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# Long-term change in ice velocity of Urumqi Glacier No. 1, Tian Shan, China

**Puyu Wang[1*], Zhongqin Li[1,2], Ping Zhou[1], Huilin Li[1], Guobin Yu[3], Chunhai Xu[1], Lin Wang[1]**

1 State Key Laboratory of Cryosphere Science/Tianshan Glaciological Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China;

2 College of Geography and Environmental Science, Northwest Normal University, Lanzhou, China;

3 Geomatics Center of Gansu Province, Lanzhou, 730000

*Correspondence to Puyu Wang (wangpuyu@lzb.ac.cn)

**Abstract** Glacier flow velocity of Urumqi Glacier No. 1 has been continuously measured at the end of every summer since 1980. The observation results show that the average surface velocity was 5.5 m $a^{-1}$, 4.6 m $a^{-1}$, 3.8 m $a^{-1}$, and 3.3 m $a^{-1}$ in 1980/1981, 1990/1991, 2000/2001, and 2010/2011, respectively. The annual average velocity was reduced by 1.3% $a^{-1}$ from 1980/1981 to 2011/2012. The climate change is the essential cause for long term velocity change because continuous mass loss or gain will result in ice thickness decrease or increase. A suddenly sharp change in the mass balance could lead to a short change in velocity. Long term change in the velocity can be analyzed by glacial dynamic model. Using the simplified equations, analysis of the surface velocity along the centerline shows that influence of the ice thickness change is most important and could be modeled well. The velocity is very sensitive to the surface slope change but the validity of its effect modeling is relatively low due to the large spatial variability of surface slope. Under the combination effect of decrease in both ice thickness and surface slope, the velocity of the West Branch has a relative large decrease. The calculated decrease in surface velocity along the centerline is 3.8 m $a^{-1}$ from 1981 to 2012, relatively close to the value of 3.6 m $a^{-1}$ from observation. Increase in surface slope of the East Branch has an offsetting effect on ice thickness decrease. To further analysis, besides more data, a better model is needed to describe physical and dynamic processes.

**Key words:** ice velocity; glacier change; ice thickness; surface slope; Urumqi Glacier No. 1; Tian Shan

## 1. Introduction

It is well known that the widespread mountain glaciers conserve huge fresh water and hence their changes have vital impacts on regional water resource and economic society besides sea level (Arendt et al., 2012; IPCC, 2013; Vaughan et al., 2013; Zemp et al., 2015; Li et al., 2016). With the global warming increasing, almost all glaciers world-wide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume and mass since the middle of the last century and their retreat has been accelerating in the most recent 30 years (Davies and Glasser, 2012; Marzeion et al., 2012; Yao et al., 2012; Gardner et al., 2013; Vaughan et al., 2013; Zemp et al., 2011, 2015).To understand past glacier variation mechanism, therefore, is needed for predicting their future change in different regions because there are regional differences in glacier variation revealed by observations (Ren et al, 2012; Vaughan et al, 2013). Even in a same region under a same climate condition, different glaciers may change differently due to differences in their dimensions, shape types and topographic characteristics. This is because that although glacier variation is generally controlled by climate conditions, the response process of a glacier to climate change is mainly dependent on the glacial dynamics. Climate conditions determine the mass budget on a glacier and the accumulated mass in the upper stream is transported down to the ablation area through ice movement. Thus both ice velocity and mass balance are significant factors controlling glacier surface and dimensional change.

Ice velocity can be studied using field measurements by repeatedly measuring stakes on the accessible glacier (e.g. Manson et al., 2000; Hubbard and Glasser, 2005; Sugiyama et al., 2013) or cross-correlation of optical remote sensing images (Berthier et al., 2005; Kääb, 2005; Scherler et al., 2008; Herman et al., 2011; Nishimura et al., 2013), interferometry of synthetic aperture radar (InSAR) data (e.g. Kwok and Fahnestock, 1996; Berthier et al., 2003; Rignot et al., 2011; Schubert et al., 2013) and offset tracking in SAR images (Michel and Rignot, 1999; Strozzi et al., 2002). The remote sensing based methods can be used to monitor a large number of glaciers in highly remote regions and they are most appropriate for analyzing glacier velocity at very short time scales (e.g. 6 days; Massonet and Feigl, 1998). Nevertheless, the accuracy largely depends on processing procedures, such as ortherectification by DEM, and the quality of the imagery, which is influenced by many factors such as cloud coverage, looking angle of the sensor, and accuracy of the altitude. Although field measurement can only be carried out on a few easy to access glaciers due to cost in funds and labor, these measurements exhibit high spatial and temporal accuracy.

Long-term stationary monitoring of selected glaciers in different regions can provide better basic data for analysis of the response of flow velocity and dynamics to climate change. Glacier No. 1 at the headwater of Urumqi River (abbreviated as Urumqi Glacier No. 1), Tian Shan, is the longest stationary monitoring glacier in China. Observations on the glacier were taken interruptedly between 1959 and 1967 and uninterruptedly since 1981. Various publications have reported its observations and study results. Among them, a few are related to ice velocity and mainly on spatial distribution of surface velocity and comparison with glaciers in other regions (Huang and Sun, 1982; Huang, 1994; Zhou et al, 2009). Only one discussed the surface velocity change and concluded that the continuous mass loss caused by climate warming had led to an ice velocity decrease (Zhou et al, 2010). Since climate and mass balance have been reported in many studies (Han et al., 2006; Li et al., 2010; Wu et al., 2011; Zhang et al., 2014), in this paper, we illustrate the ice velocity measurement result with more details and then analyze various causes of the velocity change with respect to the glacier movement principle with emphasis on causes of ice thickness and surface slope changes.

## 2. Observation and data

### 2.1. Observation methods

Urumqi Glacier No. 1 (86°49' E, 43°07' N) is a valley glacier with two branches, located in the middle part of Chinese Tian Shan, about 130 km southwest from Urumqi city, the capital of the Xinjiang Uygur Autonomous Region (Figure 1a). The glacier was firstly investigated in 1959, and then a glaciological station was set up near it. The first survey and mapping were carried out in 1962. From that map, its area and length were 1.91 $km^2$ and 2.2 km, respectively. It completely separated into two independent glaciers in 1993 and presently covers an area of 1.59 $km^2$, of which the east and west branches occupy 1.02 $km^2$ and 0.57 $km^2$ with a length of 1.99 km and 1.59 km, respectively.

Since the building of monitoring station, this glacier has been observed for mass balance, ice velocity, terminus location, meteorology and hydrology every year, except for the period of 1967-1978, during which the station was closed but some observations such as terminus and velocity were taken occasionally. The glacier surface elevation survey has been made nine times, and ice thickness has been measured four times. Moreover, borehole temperature measurements nearly down to the bed were conducted at an altitude of 3,840 m a.s.l. on this glacier in 1986, 2001, and 2006. The observations before 2010 were introduced and summarized by Li (2011) and recent observations have been reported by Wang et al. (2016). So here we only present the measurements on ice velocity.

The ice velocities were obtained traditionally by installing a network of stakes on the glacier surface and surveying the stake positions. The stakes are mainly made of plastic. The number of stakes is different in various years, but totally 42 stakes were distributed across the entire glacier recent years (Figure 1b). The stake positions were repeatedly surveyed in summer 1959 and in August and September 1973. Since 1980, the survey has been taken late August or early September every year. The measurements in different periods were performed via various methods. Before 2001, this was accomplished via repeated theodolite measurements from observation stations on the bedrock ridge near the northern edge of the glacier terminus to the stakes on the glacier surface. During 2002–2006, it was done by using the total-station instruments. The measurement procedures using theodolite and total-station instruments were introduced before (Dahl-Jensen and Steffensen, 1986; Li et al., 2009; Tianshan Glaciological Station, 2011). The real-time kinematic-global position system (RTK-GPS) was used since 2007. The RTK-GPS has become a common technique for glacial surface elevation and velocity measurement in recent years (Sunil et al., 2007; Rajner, 2010; Yang et al., 2014). The Unistrong E650 GPS has been used in our surveys and a RTK differential mode was adopted. The base station was placed at a fixed base point that is the same in each survey of different years, and roving antennas were used to concurrently survey the stakes. The repeated measurements can be used to construct stake displacements on the glacier surface during a survey interval. The GPS data were processed using Unistrong software, which results in a horizontal error of the range 0.01-0.02 m and a vertical error of the range 0.02-0.04 m in positioning.

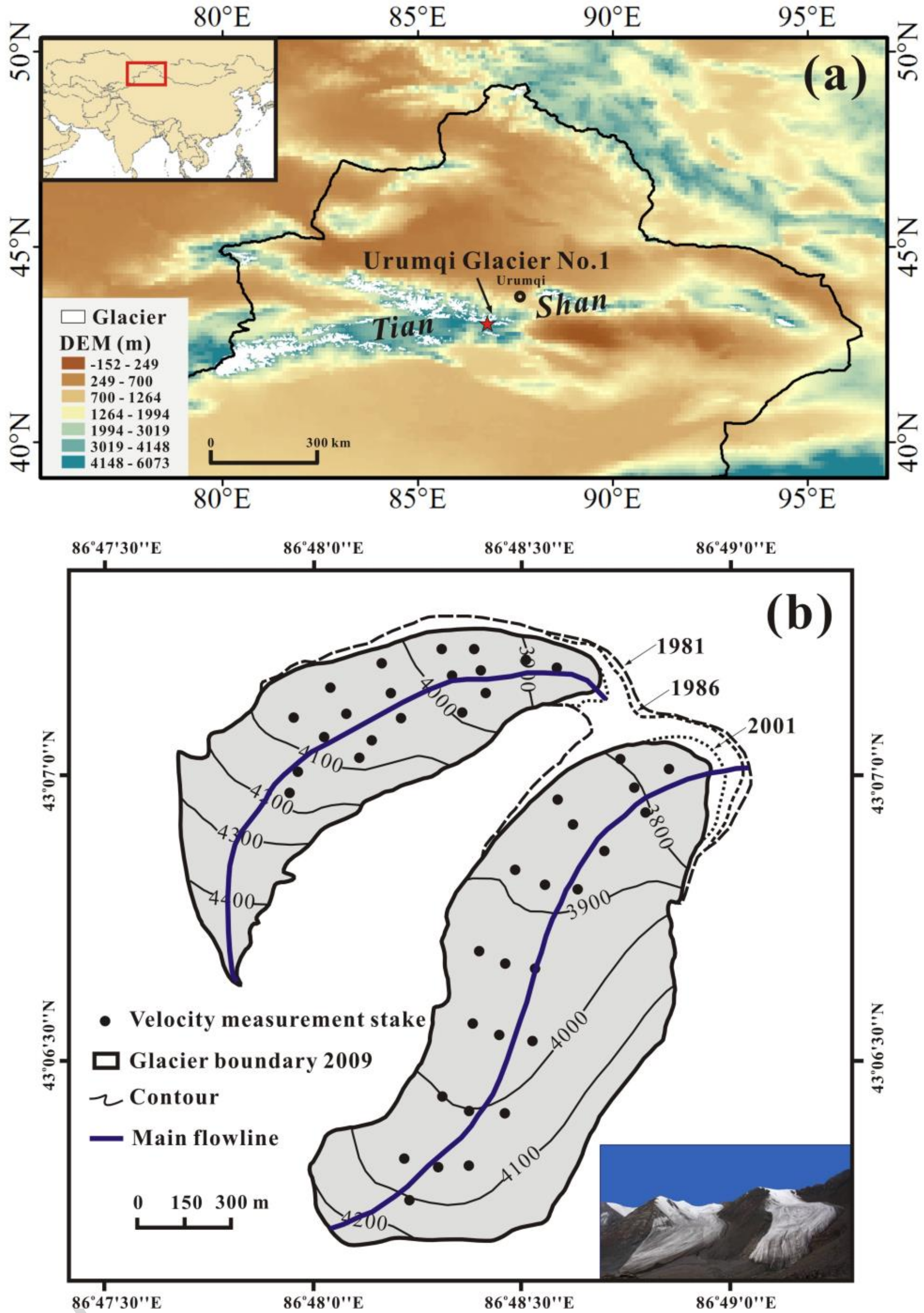



**Figure 1. (a) Location of Urumqi Glacier No. 1 in the Chinese Tian Shan. (b) The surface elevation in 2009 with the network of velocity measurement stakes in the same period shown by black dots. The contour intervals are 100 m. The boundaries in 1981, 1986, 2001, and 2009 are indicated by different line types. The solid blue line along the valley center indicates for the central flowline for the two branches. The topography of the glacier surface and surroundings are shown by the photo taken by Li in 2012 in the bottom-right corner.**

## 2.2. Data processing

Displacement vectors of the stakes could be calculated based on two measurements within a certain period and then the stake displacements were taken as the ice movement velocities at corresponding stake positions. In this way, the obtained velocity at each point was actually the surface velocity. The estimated error is less than 10% of the two dimensional glacier flow velocity according to the previous studies about glacier velocity of Urumqi Glacier No. 1 (Zhou et al., 2009; Tianshan Glaciological Station, 2011). Taking the period of 2013/2014 as an example, the estimated maximum error of the annual glacier flow velocity is about 0.4 m. The spatial distribution of glacier flow velocity can be interpolated from the velocities of the stakes using the Kriging interpolation method, and then the velocity contours can be extracted as shown in Figure 2. However, due to lack of stake measurements in the upper area, the glacier flow velocity here cannot be obtained.

## 3. Results

### 3.1. Spatial distribution of velocity

In Figure 2, we present distribution of the average annual surface velocity over Urumqi Glacier No. 1 during the past four periods (1980/1981 to 1989/1990, 1990/1991 to 1999/2000, 2000/2001 to 2009/2010 and 2010/2011 to 2013/2014). It can be seen that it accords with the general pattern of velocity distribution on a valley glacier (Cuffey and Paterson, 2010), i.e. in longitudinal direction, velocity is larger in the middle-lower part than in upper and lower streams and in the transverse section, velocity is higher at the central compared to the lateral sides. The figures also show that with the glacier shrinkage, especially its terminus retreat, the position where the maximum velocity occurred has changed a little toward upper stream. This is probably due to mainly that thickness decrease resulted in surface slope increase in lower stream while both thickness and slope changed less in upper stream. Comparison of the two branches indicates that velocity is generally higher in the West Branch than in the East Branch. For example, the average velocity in the West Branch was 6.3 m $a^{-1}$, 5.7 m $a^{-1}$, 4.4 m $a^{-1}$, and 3.4 m $a^{-1}$ with the max value of 10.6 m $a^{-1}$, 8.3 m $a^{-1}$, 6.1 m $a^{-1}$, and 4.6 m $a^{-1}$ for 1980/1981, 1990/1991, 2000/2001, and 2010/2011, respectively, while the average velocity in the East Branch was 4.6 m $a^{-1}$, 3.7 m $a^{-1}$, 3.1 m $a^{-1}$, and 3.1 m $a^{-1}$ with max values of 6.0 m $a^{-1}$, 5.7 m $a^{-1}$, 4.9 m $a^{-1}$, and 4.3 m $a^{-1}$ for 1980/1981, 1990/1991, 2000/2001, and 2010/2011, respectively. This may be caused by the distinction of surface slope. The average surface slope of the West Branch is ~8$^{o}$ higher than that of the East Branch.

It is known that ice velocity is also related to ice thickness besides the slopes of glacier surface and bed (Cuffey and Paterson, 2010). In Figure 3, therefore, we present the ice thickness distribution map of the two branches of the Urumqi Glacier No.1, which was determined by the Kriging interpolation method based on GPR (Ground Penetrating Radar) survey data in 2012 (Wang et al., 2016). Comparison of the Figure 3 with Figure 2 shows that the pattern of ice thickness distribution is similar to the velocity distribution basically, except that the maximum thickness and velocity occur at different positions. On the West Branch, the maximum velocity occurs at a place downstream from that the maximum thickness occurs, and it is reverse on the East Branch. This suggests that besides ice thickness, other factors have influence on the maximum ice velocity, such as slopes of surface and bedrock.

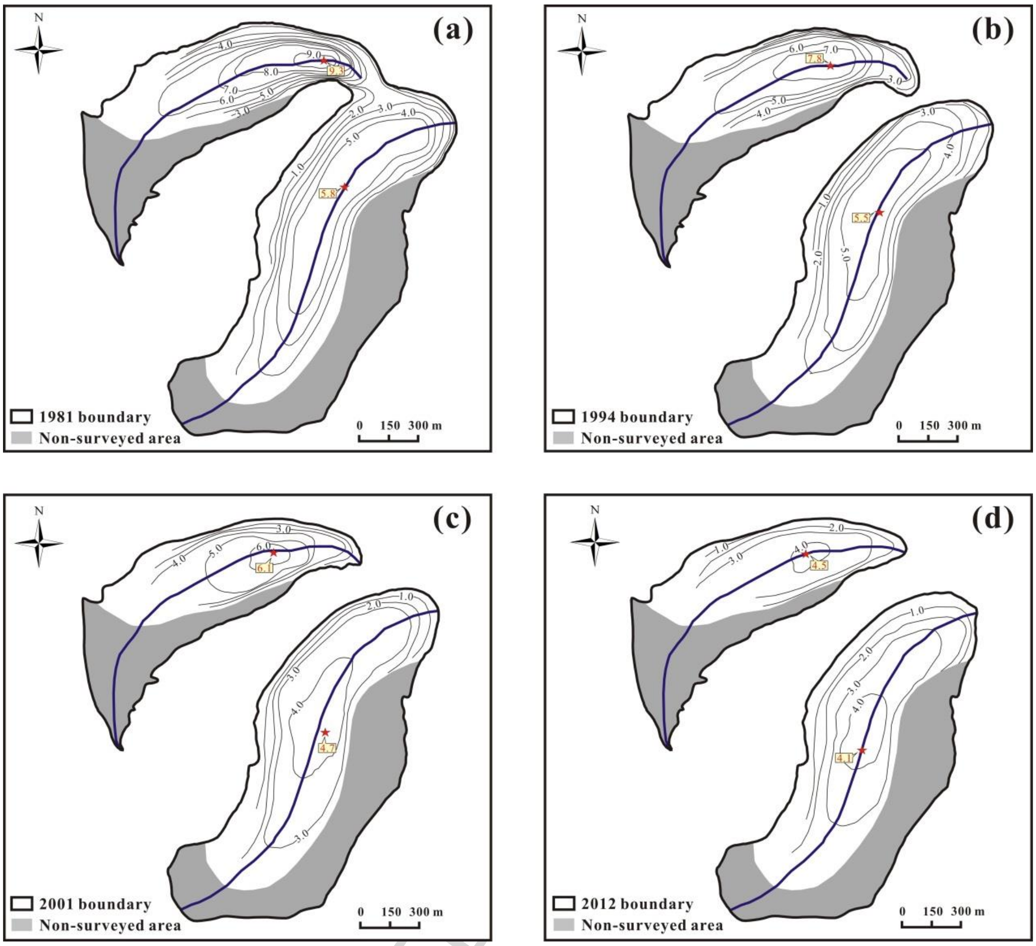



**Figure 2. Distribution of the average annual surface velocity during different periods: (a) from 1980/1981 to 1989/1990, (b) from 1990/1991 to 1999/2000, (c) from 2000/2001 to 2009/2010 and (d) from 2010/2011 to 2013/2014. The glacier outlines are determined based on the topographic maps in 1981, 1994, 2001 and 2012. The maximum velocities in the different periods are indicated with stars. There are no survey data in the gray areas in the figures.**

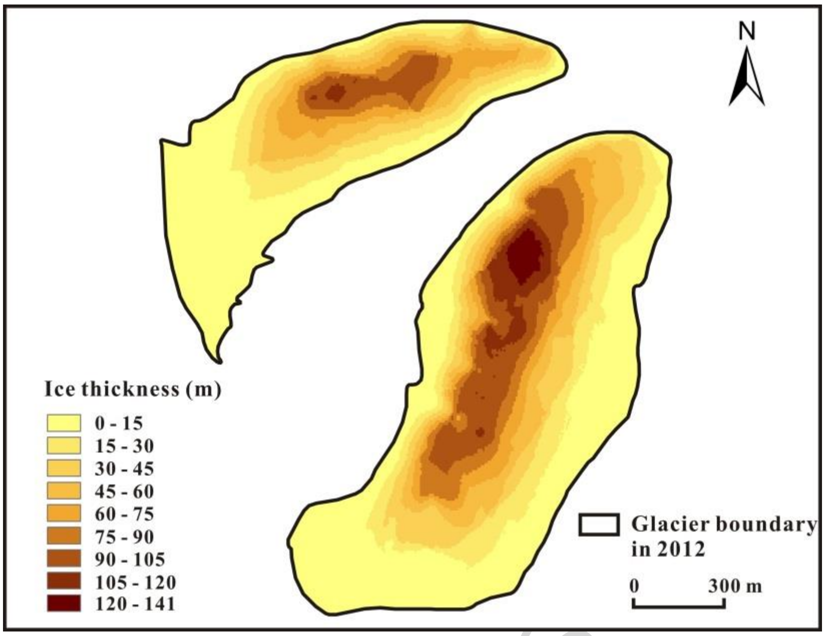



**Figure 3. Spatial distribution of ice thickness of Urumqi Glacier No. 1 in 2012, which is cited from Wang et al. (2016).**

### 3.2. Temporal changes of velocity

Figures 4 and 5 show variations of the average annual velocity and the maximum velocity of Urumqi Glacier No. 1 from 1980/1981 to 2013/2014, respectively. From these figures, it can be seen that both the average and the maximum velocities have decreased apparently since 1980. Generally, the velocity has experienced small fluctuations under the decrease tendency except for a few years. The relatively apparent abnormalities are in 1993 and around 2009/2010. When we examine other observation results, it is found that the two branches of this glacier separated completely in 1993 and hence probably caused an abrupt change in velocity. From Figure 4 and 5, we see that the maximum velocity had a very sharp increase and the average velocity increased less in this year. For the abnormal phenomenon around 2009/2010, we think it may be related to the abnormal change in mass balance to somewhat, because a positive mass balance occurred suddenly in 2009 after a continuous negative value for ten more years, and a very large negative value followed in 2010 (Figure 6; Wang et al., 2016). Generally, climate causes the mass balance firstly, and then glacier thickness and surface slope change. Consequently ice velocity changes under influence of all these causes. Moreover, liquid precipitation, melting water and ice temperature change also have impacts on ice velocity. So for further analysis of relationship between climate and these factors as well as their influence on ice velocity, we need discussion elsewhere based on more data of meteorology, processes of snow/ice melting and mass balance, glacier physical and dynamic parameters.

An abnormal value of average velocity occurred in 1987 in Figure 4. We checked all observation items and found that measurement data of this year was only available for ten stakes in the middle part of the glacier, where velocity is usually high. It can be seen also from Figures 4 and 5 that both the velocity and its decrease rate of the West Branch are higher compared to the East Branch and so difference in velocity of the two branches became less and less, especially after 2011. This could be explained from differences of the two branches in topographic feature and their changes in ice thickness and surface slope. From Figure 1 we know that the West Branch is smaller and narrower and its surface slope is larger relatively to the East Branch so that the relative shrinkage of the West Branch should be larger than that of the East Branch under the same climatic condition.

The surface elevation (1981, 1994, 2006, and 2012) and bedrock topography obtained by subtracting the ice thickness from the glacier surface have already been published in previous studies (Wang et al., 2014a, b, 2016). The profiles of surface in different periods as well as bed elevation along the central flowlines of the two branches were then extracted as shown in Figure 7, in order to see how surface slope and ice thickness change. It can be seen that decrease in ice thickness of the West Branch is larger than that of the East Branch, and surface slope in the lower part of the West Branch has decreased while surface slope of the East Branch seems to have a little increase.

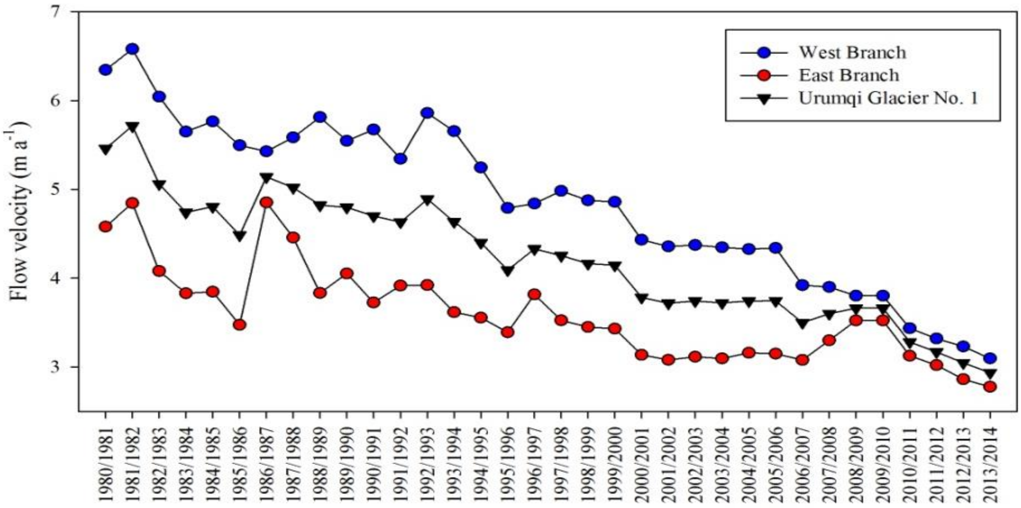



**Figure 4. The average flow velocity of Urumqi Glacier No. 1 and its West Branch and East Branch from 1980/1981 to 2013/2014, represented with various symbols in different colors.**

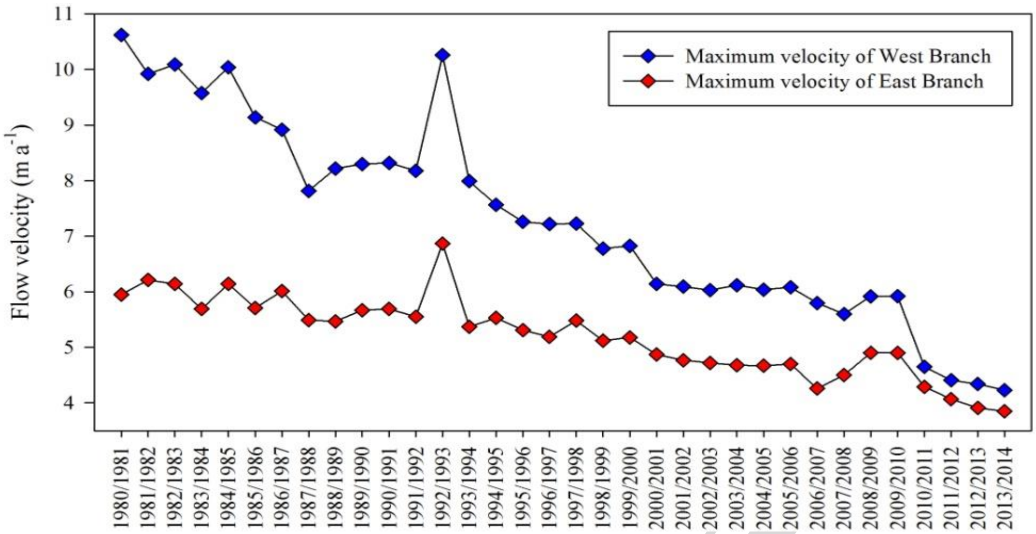



**Figure 5. The variation of maximum surface velocity of West Branch and East Branch of Urumqi Glacier No. 1 from 1980/1981 to 2013/2014. The peak occurred at a site near the glacier terminus at 1992/1993, resulting from the separation of the two branches.**

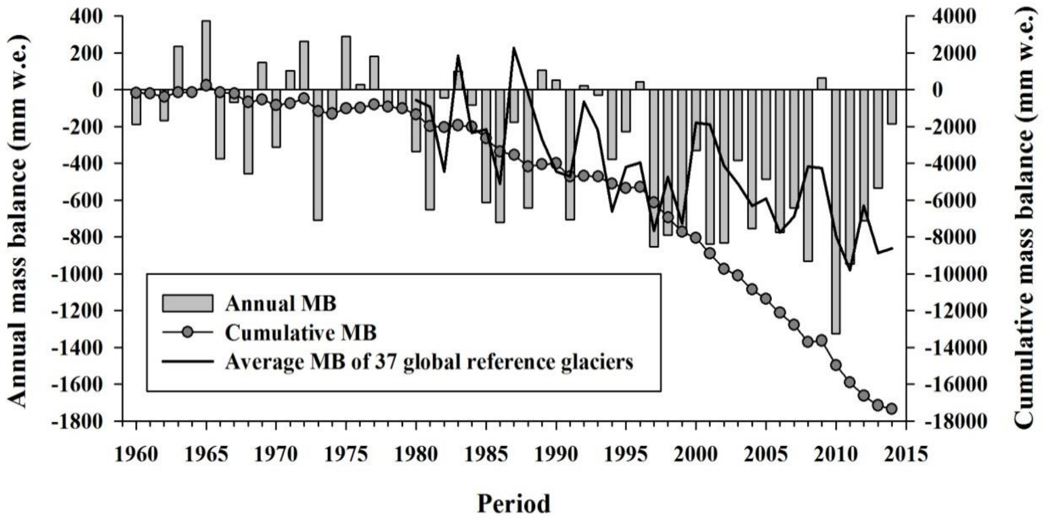
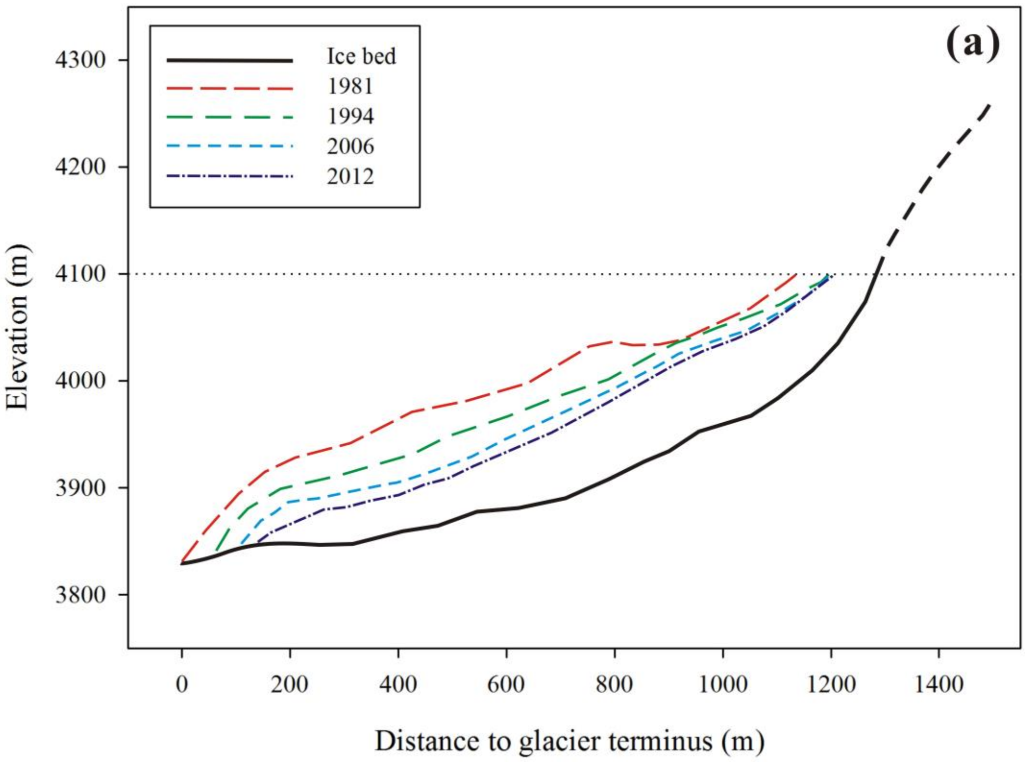



**Figure 6. Changes in the annual mass balance and the cumulative mass balance of Urumqi Glacier No. 1 since 1960, which is referring to Wang et al. (2016).**



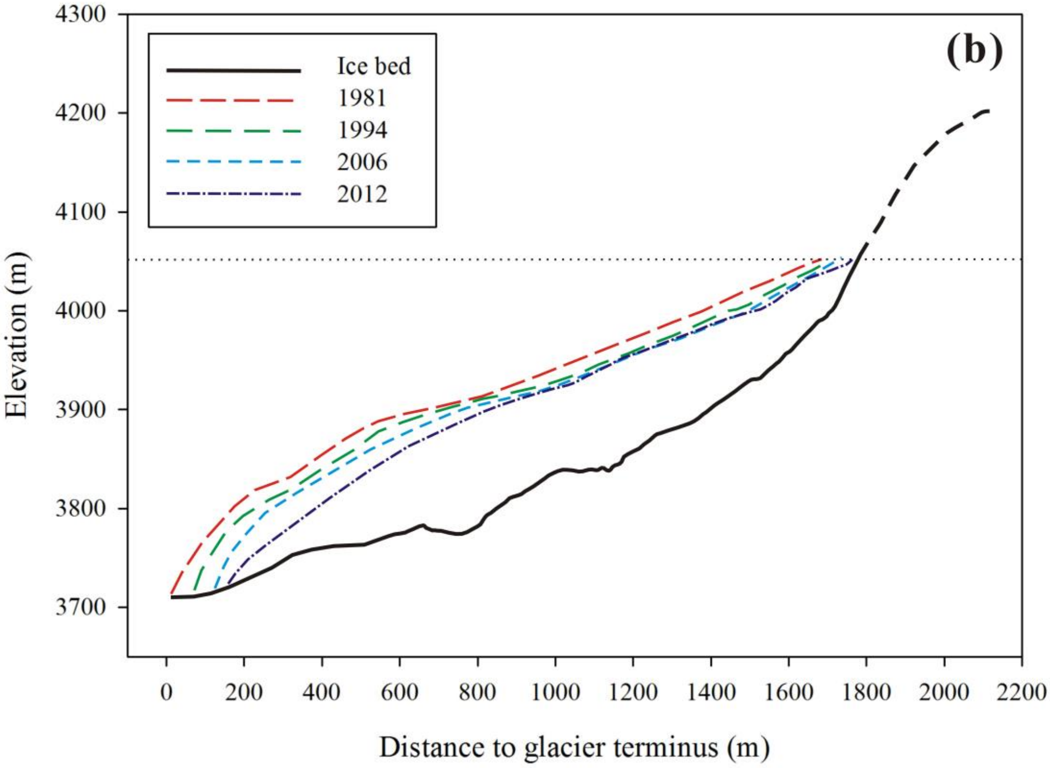




**Figure 7. The profiles of surface and bed elevations along the central flowlines of (a) West branch and (b) East branch of Urumqi Glacier No.1. The zero distance to glacier terminus is referred to the terminus position in 1980.**

## 4. Discussion

### 4.1. Simplified formula for surface velocity

In order to exam the relative importance of ice thickness and surface slope as well as other parameters such as temperature, we need to apply the surface velocity formula. From Cuffey and Paterson (2010), it is well known that under the assumption of the glacier deforming in simple shear, the simplest formula for the glacial surface velocity is

$$u_s = u_b + 2A\tau_b^n h/(n+1) \quad (1)$$

Here $u_s$ and $u_b$ are the velocities at the surface and base, $h$ is the ice thickness, $\tau_b$ the basal shear stress, and $A$ and $n$ are the Glen's flow law parameters of ice. Usually, $n$ is taken as 3 and $A$ is mainly dependent on temperature. For a valley glacier, on the centerline,

$$\tau_b = \rho g H f \sin\alpha. \quad (2)$$

Here $\rho$ is the density of the glacier ice, $g$ the gravitational acceleration, $H$ the thickness at the centerline and $f$ the shape factor of the valley cross-section.

Li et al. (2012) discussed the estimate at centerline thickness of the East Branch of this glacier using the "perfect-plasticity" rheological assumption that the basal shear stress equals to a constant yield stress $\tau_0$. Since this glacier is predominantly cold-based, with basal sliding occurring only close to its snout, they neglected the basal velocity and determined $f$ by the ratio of measured glacial half width to the thickness based on the numerical solution of Nye (1965) for the parabolic cross-section. Their result shows a good consistence between measured and estimated thicknesses. So we can analyze influences of changes in ice thickness and surface slope on the surface velocity using the simplified formula

$$u_s = 1/2AH\tau_0^3 \quad (3)$$

### 4.2. Influence of ice thickness on velocity

Using the average values of measured thickness, width and surface slope along the centerline from 1981 to 2012, we obtained that the average $\tau_0$ is 109 kPa for the East Branch and 133 kPa for West Branch (we take $\rho$ as 900 kg $m^{-3}$ and $f$ is 0.746, same for both the East and West Branches roughly according to the average width and thickness values). These are slightly higher than the value of 105 kPa for the east branch derived by Li et al. (2012) using the thickness data measured in 2006. Since thickness in 1981 was higher than in 2006, our values of the basal shear stress are reasonable. For parameter A, the basal ice temperature should be determined firstly. Temperature measurements in boreholes down to the bed and observations in artificial tunnel in the front of the East Branch were made during 1980s and 1990s. From those results, the basal ice temperature was between -2 and -1℃ in most areas (Huang, 1999). In 2006, measurement in a borehole at the same altitude with previous measurements showed no change in temperature at depths lager than 20 m (Li et al., 2007). So if we choose $A$ to be the value recommended by Cuffey and Paterson (2010) at -2℃ ($1.7 s^{-1} Pa^{-3} \times 10^{-24}$), we have $u_s = 34.71\times 10^{-3} H$ (m $yr^{-1}$) for the East Branch and $u_s = 63.06\times 10^{-3} H$ (m $yr^{-1}$) for the West Branch, respectively. Since the most recent measurement on ice thickness was done in 2012, we can get the thickness change from 1981 to 2012. According to the measured thickness changes of -25 m and -35 m, the surface velocity change was about -0.87 m $yr^{-1}$ and -2.21 m $yr^{-1}$ from 1981 to 2012 for the East Branch and the West Branch, respectively.

**4.3. Influence of surface slope on velocity**

It can be seen in Figure 7 that surface slope has a decrease on average for the West Branch and in contrast, the East Branch has an increase in surface slope. The surface slope change from the measurements of surface elevation was $0.9^o$ for the East Branch and $-1.5^o$ for the West Branch from 1981 to 2012, on average along the central flowlines. To exam influence of surface slope change on velocity, we can express the surface slope from equations (1) and (2) as

$$u_s = 1/2A(\rho gf)^3 H^4 sin^3 \alpha. \quad (4)$$

Letting $(\rho gf)$ and $A$ constant as mentioned above, we can get $u_s = 7.6357H^4 sin^3 \alpha$ (m $yr^{-1}$). Since slope change is a result of thickness change actually, it is not reasonable to assume $H$ be constant. Nevertheless, if taking $H$ as the average value along the central flowlines from 1981 to 2012, we can obtain $u_s$=447.59$sin^3 \alpha$ for the East Branch and $u_s$ = 328.69$sin^3 \alpha$ for the West Branch. For the West Branch, average slope was $15.3^o$ in 1981 and $13.8^o$ in 2012. Hence the surface velocity change caused by changing slope was calculated to be -1.61 m $yr^{-1}$. Figure 8 shows variations of the average surface velocity along the central flowlines of the glacier from 1980/1981 to 2013/2014. According to the calculations above, the combination effect of thickness and slope changes is -3.82 m $yr^{-1}$ for the west branch, close to the measured velocity change of 3.6 m $yr^{-1}$ from 1981 to 2012.

For the East Branch, although the average slope increased by $0.9^o$ along the central flowline, the slope change occurred mainly in the lower altitudes (below 3900 m a.s.l.) as well as thickness decrease (Figure 7). The equation (4) shows that one degree change in slope could cause more than 1 m $yr^{-1}$ change in surface velocity if ice thickness is about 100 m, the average value of the East Branch. However, due to large spatial variability of slope, it is difficult to take a proper average value for the branch or even a given range such as below 3900 m a.s.l. Nevertheless, since the surface slope has increased on average, its effect is enhancement of the velocity, i.e. offsetting the thickness decrease influence to somewhat. For further quantitative analysis, besides more sufficient data, a better model describing physical and dynamic processes should be used.

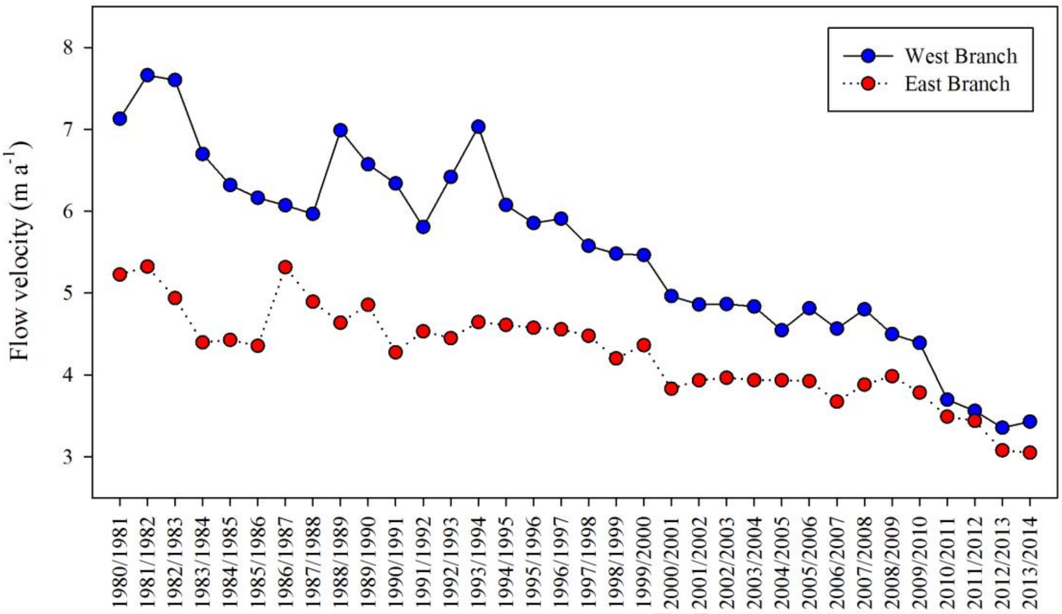



**Figure 8. Variation of the average surface velocity along the central flowlines of the two branches of Urumqi Glacier No. 1 from 1980/1981 to 2013/2014.**

## 5. Conclusion

In the past decades, with climate warming, Urumqi Glacier No. 1 has experienced continuous shrinkage and ice velocity has been in a decreasing tendency. The observation results show that both average and maximum velocities decreased remarkably since 1981. Due to abnormal changes in the mass balance in 2009-2011 and other causes such as the complete separation of the two branches of this glacier in 1993, the velocity has had sharp changes in these years. Using the simplified glacier dynamic model, analysis of the surface velocity along the centerline shows that influence of the ice thickness change was modeled. The analysis shows that ice thickness makes most important contribution to ice velocity. The velocity is also very sensitive to the surface slope change but its change is a result of thickness change. For the East Branch, due to the large spatial variability, effect of surface slope is hard to be modeled well. For the West Branch of this glacier, both thickness and slope have decreased and the calculated velocity decrease under their combination effect is relatively close to the measured result. For further analysis, besides more observation data, a better model is needed to describe actual physical and dynamic processes.

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**Highlights:**

1. **Glacier flow velocity of UG1 has been continuously measured since 1980.**
2. **Long term change in the velocity has been analyzed quantitatively.**
3. **The velocity is very sensitive to the surface slope change, but complicated.**