

Article

Glaciers in Xinjiang, China: Past Changes and Current Status

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Abstract: The Xinjiang Uyghur Autonomous Region of China is the largest arid region in Central Asia, and is heavily dependent on glacier melt in high mountains for water supplies. In this paper, glacier and climate changes in Xinjiang during the past decades were comprehensively discussed based on glacier inventory data, individual monitored glacier observations, recent publications, as well as meteorological records. The results show that glaciers have been in continuous mass loss and dimensional shrinkage since the 1960s, although there are spatial differences between mountains and sub-regions, and the significant temperature increase is the dominant controlling factor of glacier change. The mass loss of monitored glaciers in the Tien Shan has accelerated since the late 1990s, but has a slight slowing after 2010. Remote sensing results also show a more negative mass balance in the 2000s and mass loss slowing in the latest decade (2010s) in most regions. This needs further investigation on whether the slowing is general and continuing. In addition, glacier surging occurs more frequently in the Karakoram and Kunlun Mountains.

Keywords: glacier change; mass loss; climate change; Xinjiang; Central Asia

1. Introduction

The cryosphere collectively describes the portions of the Earth's surface where water is in its frozen state, including glaciers and ice sheets, snow cover, permafrost and seasonally frozen ground, river and lake ice, sea ice, ice shelves, icebergs and also ice in the atmosphere [1–3]. The wide distributed glaciers are not only an important contributor to global sea level rise, but are also a crucial water resource in many regions, and have significant influences on eco-environment and human livelihoods [4–6].

It is well known that populations in Central Asia are heavily dependent on snow and glacier melt for their water supplies [7–9]. The Xinjiang Uyghur Autonomous Region of China (abbreviated as Xinjiang hereafter) is the largest arid region in Central Asia (Figure 1) and glacier meltwater in high mountains accounts for ~31% of the total discharge for the downstream rivers on average [10] and to ~50% of the total runoff in the Tarim River, the largest interior river in Xinjiang, as well as in China [11]. Therefore, glaciers play a more important role in natural eco-environment system and social development in Xinjiang than in other regions of China.

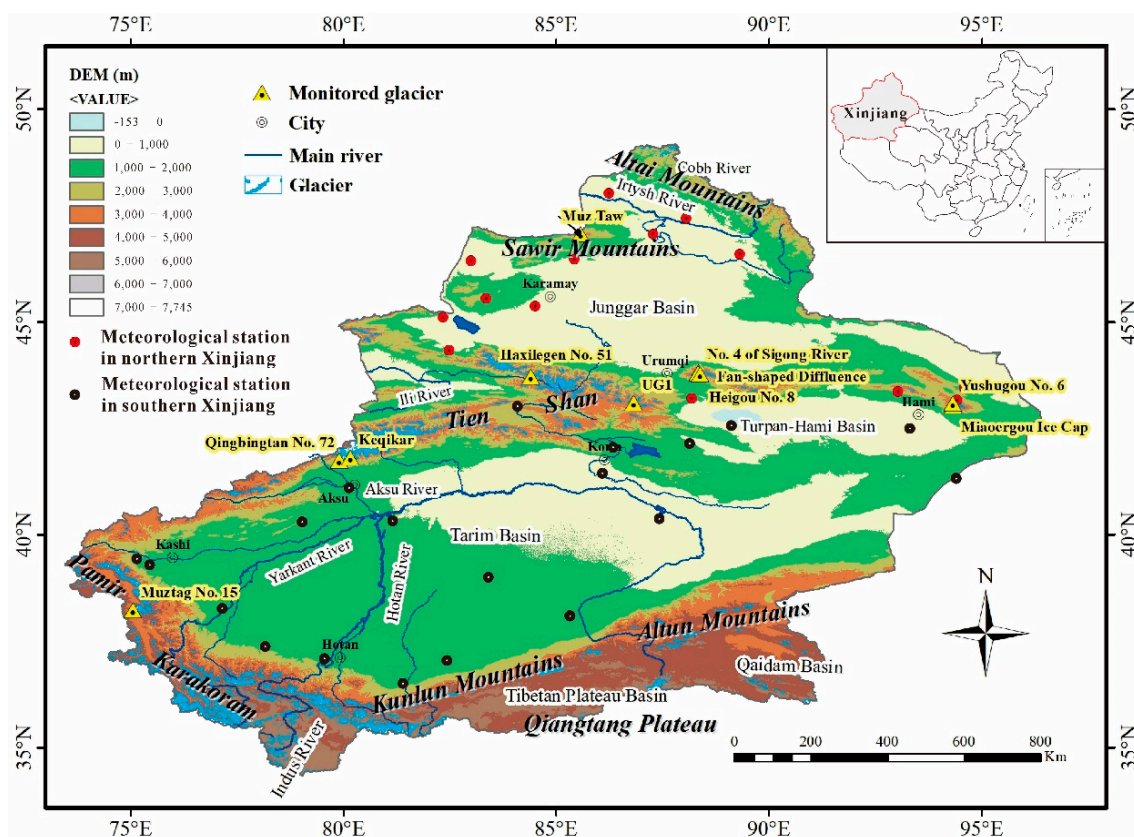


Figure 1. Geographical distribution of glaciers, monitored individual glacier and meteorological stations in Xinjiang, China.

To date, glaciers in Xinjiang have been investigated broadly in various ways such as long term station-based monitoring for a single glacier [12–14], short term field investigation for some glaciers [15–18], and remote sensing retrieval for a basin or a mountain region [19–21]. Part of glacier changes in Xinjiang are also involved in some larger scale investigations, such as on High Mountain Asia [6,22–25], on the Tibetan Plateau [26] and Tien Shan ranges [9]. Although all these studies have reached consistently the conclusion that glaciers in Xinjiang have been shrinking generally in past decades, the spatial range and time period varied between different studies, and no systematic analysis of recent glacier changes has been performed. In addition, it is not clear if the rate of ice loss is accelerating, which is the most interesting topic for assessment on glacier change impacts since on a large scale the glacier mass loss seems to be slowing down in High Mountain Asia, according to comparison between the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [27] and the Special Report on the Ocean and Cryosphere in a Changing Climate [5].

Taking this into account, in this paper, the glacier changes in Xinjiang from the 1960s to 2000s are presented first from the two glacier inventory sets, and then various research results related to glacier change in Xinjiang are summarized to reveal the glacier change process in past decades according to local observations, either short term field survey or long term monitoring of individual glaciers, and to remote sensing retrievals. Lastly but most important, glacier mass balance status is discussed, based on an analysis of more recent research and meteorological data, to understand if the glacier mass loss has been increasing or decreasing in recent years.

2. Study Region

Xinjiang, situated between $73^{\circ}40' - 96^{\circ}23'$ E and $34^{\circ}25' - 49^{\circ}10'$ N, with total area of 1.66×10^6 km², is located in the northwest of China, and in the arid regions of Central Asia (Figure 1). It is 2200 km from east to west at the longest and 1650 km from north to south at the widest [28]. There are three

main mountain ranges running from east to west in Xinjiang, including the Altai Mountains in the north, the Kunlun Mountains in the south, and the Tien Shan traversing the central part. The Tien Shan divides Xinjiang into the north and the south with the Junggar Basin in the north and the Tarim Basin in the south. Around the southwest boundary are the eastern Pamir Plateau and Karakoram Mountains (Figure 1).

Dominated by the westerlies, the climate condition of Xinjiang is continental due to that it is located in the middle of the Eurasian continent and far from oceans. Under the influence of atmospheric circulation pattern and characteristics of orographic and land surface, temperature and precipitation are unevenly distributed [29]. The annual mean temperature in Xinjiang is higher in the south and the east than in the north and west. The annual precipitation shows a south-north and basin-mountain range increasing pattern. It is characterized by longtime sunshine, less rain, more sand wind, and large daily and annual ranges of temperature in lower altitudes. The water resources are mainly from relatively high precipitation and melting of snow and glaciers in the mountainous areas.

3. Data and Methods

In this study, the basic glacier data include the first Chinese Glacier Inventory [30] and the second Chinese Glacier Inventory [31–33]. The data are provided by A Big Earth Data Platform for Three Poles (<http://westdc.westgis.ac.cn/>). The first inventory is based on aero-photographical data acquired mainly in the 1960s and some in the 1970s. The second inventory is from the remote sensing images around 2006. Experienced researchers manually revised the automatically derived glacier boundary and the accuracy has been estimated by [31,32].

The available data from in situ observed or field surveyed individual glaciers are collected from the literature and a first-hand survey, which is shown in Table 1. The locations of these glaciers are marked in Figure 1. The nine monitored glaciers are in Tien Shan and the other two are in Altai and Pamir, respectively. Among these glaciers, Urumqi Glacier No. 1 (UG1) in the Tien Shan has been observed continuously since 1959 and is selected as a representative in the arid region of Central Asia by the World Glacier Monitoring Service (WGMS) [12,34], and the others were observed less than 20 years. There have been a large number of publications related to glacier change in Xinjiang, at least a hundred, but more than 40 published in the latest decade are selected in this study to be reviewed for discussion of the current mass balance status.

For Urumqi Glacier No.1, glaciological mass balance is measured on a monthly basis throughout the mass balance year (from 1 May to 30 August) using the stake/snowpit method. Specific mass balances are achieved from every single stakes. There are forty stakes at least drilled into the two glacier branches despite of the variation in the number of stakes measured every year. Annual mass balance is converted from specific mass balance dataset, which has already been introduced in detail by [12–14]. Terminus variations are measured in field surveys on yearly basis by repeatedly measuring the distance from glacier terminus to the fixed point. Since the glacial branches split in 1993 from melting, the measurements are performed separately for the two branches.

In order to analyze the climatic background of glacier changes, a climate dataset is obtained from the National Climate Center, China Meteorological Administration (CMA) (<http://data.cma.cn/>), including annual mean temperature, maximum temperature, minimum temperature, and annual precipitation at 34 meteorological stations, which are selected as close to mountain regions as possible except a few in basin regions, as shown in Figure 1. The time span of the temperature data used is from 1961 to 2018, while the precipitation data is from 1961 to 2017. Linear regression was then used to quantify temporal trends of annual mean temperature and annual precipitation. Moreover, the $0.5^{\circ} \times 0.5^{\circ}$ gridded dataset of monthly temperature and precipitation from 1961–2018 provided by CMA was also adopted to analyze inter-decadal spatial variability in Xinjiang.

Table 1. Geodetic and glaciological mass balance (MB) and terminus changes of the in situ observed or field surveyed individual glaciers in Xinjiang.

Mountain	Region	Glacier Name	Lat. (N)	Long. (E)	Period	Geodetic MB (m w.e./a)	Period	Glaciological MB (m w.e./a)	Period	Terminus Change (m/a)	Source
Tien Shan	Mt. Tomor	Qingbingtan No. 72	41°45′	79°54′	1964–2008	−0.20	2008–2014	−0.38	1964–2008; 2008–2013	−41.2; −32.2	[15,35]
		Keqikar	41°49′	80°10′	1981–2004	−0.45~−1.35	2003–2005	−0.44	1976–2003	−10.3	[36,37]
	Kuitun River Basin	Haxilegen No. 51	43°43′	84°24′	1999–2015	−0.37	1999–2003; 2004–2006; 2010–2011	−0.22; −0.38; −0.68	1964–1999; 1999–2010	−1.4; −5.3	[17,38]
	Urumqi River Basin	UG1	43°06′	86°49′	1981–2009;	−0.44;	1981–1996	−0.25;	1962–2018;	−4.8;	This study
					2015–2017	−0.70	1996–2010 2010–2018	−0.69; −0.67	1962–1993; 1994–2018	−4.5; −5.2	
	North of Mt. Bogda	No. 4 of Sigong River	43°49′	88°21′	1962–2009	−0.29			1962–1981; 1981–2006; 2006–2009	−6.0; −8.9; −13.3	[39,40]
		Fan-Shaped Diffluence	43°48′	88°20′	1962–2009	−0.27			1962–2009	−8.8	[39,41]
	South of Mt. Bogda	Heigou No. 8	43°46′	88°23′	1969–2000; 2000–2009	−0.38; −1.37			1962–2009	−11.0	[41–43]
	Harlik Mountains	Miaoergou Ice Cap	43°02′	94°20′	1981–2005; 1981–2007	−0.21; −0.35			1972–2005; 2005–2009	−2.3; −2.7	[16,44]
		Yushugou No. 6	43°05′	94°19′	1972–2011	−0.46			1972–2005; 2005–2011	−6.4; −7.0	[16]
Altai	Sawir Mountains	Muz Taw	47°04′	85°34′			2015–2016; 2016–2017; 2017–2018	−0.98; −1.19; −1.29	1989–2018	−11.5	[45]
Pamir Plateau	Eastern Pamir	Muztag No. 15	38°14′	75°03′	1980–1997; 1998–2012	−0.16; +0.06	2005–2009	+0.25	2002–2010	−1.70	[18,26]

4. Glacier Changes from the 1960s to 2000s

According to the second Chinese Glacier Inventory [30–32], there are 20,695 glaciers in Xinjiang with an area of 22,623.82 km² and volume of ~2156 km³, accounting for 43%, 44%, and 48% of number, area, and volume of the glaciers in China, respectively. There are 22 glaciers larger than 100 km² in China, 14 of which are distributed in Xinjiang and the top three are the Isugeti Glacier (359.05 km²) in the Karakoram Mountains, Tomor Glacier (358.25 km²), and the Tugberizi Glacier (282.72 km²) in the Tien Shan, all belonging to the Tarim River Basin. Although the large glaciers in Xinjiang are more than other provinces, the proportion of small glaciers (<1 km²) accounts for more than 70% of the total number of glaciers in Xinjiang, and the average area of individual glaciers is approximately 1.09 km². Glaciers in Xinjiang are distributed mainly in Kunlun Mountains and Tien Shan. In terms of area, glaciers in Kunlun Mountains account for 37% and in Tien Shan for 32%, while in terms of number, they account for 33% and 38%, respectively.

A comparison between the first and second inventory data sets shows that the total area and volume of glaciers in Xinjiang decreased by 3914 km² or 14.7%, and 361.7 km³ or 14.4%, from the 1960s/1970s to around 2006, respectively. Relative to the area determination, the glacier volume estimation has a large uncertainty because the area-volume empirical formula was used from limited thickness measurements on a few glaciers [30–33]. In addition, some small glaciers had faded away and multi-branched glaciers had separated. Therefore, the area shrinkage is the most important indicator of glacier change. Figure 2 shows the glacier area change percentages in various mountain regions. The percentages in four sub-regions of Tien Shan are also given in view of that this big mountain range traverses Xinjiang and the glacier changes are important both to south and north basins.

It can be seen from Figure 2 that glacier area reduction is strongest in the Sawir Mountains and Altai Mountains in the northeast, with area reduction rate of ~47% and ~37%, respectively, compared with other mountains, but only 12 small glaciers are in the Sawir Mountains with a total area of 9 km² and 273 glaciers with a total area of 179 km², in the Altai Mountains, much less than other mountains. The glaciers in these two regions mainly belong to the Irtysh River Basin, the upstream tributary of the Ob river within China, and four glaciers drain into the Cobb River.

The glacial meltwater in the Tien Shan mainly supplies the Tarim River Basin in the southwest, Ili River Basin in the northwest and other inland rivers in the Junggar Basin in the north and Turfan-Hami Basin in the southeast. From the 1960s to 2000s, glacier area shrank ~19% on average in the Tien Shan. The glacier area reduction is only ~10% in the Aksu River Basin, the largest tributary of the Tarim River, due to the retardant melting effect of debris cover on Mt. Tomor. The glacier area in the Ili River Basin decreased by ~24%, and the absolute area and volume reductions are the largest in the Tien Shan, because of the larger average glacier size. The glacier area decreased by ~27% in the Junggar Basin and ~33% in the Turpan-Hami Basin.

A part of the glaciers in the Pamir drains into the western tributaries of the Tarim River, while another part drains into the outside of China. The glacier area decreased significantly with the percentage of ~20% from the 1960s to 2000s. The Yarkant River and Hotan River, west and south tributaries of the Tarim River, are mainly supplied by glaciers in the Karakoram and Kunlun mountains. The average glacier size is larger, and the area reduction percentage is smaller, only ~11% and ~10%, respectively, in these two mountain areas. Glaciers in the Altun Mountains, on the south edge of Xinjiang, shrank by only ~5%, while glacier area of the Qiangtang Plateau slightly increased at the rate of ~3%; nevertheless, there are less than thirty glaciers in total in this region.

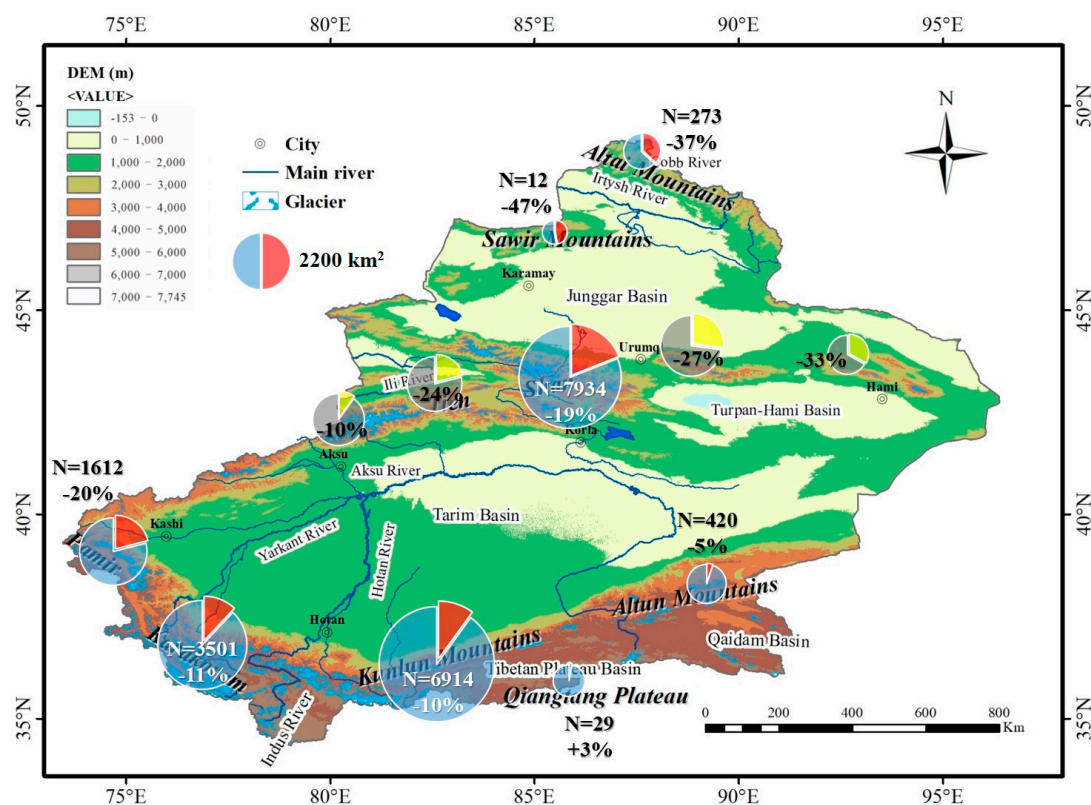


Figure 2. Glacier area changes in the different mountain ranges in Xinjiang from the 1960s to 2000s. The area change percentage is indicated by red portion in the blue circle; the size of the circle reflects the glacier area in the 1960s. N represents the number of glaciers in different mountain ranges according to the second Chinese Glacier Inventory [31–33]. The four gray circles with yellow portion show the glacier changes in drainage basins of glaciers in Tien Shan, including the Aksu River Basin, Ili River Basin, Junggar Basin, and Turpan-Hami Basin from west to east.

5. Monitored Glacier Change Process

As mentioned above, more than ten glaciers have been monitored in Xinjiang, and these continuous field observations illustrate the glacier change process in the past decades. Table 1 lists the observed mass balance and terminus changes of these glaciers. The geodetic mass balance is derived by the comparison of glacier surface elevations in different periods measured by field survey, such as GPS, the terrestrial laser scanner (TLS), etc., assuming ice density of 900 kg/m^3 . The glaciological mass balance is the average value of yearly measurements using stake/snow pit method over the observation period. The terminus change refers to the averages of the glacier terminus change over the observation periods. Among these glaciers, UG1 is one of the reference glaciers of WGMS in Central Asia (https://wgms.ch/products_ref_glaciers/) and has been observed continuously since 1959. The observation period is relatively short for the other glaciers. Therefore, long-term changes in mass balance and terminus can be displayed from UG1 data.

Figure 3a and Table 1 show that UG1 has seen overall mass loss since 1960 and significant increases after the mid-1990s. The cumulative mass balance is -20.34 m w.e. and the annual average mass balance is -0.35 m w.e./a during the period 1960–2018, while it is -0.68 m w.e./a during the period 1996–2018, meaning much more mass loss since the late 1990s. The mass balance is -1.33 m w.e. in 2009/2010, which is the lowest value of all observed data. After a short slowing from 2010 to 2014, the mass loss increased again in recent several years. As shown in Table 1 and Figure 3b, the average retreat rate of glacier terminus is 4.8 m/a since 1962 and the retreat rate has an increase trend with an average retreat rate of 4.5 m/a between 1962 and 1993 before the east branch and west branch separated in 1993. From 1994 to 2018, the average retreat rates of the east and west branches were 4.7 m/a and

5.7 m/a, respectively, suggesting that a slight slowing of mass loss over several years do not stop the continuous increasing of terminus retreat.

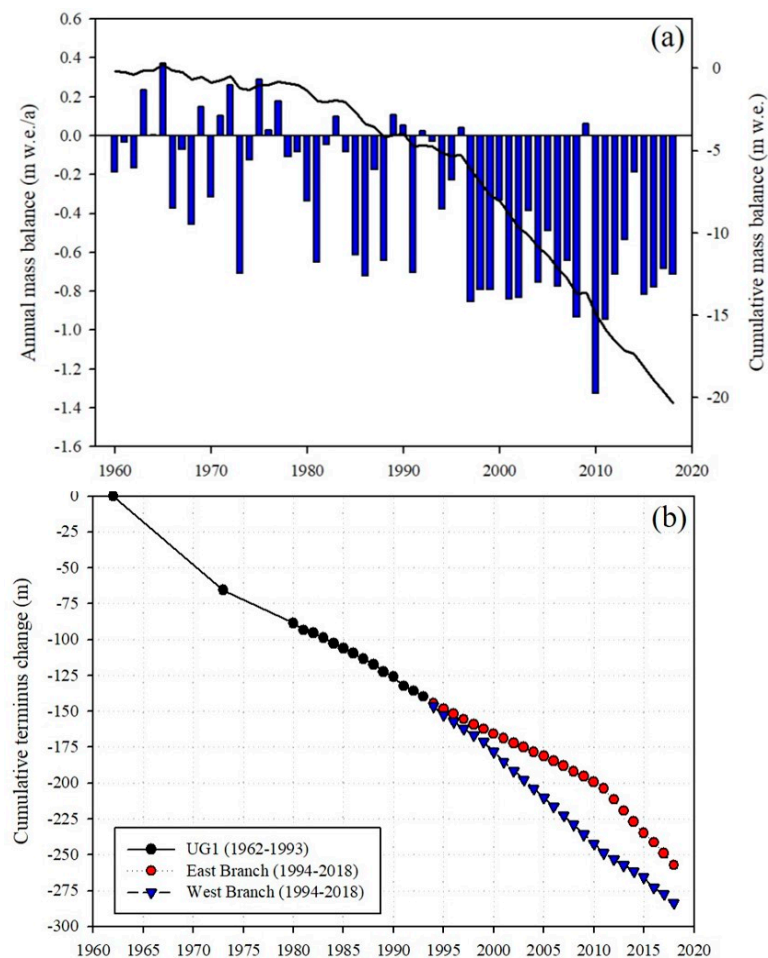


Figure 3. The example of the (a) annual and cumulative mass balance during 1960–2018 and (b) terminus changes during 1962–2018 for the UG1 in the Tien Shan.

From Table 1, it can be seen that the other observed glaciers show a general feature of increase in both the mass loss and terminus retreat up to around 2010. On the mass balance, for instance, it is -0.22 m w.e./a in 1999–2003, -0.38 m w.e./a in 2004–2006, and -0.68 m w.e./a 2010–2011 for Haxilegen Glacier No. 51, and is -0.38 m w.e./a in 1969–2000 and -1.37 m w.e./a in 2000–2009 for Heigou Glacier No. 8. On the terminus change, the retreat rate is larger after around 2000 than before for most observed glaciers. There are exceptional for Keqikar Glacier, Qingbingtan Glacier No. 72 and Muztag Glacier No. 15. The first two glaciers are debris-covered to some extent and hence their melting and terminus changes are influenced by the debris alleviating ablation effect [15,37]. A minimal positive mass balance of Muztag Glacier No. 15 in the first decade of the century was attributed to the precipitation increase caused by westerly circulation strength [26], but no more recent data was acquired.

6. Discussion: Current Status

6.1. Is the Glacier Mass Loss Accelerating or Slowing Recently?

IPCC AR5 [27] gives the glacier mass loss rate of 220 ± 100 kg/(m²·a) in High Mountain Asia for the period 2003–2009 and IPCC SROCC [5] gives 150 ± 110 kg/(m²·a) for the period 2006–2015. These seemingly mean that the ice loss has been slowing down recently to some extent in the large region. The mountains in Xinjiang are constituent parts of High Asia Mountains, so it is interesting to

see if the glaciers in Xinjiang have a similar trend of ice loss or what differences have been recorded in recent decades.

From continuous observations of a few glaciers (Table 1 and Figure 3), we have obtained valuable information on the mass balance and terminus changes of representative glaciers in the recent years as mentioned above. The mass loss of UG1, a regular valley glacier, increased significantly around the turn of the century and slowed down a little after 2010, and in the latest several years it increased again but has not reached the level in the early of the century. In other words, the mass loss in the latest decade does not show an accelerating trend compared with a decade ago. The mass loss of Haxilegen Glacier No. 51, a cirque glacier, increased also significantly in the period 1999–2011 but has not been observed thereafter. The Qingbingtan Glacier No. 72 is a complex topographic valley glacier and partially covered by two debris belts on the lateral sides of its tongue. From comparison of observation from 2008 to 2014 with earlier data, it is believed that the strongest mass loss of this glacier occurred at the turn of the century too because glacier area shrinkage began to decrease since 2009 [15]. The other observed glaciers do not have new data after 2010 except the Muz Taw Glacier, which has only several years' data.

The geodetic method and remote sensing are beneficial to regional scale investigation, but most results show the total mass loss or the average mass balance over a period in a basin or mountain region, and it is often the case that different researchers obtained different results for a same region in a same period. For example, [46] found the glacier elevation change of -0.58 ± 0.21 m/a, which is equivalent to mass balance of -0.52 ± 0.19 m w.e./a, assuming an ice density of 900 kg/m^3 , during 2003–2009 in the Tien Shan, while [47] obtained glacier elevation change of -0.40 ± 0.05 m/a (-0.36 ± 0.05 m w.e./a) and -0.75 ± 0.05 m/a (-0.68 ± 0.05 m w.e./a) in the western (larger) and eastern (smaller) regions of Tien Shan in the same period. For the western Kunlun Mountains during 2003–2009, the glacier elevation change of -0.21 ± 0.18 m w.e./a was given by [48], whilst $+0.17 \pm 0.15$ m/a or $+0.15 \pm 0.14$ m w.e./a was obtained by [46], and $+0.03 \pm 0.25$ m w.e./a was found by [49], respectively. [23] investigated the glacier mass balance changes in almost the whole of High Mountain Asia from remote sensing data and derived that between the periods 2003–2008 and 2000–2016, the mass balance is -0.37 ± 0.31 m w.e./a and -0.28 ± 0.20 m w.e./a in the Tien Shan, $+0.18 \pm 0.14$ m w.e./a and $+0.14 \pm 0.08$ m w.e./a in the Kunlun, -0.09 ± 0.12 m w.e./a and -0.03 ± 0.07 m w.e./a in the Karakoram and -0.41 ± 0.24 m w.e./a and -0.08 ± 0.07 m w.e./a in the Pamir. These figures show that the mass balance is more negative in the penultimate decade than in the latest decade, i.e., no recent accelerating mass loss.

Although there have recently been many publications specifically on glacier change in Xinjiang, most of them focus on a small basin or sub-regions in a period after 2000. For instance, [50] obtained the glacier area reduction rate of 0.15%/a in the Shaksgam River Basin of the Karakoram Mountains from 2001 to 2015, and [51] derived 0.59%/a and 0.74%/a in the Harlik Mountains from 2002 to 2010 and the Mt. Bogda from 1999 to 2013 in eastern Tien Shan. These figures of glacier area changes are not larger than those from glacier inventory results [33], meaning that the glacier area reduction rate has not increased in these regions after 2000. Only the area reduction of 2.02%/a in the Sawir Mountains, Altai from 2006 to 2017 is significantly larger than inventory results [52]. It is probably because that the glaciers with the area smaller than 1 km^2 accounting for 94% in number, which is more sensitive to climate warming.

Some researchers reported that glaciers are stable and even in advance in the Karakoram [53], west Kunlun [54] and Pamir [26] after the 1990s, with unclear spatial and period ranges. These are opposite to the recent study of [23] mentioned above.

From the above-mentioned points, mass loss and area reduction of glaciers in Xinjiang seemed to be higher during the period from the turn of the century to around 2010 than other periods. Since the early of the century, the monitored glaciers in the Tien Shan have shown a continuous increase trend of terminus retreat but the recent mass balance is not more negative than in the 2000s. Regional remote sensing results have not shown a clear trend of recent change.

6.2. Glacier Response to Climate Change

According to meteorological data statistics, Xinjiang has experienced a warming and wetting trend for the past half of a century. Figure 4 shows the change trends of temperature and precipitation in the whole Xinjiang, the southern and northern regions. The average annual temperature from 1961 to 2018 is 8.35 °C in the whole Xinjiang, 10.13 °C in the south and 5.94 °C in the north. It can be seen from Figure 4a that the annual mean temperature from 1961 to 2018 has a significant increasing trend with a rate of 0.32 °C/10a in the whole Xinjiang, 0.29 °C/10a in the south and 0.36 °C/10a in the north.

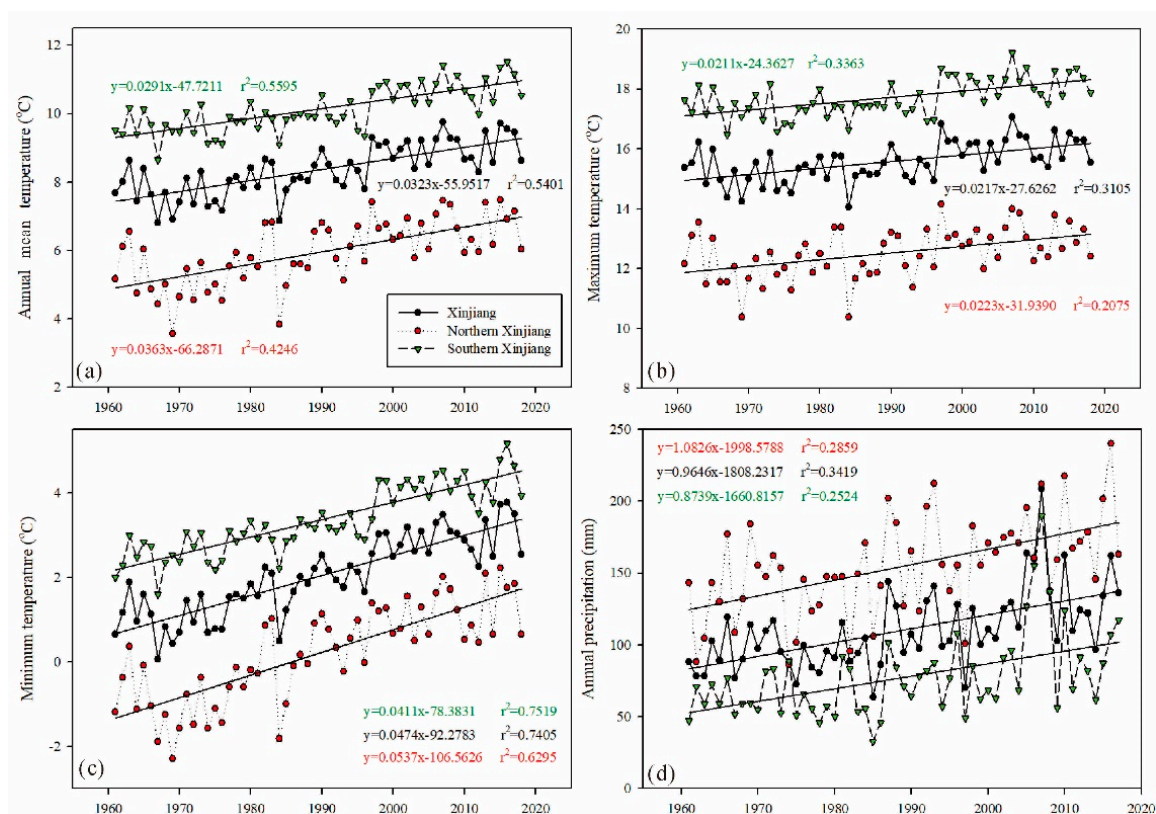


Figure 4. Changes of the (a) annual mean temperature, (b) maximum and (c) minimum temperature from 1961 to 2018, and (d) annual precipitation from 1961 to 2017, in the whole, the northern, and the southern Xinjiang.

Annual mean maximum and minimum temperatures also have increasing trends, but comparing with the annual mean temperature, the increasing rate of maximum temperature is the lowest and the increasing rate of minimum temperature is the highest. The maximum temperature increasing rate is almost the same in the whole Xinjiang (0.22 °C/10a), the south (0.21 °C/10a) and the north (0.22 °C/10a) (Figure 4b). The minimum temperature increasing rate is 0.47 °C/10a in the whole Xinjiang, 0.41 °C/10a in the south and 0.54 °C/10a in the north (Figure 4c). These indicate that the minimum temperature increase contributes a major to the climate warming in Xinjiang and the northern Xinjiang has become warming more significant than the southern Xinjiang. Moreover, temperature had a lift around the late 1990s, no matter the annual mean, maximum, and minimum values, and the maximum temperature increase has a slight slowing trend since 2007.

The average of annual precipitation from 1961 to 2017 is 110.31 mm in the whole Xinjiang, 77.29 mm in the south and 154.79 mm in the north. The annual precipitation shown in Figure 4d has increased at a rate of 9.65 mm/10a in the whole Xinjiang, 8.74 mm/10a in the south and 10.83 mm/10a in the north, but the northern side has a larger inter-annual variability.

In order to see more about the spatial differences of changes in temperature and precipitation, Figure 5 shows the $0.5^\circ \times 0.5^\circ$ gridded dataset of monthly temperature and precipitation from 1961–2018 provided by CMA. This figure indicates that temperature increased more in the north than in the south and more in the east than in the west (Figure 5a), and precipitation increased most significantly in the northwest and southeast (Figure 5b). It is worth noting that both temperature and precipitation did not have a noticeable increase in the region around the southwest border.

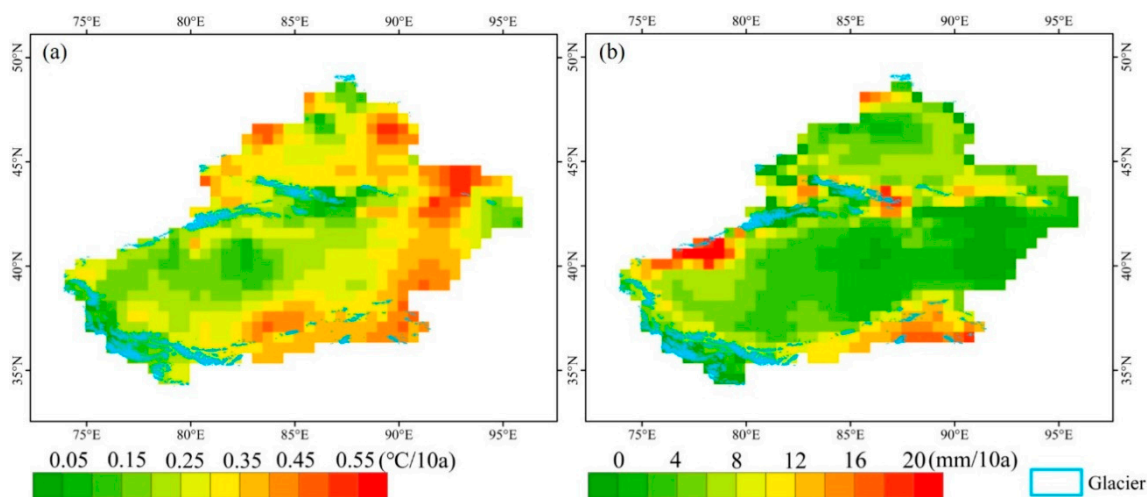


Figure 5. Spatial changes in the (a) annual mean temperature and (b) annual precipitation in Xinjiang from 1961 to 2018.

It is well known that glacier change is controlled essentially by climate change and the combination of temperature and precipitation determines the glacier mass balance. Consequently, the mass change causes glacier dimensional changes. Some studies have demonstrated that the mass balance is more sensitive to temperature than to precipitation in the Tien Shan and other regions in Xinjiang [55–57]. Therefore, the temperature increase (Figure 4a) is undoubtedly the main cause of glacier shrinkage in Xinjiang since the 1960s and precipitation increase is insufficient to offset the melting increase. The higher temperature increase rate has resulted in larger glacier shrinkage in the northern than in the southern regions.

Reference [26] suggested that the enhanced westerly circulation benefits to glacier mass loss decrease in the Pamir and Karakoram. From Figure 4d we can see that precipitation has been in continuous increase on average both in the northern and southern Xinjiang and the maximum temperature increase has a slowing trend since 2007. Figure 5 does not show noticeable increase in temperature and precipitation in past decades in the Pamir and Karakoram. So the recent decrease of glacier mass loss should be attributed to both the long-term steady climate and the recent increase precipitation, and less change of the maximum temperature in these regions. Moreover, the continuous increase in precipitation and the slowing increasing maximum temperature may have also influenced glacier mass balance in the western Tien Shan. This coincides with recent remote sensing result of [23] on mountains scale and the long-term monitoring glacier, i.e., the mass loss has a decrease trend after 2010 not only in the Karakoram, Kunlun, and Pamir regions, but also in the Tien Shan.

In addition, [46] pointed out that individual observed glaciers tend to be thinning more rapidly than the region as a whole. On a regional scale, different methods, data sources, and investigation periods may obtain different results. Especially the shorter the period, the larger error. Therefore, it needs to investigate further on a regional scale if the recent slowing of glacier mass loss and area reduction are general and continuing. On the other hand, the meteorological stations are located basically in the lower altitudes relative to the glacierized altitudes and in general, precipitation has a large spatial variability, especially in mountain regions. The shortage of precipitation data at high

altitudes is limiting the understanding of the glacier response to climate change, so it is important to improve remote sensing precipitation data and to carry out more in situ measurements of precipitation at high altitudes.

Moreover, glacier surging events seem to occur more frequently in Karakoram and Kunlun [58,59], likely to be related to the increase both in glacier temperature and liquid precipitation.

7. Conclusions

Glaciers in Xinjiang have been in continuous mass loss and dimensional shrinkage during the past decades, although there exist spatial differences between mountains and sub-regions. The significant temperature increase is the dominant controlling factor of glacier change. Although some research reported that glaciers had less mass loss or even slight mass gain in some regions, it seems to be general that the most intensive mass loss and area reduction of glaciers occurred in the early part of the new century due to the sharp increase of temperature in the late 1990s. The slowing of mass loss after around 2010 has been observed on some individual glaciers and reported by recent studies for several regions, but it needs to be further investigated to see if the slowing is general and continuing. Moreover, it is important to acquire meteorological data, especially precipitation, at high altitudes for understanding of the glacier response to climate change.

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