickness decrease, and ice velocity change. Difference in glacier area shrinkage between two branches was not large, although east branch shrunk slightly more. From comparison of topographic features of two branches, greater negative glacier mass balance in east branch was mainly attributed to lower average altitude and accumulation area ratio. As expected, larger negative glacier mass balance led to higher average thinning rate of east branch, although thinning rate between east and west branches differed in different years. Narrow and pointed snout of west branch and its southeast aspect resulted in larger terminus retreat for west branch. Ice velocity decreased in both branches, but decrease rate was lower in east branch owing to its increase in slope.

A topographic solar radiation model was used to quantify spatial variability of SWin across glacier surface. It indicated that SWin became much larger as altitude increased based on UAV-DEM, and north aspect could receive more SWin, resulting in glacier melting. Importantly, SWin was greatest at lower altitudes (<3886 m a.s.l.) and then began to decrease with altitude increase; however, at higher altitudes (>4300 m a.s.l.), it exhibited slightly increasing trend. SWin received by east branch was slightly larger than that received by west branch, probably due to lower altitudes of east branch.

In future, both branches of Urumqi Glacier No. 1 will continue to shrink due to climate warming; however, differences between two branches will persist owing to their topographic differences. East branch retained more negative glacier mass balance and larger thinning rate than west branch. Ice velocity of both branches will decrease continuously, but velocity of east branch may catch up to and even exceed that of west branch after some years. With continuous decrease in glacier area, terminus retreat of east branch may exceed that of west branch because east branch has lower average altitude and western-facing direction would lead to more ice loss compared to west branch.

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Note: Figure translations are in progress. See original paper for figures.