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Analysis and prediction of glacier evolution trend (2020–2100) in Northern Xinjiang

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A B S T R A C T

Glaciers, as “solid reservoirs”, are precious resources in arid areas. The study of glaciers is of great significance to the sustainable development and management of agriculture and the economy in northern Xinjiang. The area of glacier distribution on the 1963 topographic map data, 1975 MSS data, 2000 ETM data, 2008 CBERS-2 data, 2014 and 2018 ETM+ were collected as secondary data. According to the remote sensing survey, the glacier areas in Northern Xinjiang are identified during 1963–2018. Based on the evolution of glacier area in the past 55 years, and using two scenarios, the average annual decrease area of a region during the whole 1963–2018 and the period with the minimum reduction area, the glacier areas of Southern Tianshan Mountains, Western Tianshan Mountains, Eastern Tianshan Mountains, the Sawuer Mountains and Altai Mountains in Northern Xinjiang, and the whole northern Xinjiang in 2030, 2040, 2050, and 2100 are examined and predicted. In 2100, the glacier area in Northern Xinjiang may decrease by 43%–59%.

1. Introduction

Glaciers are sensitive indicators of climatic and environmental change, and are an important component of regional water cycle, which is closely related to human beings (Oerlemans J, 2005). Glacier change directly affects the water volume of lakes with glacial meltwater as the main water source, thus affecting the water supply of human production and living, and causing great damage to the sustainable development of ecology, economy, and society. At the same time, they also have a significant impact on sea level rise and atmospheric circulation patterns (Piao SL et al., 2010). According to the second glacier cataloging data (Liu CH et al., 1999), there are 48571 glaciers in China, with a total area of 5.18×10^4 km^2, accounting for 7.1% of the world glaciers (except the Antarctic and Greenland ice sheets).

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Xinjiang is the largest inland province in China, with an extremely arid continental climate. Xinjiang is dominated by traditional agriculture and animal husbandry. Due to the scarcity of precipitation, water for production and living are mainly provided by glacial melt water of “solid reservoir”, which leads to the famous “oasis economy” (Wang ZT et al., 1990). Water resources are linked to the development and utilization of land resources and the sustainable development of Xinjiang (Kareshnik CB, 1982). Therefore, glaciers are important to the current economic and social level of Xinjiang, and this development level will be restricted by the continuous depletion of glacial resources (Sun A et al., 2022). After the glacial retreat of the Qinghai-Tibet Plateau has caused the deterioration of the geological ecological environment, it will threaten the production and life of human beings, the survival and reproduction of animals and plants, which will cause great uncertainty in the integrity of the ecological chain. The warming effect leads to the shrinking of the cryosphere, which will lead to frequent epidemics and the reduction of biodiversity. The sharp reduction of mountain glaciers will greatly dwindle and eliminate species (Sun XY et al., 2019).

With the escalation of global warming, especially since the 1980s, most glaciers in the arid region of northwest China are generally in a state of material loss, and trend to retreat and become thinner (Lai ZM et al., 1986). Therefore, it is more and more important to improve the accuracy of glacier changes monitoring in Northern Xinjiang. The introduction of remote sensing technology into the field of glacier monitoring has reduced the difficulty in obtaining glacier data and increased the accuracy of that data (Zhang JT et al., 2012), especially with the public release and free use of Landsat MSS /ETM/ETM+ and CBERS-2 series data. In recent years, many scholars have conducted numerous studies on glaciers such as Tianshan Mountains by using topographic maps and remote sensing data, and found that the glaciers in the study area show a regression trend, with a retreat rate exceeding 11% (Li ZQ et al., 2010). From 1960 to 2009, the glaciers in Altai Mountains of China generally receded, and their number, area, and ice reserves decreased by 116 km^2, 104.61 km^2, and 6.19 $km^{3,}$ respectively Yao XJ et al., (2012). Tian HZ et al. (2016) found that the glacier area in Tibetan Plateau and surrounding mountains decreased by 15.7% from 1963 to 2010, with an annual area change of 0.33%. Farinotti D et al. (2009) used gravity satellites, laser altimetry data, and glacier models to assess the glacier material loss of the entire Tianshan Mountains, and the results indicated that the glacier area and material loss ratios from 1961–2012 were 18% ± 6% and 27% ±15 % (Wang SJ et al., 2011; Xie WR et al., 1986), respectively. Due to the inconsistency of data sources, calculation methods and research periods, the change of glacier area in this area lacks comparative results of regions and time spans, and there are few literatures on specific predictions of glacier retreat, which is not conducive to the protection of glacier resources.

Based on these factors, the China Geological Survey has conducted an investigation of modern glaciers and snow lines in the downstream areas with a high demand for water resources in small watersheds using the project of "*Remote Sensing Investigation and Monitoring of Eco-geological Environment of Qinghai-Tibet Plateau*" (Zhang RJ et al., 2010a, 2010b, 2010c), supported by modern remote sensing technology, and taking the Southern Tianshan, Western Tianshan, Eastern Tianshan, Sawuer, and Altai Mountains as units (Fang HB et al., 2011, 2013; Fig. 1). According to the evolution data of glacier resources, the changing trend of glacier resources in this area and the quantity of glacier resources in different periods from 1963–2100 would be better comprehended, which can provide reference for the development, utilization and preservation of glacier resources in this area.

2. Study area and data

Modern glacier and snowline surveys are based on natural mountain systems in the northern region of Xinjiang, and then larger mountain systems are divided and surveyed (Cheng YQ et al., 1994). Since glacier water resources are closely related to the production and lives of people in the working area, they are the only surface water resources that can be considered to

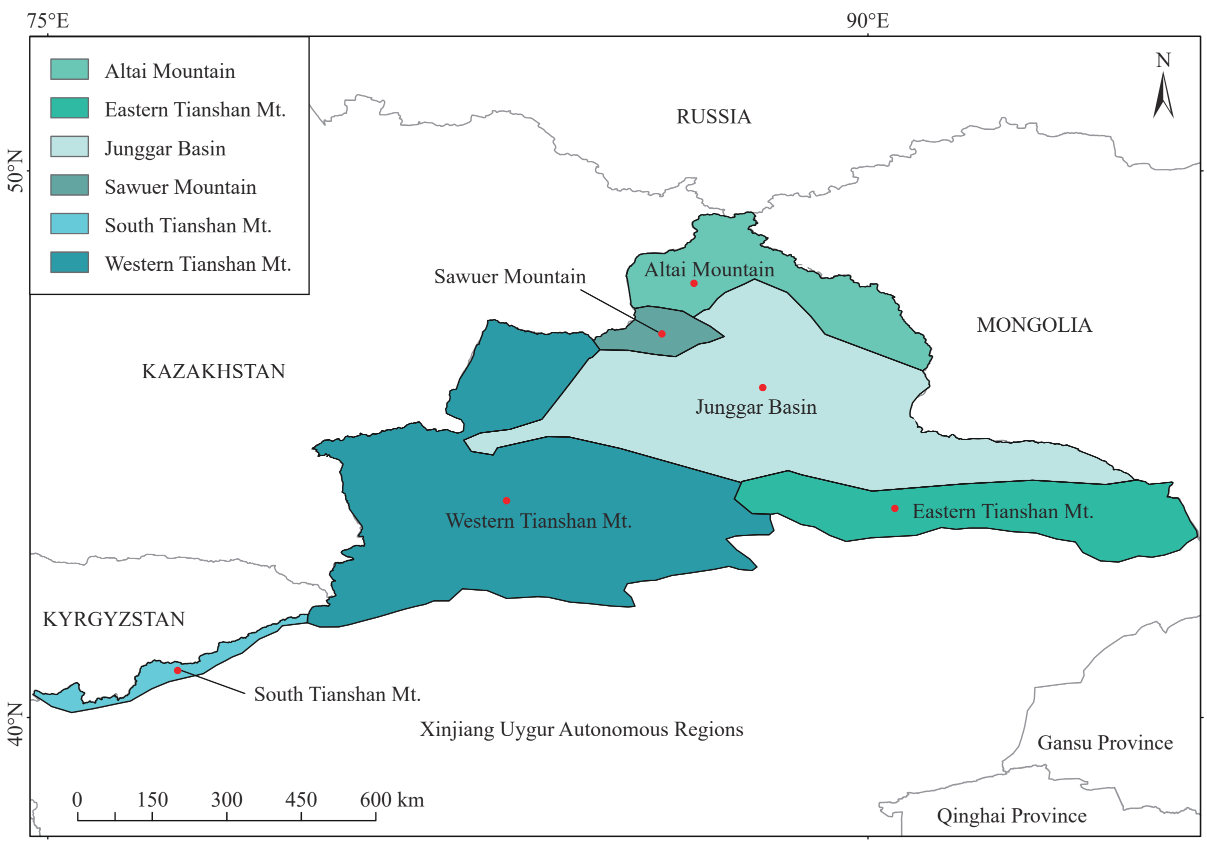

Fig. 1. Glacier study areas in Northern Xinjiang.

be depended on, so the investigation is conducted according to the characteristics of agriculture, industry, and cities in the downstream, and then the main river basin. The northern region of Xinjiang consists of three mountain ranges: the Tianshan Mountains, the Sawuer Mountains and the Altai Mountains. The Tianshan Mountains are divided into three sections: the Southern Tianshan Mountains, the Western Tianshan Mountains and the Eastern Tianshan Mountains, as shown in Fig. 1. In this study, field investigations in some areas of the Tianshan were also conducted, as shown in Fig. 2.

The baseline data was obtained from the glacier region on the early 1963 1∶100000 topographic map. This data was compared to the glacier distribution area data from the 1975 MSS, 2000 ETM, and 2008 CBERS-2 to evaluate variations in glacier area during these three time periods. The modern snowline changes were investigated based on the ETM data and a 1∶100000 topographic map for both periods. The glacier area in northern Xinjiang was measured in four periods: 1963, 1975, 2000, and 2008, with a change in glacier area between the periods. The snowline height survey was conducted in terms of mountain systems. The height of the topographic map in 1963 was first obtained, and then the position of the snowline was determined based on the various characteristics of the accumulation and ablation areas on the remote sensing images in 2000 or 2008. Elevation was used to determine the average height of the snowline as well as the changes in the snowline from 1963–2008. Lastly, the 2014 and 2018 ETM+ data, which examined and predicted the change in glacier area from the 1963 to the 2100. The remote sensing image data from some key areas with visible glacier reduction are shown in Fig. 3.

3. Prediction of future glacier area based on the reduction rate of glacial area

Changes in glacier area are influenced by a variety of factors, and there is no established method to predict these changes. Annual percentage of area changes (APAC) is a common indicator for evaluating the extent of glacier area changes, allowing researchers to better compare results of glacier change studies results at different periods (He Y et al., 2018). Similar to the average rate of change of glacier area, this study uses the rate of glacier area loss to analyze and predict the change of glacier area. The decrease of glaciers is divided into the total reduction rate (R) and the annual average reduction area (R_a). The total reduction rate is defined as the ratio of the amount of glacier area reduction to the initial annual glacier area over a period of time, while the average annual reduction area is defined as the average annual reduction area of the glacier over a period of time. The formulas are as follows:

$$R = (s_n - s_0) / s_0 \times 100\% \tag{1}$$

$$R_a = (s_n - s_0) / n \times 100\% \tag{2}$$

Where, S_0 represents the glacier area in the initial state of a period; S_n represents the glacier area in the final state of a period and n represents the number of years in the period. In this study, R was used to reflect the overall glacial recession in a region from 1963–2018. In addition, two types of R_a, i.e.

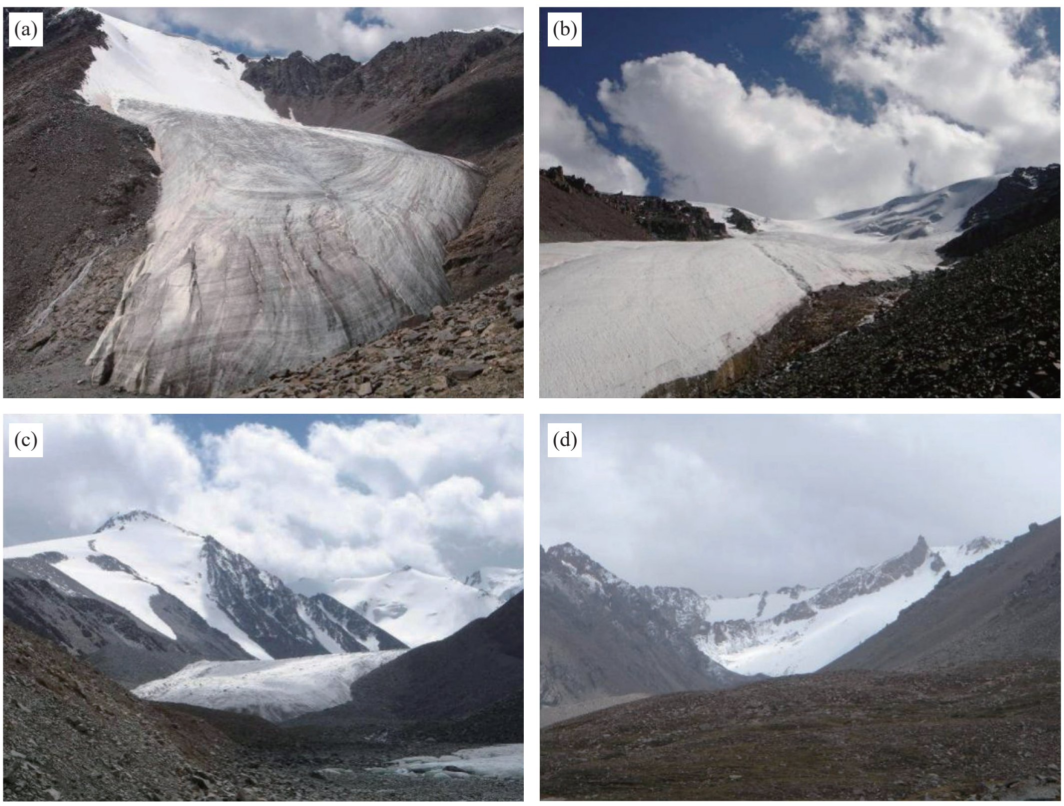

Fig. 2. Some examples of glaciers in the Northern Xinjiang.

the average annual areas of decline for a region over the entire 1963–2018 and the time period with minimum decline area, were selected as the basis for predicting glacier change in 2030, 2040, 2050, and 2100. The reason for this is, on the one hand, to explore how glaciers might change according to the average annual decline area of the overall last 55 years. Moreover, if the best-case scenario of past glacier reduction i.e. minimum average annual decline area over a period of time is extrapolated, what would the future glacier area eventually become would be a vital question.

4. Prediction and evaluation of the evolution trend of glacier resources in Northern Xinjiang

4.1. Dynamic change law of modern glacier snow line in Northern Xinjiang

According to the results of this survey, the glacier area in Northern Xinjiang was 12216.58 km^2 in 1963, 11832.63 km^2 in 1975, 10557.03 km^2 in 2000, 9999.15 km^2 in 2008, 6911.58 km^2 in 2014, and 6081.93 km^2 in 2018, as shown in Fig. 4. The data in 2014 was the verified Second Glacier Inventory Data, which was also consistent with the evolutionary pattern of glacier area reduction in Fig. 4, proving the long time series of data used in this study was more accurate.

In the past 55 years, the glacier area has decreased by 6134.65 km^2, a decrease of 50.22% from 1963, with an average annual decrease of 111.54 km^2. During 1963–2018, the minimum reduction rate of glacier area was from 1963–1975, with a total reduction rate of 3.14% and an average annual decrease of 32.00 km^2. However, the glacier area declined sharply from 2008–2014, with the highest total decline rate of 30.88% and an average annual decrease of 514.60 km^2.

The glacier retreat in Northern Xinjiang has escalated and accelerated significantly. Between 2008 and 2014, the rate of decrease reached its highest point in the past 55 years, however, the rate of decrease declined significantly in 2014–2018. This may be due to the continuous shrinkage and thinning of some small glaciers after a long period of glacial decline, and the thinning of the edges of large glaciers as the region warms and precipitation intensifies. As a result, the glacier area has a significant decrease trend during 1963–2020. However, between 2014 and 2018, the trend of decreasing glacier area began to slow down, and the sharp decline in glacier area was curbed.

In this study, the authors selected the minimum annual decline area (32.00 km^2) from 1963–1975 and the average annual decline area (111.54 km^2) during 1963–2018 as the basis for predicting the glacier area in 2030, 2040, 2050, and 2100 in the Northern Xinjiang. The prediction results are shown in (Fig. 5), and the glacier areas in 2030, 2040, 2050,

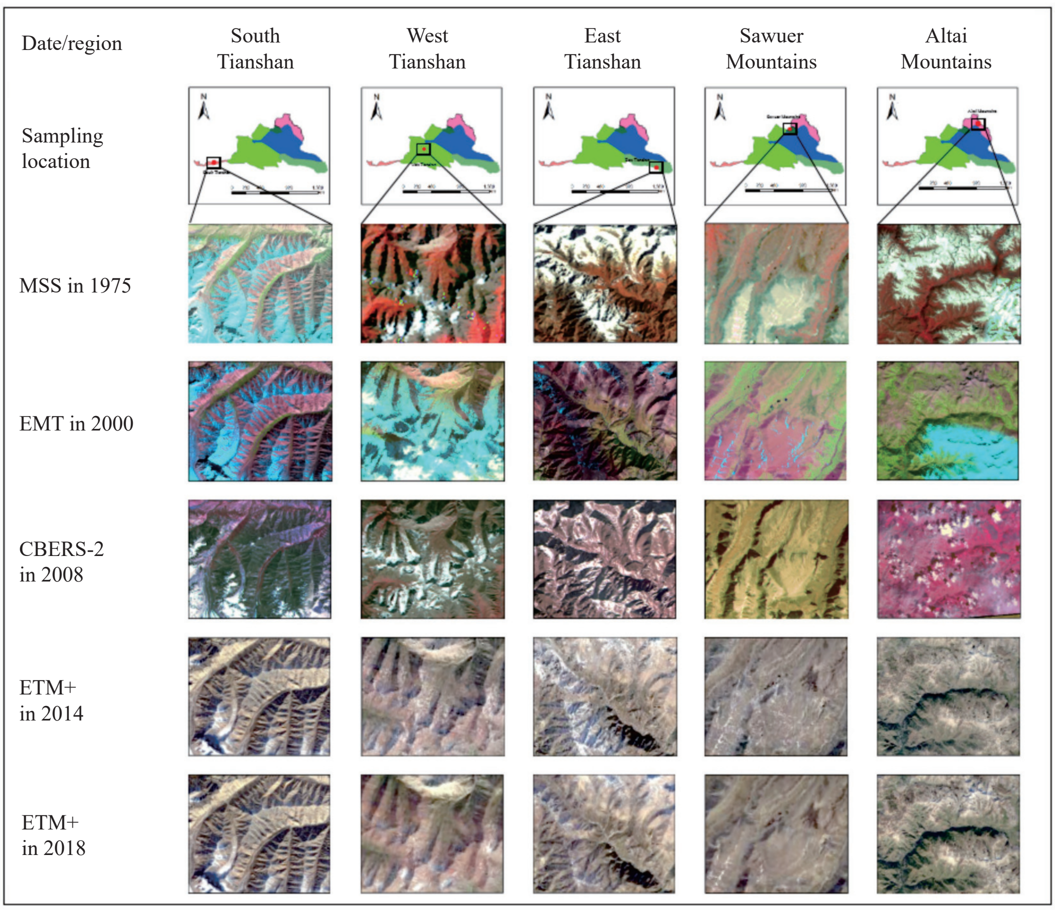

Fig. 3. Remote sensing image data of some key areas with visible glacier reduction.

and 2100 will be 5697.98 km^2, 5378.02 km^2, 5058.06 km^2, and 3458.27 km^2, respectively, according to the minimum average annual decline area. If the average annual decline area is used to predict, the glacier area in 2030, 2040, 2050, and 2100 will be 4743.46 km^2, 4423.50 km^2, 4103.54 km^2, and 2503.75 km^2, respectively, implying the glacier area in Northern Xinjiang may decline by 43%–59% in 2100, which a more significant decrease in Northern Xinjiang's glacier area.

4.2. Southern Tianshan Mountains region

According to the statistics, there are 692 glaciers of various sizes in the Southern Tianshan Mountains of China (data from the first National Glacier Inventory Data, hereinafter referred to as the data). According to the results of this remote sensing survey, the glacier area was 907.39 km^2 in 1963, 856.67 km^2 in 1975, 811.74 km^2 in 2000, 704.85 km^2 in 2008, 298.41 km^2 in 2014, and 251.77 km^2 in 2018, as shown in (Fig. 6; Table 1).

After nearly 55 years, the glacier area has decreased significantly by 655.62 km^2, a decline of 72.25% from 1963, with an average annual decrease of 11.92 km^2. During 1963–2018, the minimum decline rate of glacier area was from 1975 to 2000, with a total decline rate of 5.24% and an average annual decrease of 1.80 km^2. However, the glacier area declined sharply between 2008 and 2014, with the highest total decline rate of 57.66% and an average annual decrease of 11.92 km^2.

Based on the minimum annual decrease area (1.80 km^2) during 1975–2000 and the average annual decrease area (11.92 km^2) during 1963–2018, the glacier area in the Southern Tianshan Mountains in 2030, 2040, 2050, and 2100 is thus predicted.

The glacier areas is projected to be 230.2 km^2 in 2030, 212.23 km^2 in 2040, 194.26 km^2 in 2050 and 104.4 km^2 in 2100 based on the minimum average annual decline area (Fig. 6; Table 1). However, if the average annual decline area is used to predict, the glacier area in 2030 and 2040 will be 108.73 and −10.48 km^2 respectively. In fact, it is unlikely that the glacier area will be negative. the predicted glacier area in 2040 suggests that the Southern Tianshan glacier will disappear by 2040.

4.3. Western Tianshan Mountains region

According to the statistics, there are 7550 glaciers of

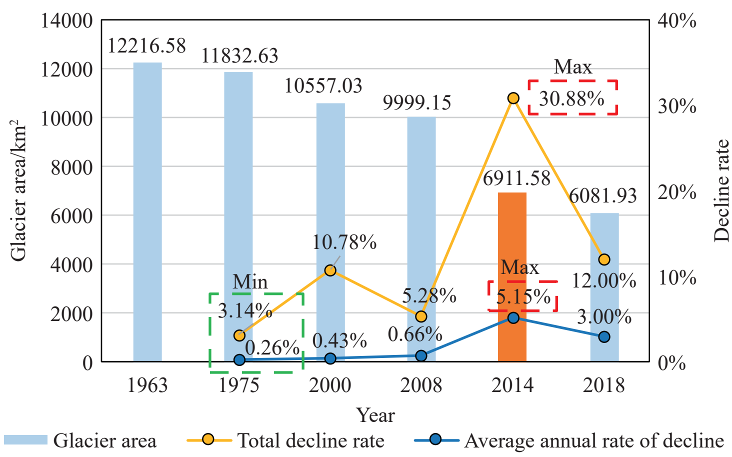

Fig. 4. Changes in the glacier area of Northern Xinjiang during 1963–2018.

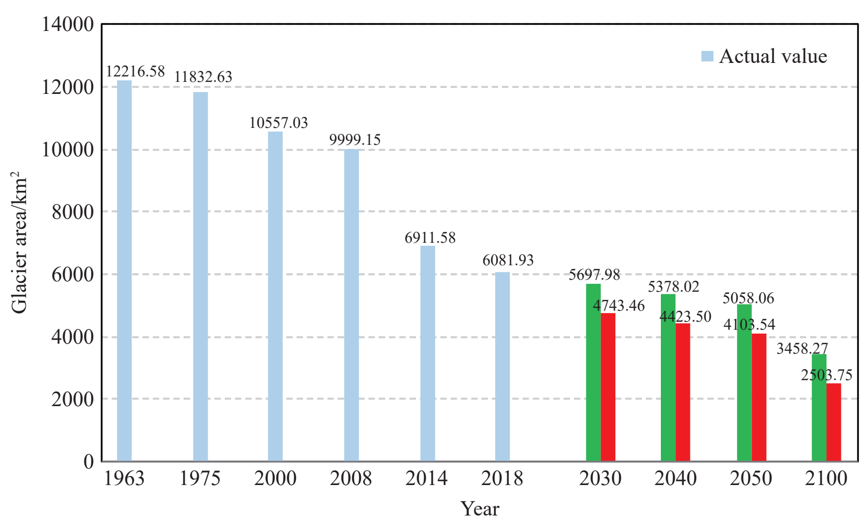

Fig. 5. Prediction of glacier evolution of two declining areas in Northern Xinjiang.

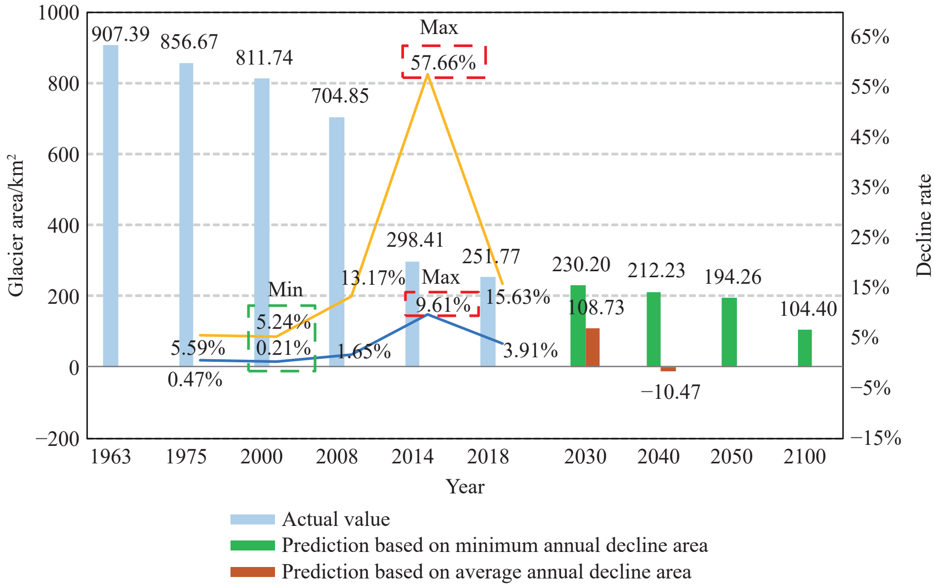

Fig. 6. Changes and prediction of glacier evolution in the South Tianshan.

various sizes in the Western Tianshan Mountains of China. According to the results of this remote sensing survey, the glacier area covered 10548.07 km^2 in 1963, 10241.30 km^2 in 1975, 9141.35 km^2 in 2000, 8763.35 km^2 in 2008, 6190.80 km^2 in 2014, and 5489.97 km^2 in 2018, as shown in (Fig. 7; Table 1).

In the past 55 years, the glacier area has been significantly decreased by 5089.10 km^2, a decline of 48.25% from 1963, with an average annual decrease of 92.53 km^2. During 1963–2018, the period of the minimum decline rate of glacier area was 1963–1975, with a total decline rate of 2.91% and an average annual decrease of 25.56 km^2. Consistent with the Southern Tianshan Mountains, the glacier area decreased sharply from 2008–2014, with the highest total decrease rate of 29.36% and an average annual decrease of 428.76 km^2.

Based on the minimum annual decreasing area (25.56 km^2) from 1963–1975 and the average annual decreasing area (92.53 km^2) from 1963–2018, the glacier area in the Western Tianshan Mountains in 2030, 2040, 2050, and 2100 is predicted, which are shown in (Fig. 7; Table 1). Based on the minimum mean annual decline area, the glacier areas in 2030, 2040, 2050, and 2100 are 5152.20 km^2, 4896.55 km^2, 4640.91 km^2, and 3362.70 km^2, respectively. However, if the average annual decrease area is used, the glacier area will be 4348.62 km^2 in 2030, 3423.32 km^2 in 2040, 2498.03 km^2 in 2050 and −2128.43 km^2 in 2100. In particular, the glaciers in the Western Tianshan Mountains will be extinct by 2077 according to the annual average decline area.

4.4. Eastern Tianshan Mountains region

According to the statistics, there are 658 glaciers of various sizes in the Eastern Tianshan Mountains region of China. According to the results of this remote sensing survey, the glacier area was 431.66 km^2 in 1963, 424.51 km^2 in 1975, 359.01 km^2 in 2000, 340.88 km^2 in 2008, 248.75 km^2 in 2014, and 221.99 km^2 in 2018, as shown in (Fig. 8; Table 1).

In the past 55 years, the glacier area has been significantly decreased by 209.67 km^2, a decline of 48.57% from 1963, with an average annual decrease of 3.81 km^2. During 1963–2018, the period of the minimum decline rate of glacier area was 1963–1975, with a total decline rate of 1.66% and an average annual decrease of 0.60 km^2. The glacier area was also decreased sharply from 2008–2014, with the highest total decline rate of 27.03% and an average annual decrease of 15.36 km^2.

Based on the minimum annual reduction area (0.29 km^2) during 1963–1975 and the average annual reduction area (3.81 km^2) during 1963–2018, the glacier area in the Eastern Tianshan Mountains in 2030, 2040, 2050, and 2100 is predicted. The prediction results are shown in (Fig. 8; Table 1). Based on the minimum mean annual decline area, the glacier areas in 2030, 2040, 2050, and 2100 are 218.55 km^2, 215.69 km^2, 212.83 km^2, and 198.53 km^2, respectively. However, if the average annual decline area is used, the glacier area will be 176.24 km^2 in 2030, 138.12 km^2 in 2040, 99.99 km^2 in 2050 and −90.62 km^2 in 2100. In particular, the glacier in the Eastern Tianshan Mountains will become extinct by 2077 according to the average annual decline area.

4.5. Altai Mountains region

According to the statistics, there are 403 glaciers of various sizes in the Altai Mountains region of China. According to the results of this remote sensing survey, the glacier area was 311.47 km^2 in 1963, 292.91 km^2 in 1975, 231.81 km^2 in 2000, 177.67 km^2 in 2008, 165.36 km^2 in 2014, and 141.80 km^2 in 2018, as shown in (Fig. 9; Table 1).

In the past 55 years, the glacier area has been significantly decreased by 169.67 km^2, a decline of 54.48% from 1963, with an average annual decrease of 3.08 km^2. During 1963–2018, the period of the minimum decline rate of glacier area was 1963–1975, with a total decline rate of 5.96% and an average annual decrease of 1.55 km^2. The glacier area was

Table 1. Changes and prediction of glacier evolution in the different regions of the Northern Xinjiang.

Region	Year	Actual value /km^2	Predicted with minimum decline area /km^2	Predicted with average decline area /km^2	Total decilne rate	Average annual decline rate
Southern Tianshan Mountains	1963	907.39				
	1975	856.67			5.59%	0.47%
	2000	811.74			5.24%	0.21%
	2008	704.85			13.17%	1.65%
	2014	298.41			57.66%	9.61%
	2018	251.77			15.63%	3.91%
	2030		230.20	108.73		
	2040		212.23	Disappear		
	2050		194.26			
	2100		104.40			
Western Tianshan Mountains	1963	10548.07				
	1975	10241.30			2.91%	0.24%
	2000	9141.35			10.74%	0.43%
	2008	8763.35			4.14%	0.52%
	2014	6190.80			29.36%	4.89%
	2018	5458.97			11.82%	2.96%
	2030		5152.20	4348.62		
	2040		4896.55	3423.32		
	2050		4640.91	2498.03		
	2100		3362.70	Disappear		
Eastern Tianshan Mountains	1963	431.66				
	1975	424.51			1.66%	0.14%
	2000	359.01			15.43%	0.62%
	2008	340.88			5.05%	0.63%
	2014	248.75			27.03%	4.50%
	2018	221.99			10.76%	2.69%
	2030		214.84	176.24		
	2040		208.88	138.12		
	2050		202.92	99.99		
	2100		173.13	Disappear		
Altai Mountains	1963	311.47				
	1975	292.91			5.96%	0.50%
	2000	231.81			20.86%	0.83%
	2008	177.67			23.36%	2.92%
	2014	165.36			6.93%	1.15%
	2018	141.80			14.25%	3.56%
	2030		123.24	104.84		
	2040		107.77	74.04		
	2050		92.30	43.24		
	2100		14.97	Disappear		
Sawuer Mountains	1963	17.99				
	1975	17.24			4.17%	0.35%
	2000	13.12			23.90%	0.96%
	2008	12.40			5.49%	0.69%
	2014	8.26			33.40%	5.57%
	2018	7.41			10.29%	2.57%
	2030		6.66	5.13		
	2040		6.03	3.23		
	2050		5.41	1.33		
	2100		2.28	Disappear		

also decreased sharply from 2000 to 2008, with the highest total decline rate of 23.36%, and an average annual decrease of 6.77 km^2. Meanwhile, the period of the highest average annual rate of decline was 2014–2018 (3.56%), with an average annual decline area of 5.89 km^2.

Based on the minimum annual decline area (1.55 km^2) during 1963–1975 and the average annual decline area (3.08 km^2) during 1963–2018, the glacier area in the Altai

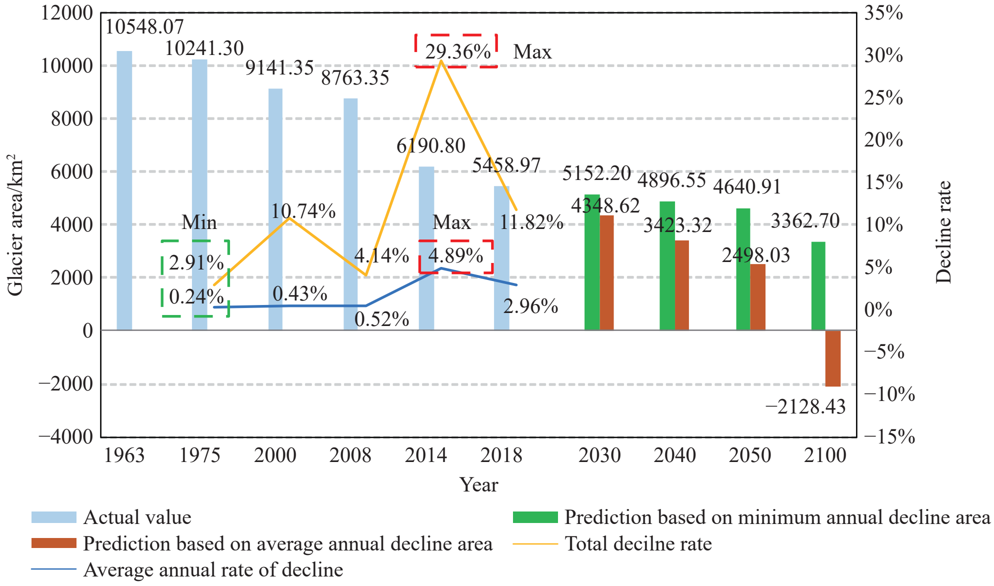

Fig. 7. Changes and prediction of glacier evolution in the Western Tianshan.

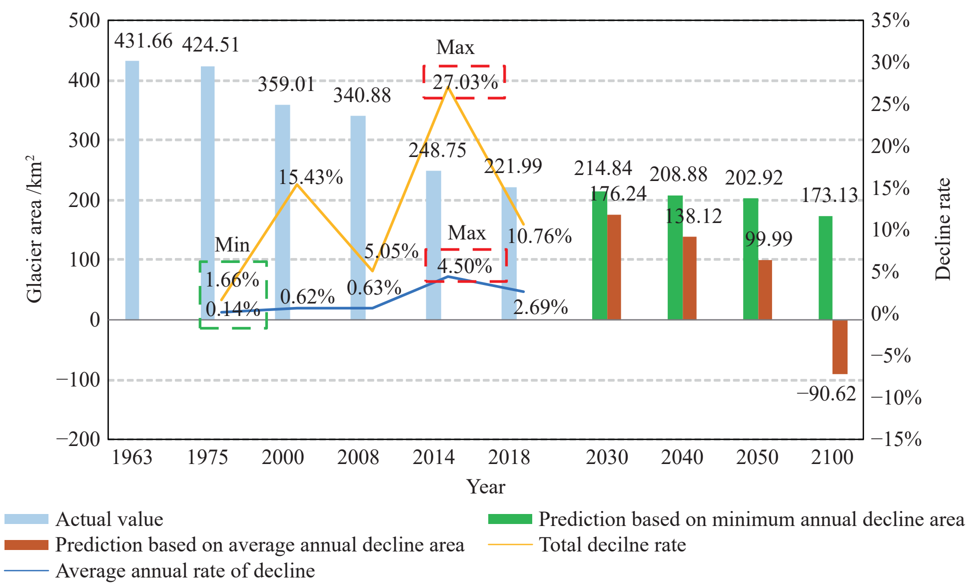

Fig. 8. Changes and prediction of glacier evolution in the Eastern Tianshan.

Mountains in 2030, 2040, 2050, and 2100 is predicted. The prediction results are shown in (Fig. 9; Table 1). Based on the minimum mean annual decline area, the glacier areas in 2030, 2040, 2050, and 2100 are 123.24 km^2, 107.77 km^2, 92.30 km^2, and 14.97 km^2, respectively. However, if the average annual decline area is used, the glacier area will be 104.84 km^2 in 2030, 74.04 km^2 in 2040, 43.24 km^2 in 2050 and −110.76 km^2 in 2100. In particular, the glacier in the Altai Mountains will also be extinct by 2064 based on the annual decrease in area.

4.6. Sawuer Mountains region

According to the statistics, there are 21 glaciers of various sizes in the Sawuer Mountains region of China. According to the results of this remote sensing survey, the glacier area was 17.99 km^2 in 1963, 17.24 km^2 in 1975, 13.12 km^2 in 2000, 12.40 km^2 in 2008, 8.26 km^2 in 2014, and 7.41 km^2 in 2018, as shown in (Fig. 10; Table 1).

In the past 55 years, the glacier area has been significantly decreased by 10.58 km^2, a decline of 58.82% from 1963, with an average annual drop of 0.19 km^2. During 1963–2018, the period of the minimum decline rate of glacier area was 1963–1975, with a total decline rate of 4.17% and an average annual decrease of 0.06 km^2. The glacier area also declined sharply from 2008 to 2014, with the highest total decline rate of 33.40% and an average annual decrease of 0.69 km^2.

Based on the minimum annual decline area (0.06 km^2) during 1963–1975 and the average annual decline area (0.19 km^2) during 1963–2018, the glacier area in the Sawuer Mountains in 2030, 2040, 2050, and 2100 is predicted. The prediction results are shown in (Fig. 10; Table 1). Based on the minimum mean annual decline area, the glacier areas in

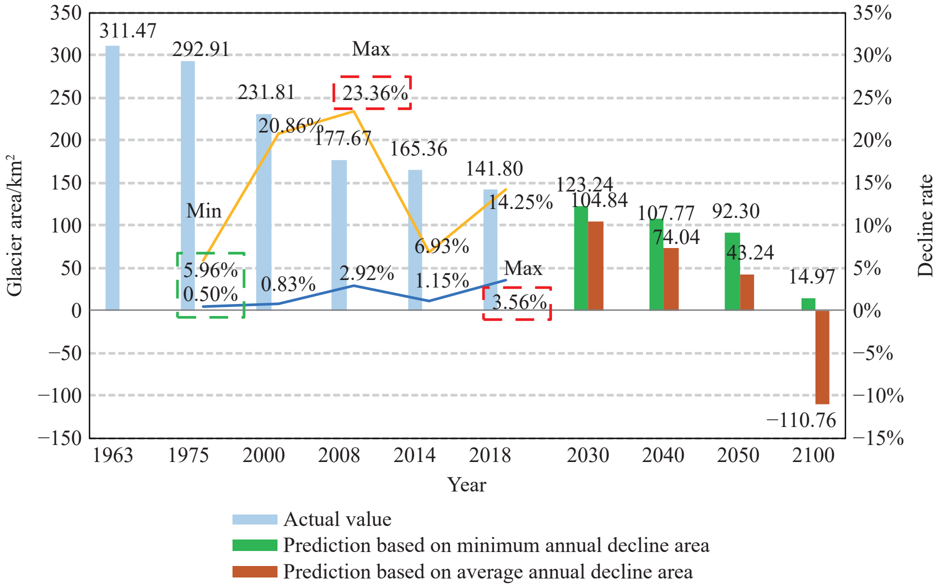

Fig. 9. Changes and prediction of glacier evolution in the Altai Mountain.

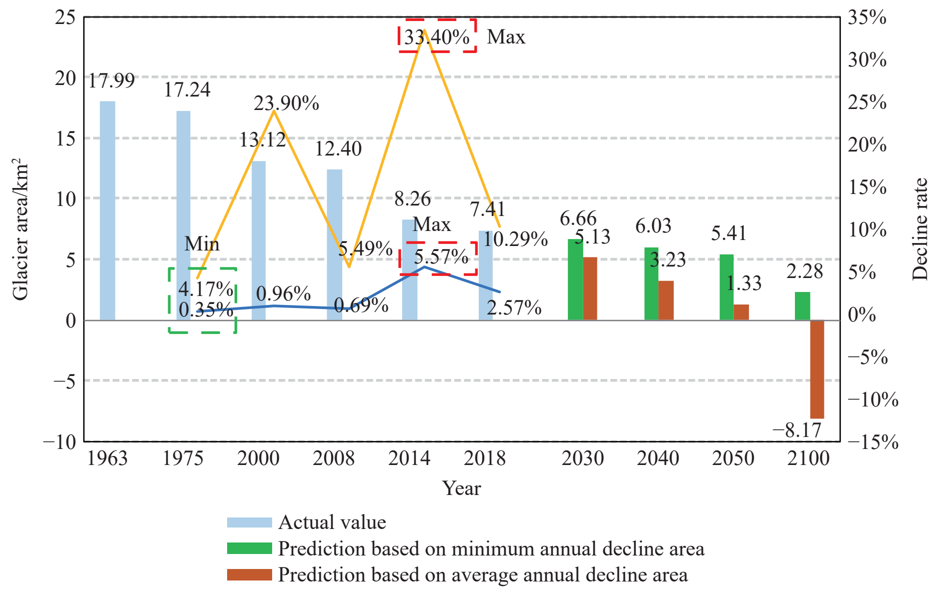

Fig. 10. Changes and prediction of glacier evolution in Sawuer Mountain.

2030, 2040, 2050, and 2100 are 6.66 km^2, 6.03 km^2, 5.41 km^2, and 2.28 km^2, respectively. However, if the average annual decline area is used, the glacier area will be 5.13 km^2 in 2030, 3.23 km^2 in 2040, 1.33 km^2 in 2050 and −8.17 km^2 in 2100. In particular, the glacier in the Sawuer Mountains will be extinct by 2057 based on the average annual decline area.

5. Discussion

The IPCC fifth report projected that the future climate will continue to increase under the global coupling model. Climate change has an important impact on many natural systems, especially in arid areas that are sensitive to climate change and human activities. The IPCC Sixth Assessment Report (AR6) indicated that human-induced climate change has already affected many weather and climate extremes worldwide. Continued global warming is projected to further intensify the global water cycle and many changes in the ocean, ice sheets and global sea level will be irreversible for centuries to millennia (Zhang QF et al., 2022).

There are abundant glacier water resources in Northern Xinjiang, which have an important impact on the ecological environment and sustainable development of Xinjiang. However, according to the results of this paper, glaciers in Northern Xinjiang are experiencing a sustained and rapid decline, and the glacier area has decreased from 12216.58 km^2 in 1963 to 6081.93 km^2 in 2018, with a decline of 50.22%. By 2100, it is expected to further decrease by 43%–59% compared with 2018. In addition, due to the obvious warming of the climate, the retreat of glaciers may accelerate, so the glaciers in northern Xinjiang are seriously threatened.

There are differences in glacier evolution trends in various regions of Northern Xinjiang, but they all face the risk of glacier loss. Glaciers are distributed in Western Tianshan Mountains, Southern Tianshan Mountains, Eastern Tianshan Mountains, Altai Mountains and Sawuer Mountains from large to small, as shown in Table 1. The Southern Tianshan Mountains, Eastern Tianshan Mountains, Sawuer Mountains and Altai Mountains have low altitude and small glacier volume, which can increase temperature. In particular, the moraine coverage on the glacier surface in East Tianshan Mountains, Sawuer Mountains and Altai Mountains is reduced, which is not conducive to the preservation of glaciers and causes obvious glacier retreat. If unprotected, according to the annual average decline area in 55 years, most glaciers in these areas may gradually disappear around 2100, and glaciers in the Southern Tianshan Mountains may even disappear in 2040.

As the mountains are higher than other areas on the northern border, the glaciers formed in the Western Tianshan Mountains are larger and there are more moraines on the surface, which is conducive to the preservation of glaciers. In the future, the main distribution area of glaciers will still be in the north. Despite these advantages, according to the average decline rate in the past 55 years, the glaciers in the Western Tianshan Mountains will disappear by 2100. Even under the most ideal circumstances, that is, under the minimum average annual reduction area, glaciers in most areas are on the verge of disappearance.

As glacier retreat is irreversible in a short term, it will seriously threaten animal husbandry, downstream industrial and agricultural production and residents' livelihoods in Northern Xinjiang, posing a challenge to the sustainable development of Xinjiang. Therefore, this study recommends that reservoirs should be established in glacial areas to store glacial meltwater. In the lower part of Tarim Basin, a Chinese super underground reservoir can be considered to be formed around the basin to store glacial meltwater. At the same time, the government can strengthen environmental protection and restoration, reduce the amount of wind and sand materials falling into glaciers, reduce the absorption of heat by glaciers and slow down the melting rate of glaciers.

6. Conclusions

This study firstly demonstrated the glacier area data from remote sensing of multiple sources in 1963, 1975, 2000, 2008, 2014 and 2018. Then, the glacier area changes in Nothern Xinjiang during 1963–2018 are captured and analyzed. Furthermore, the glacier evolution in Northern Xinjiang from 2030 to 2100 is predicted, which the results are as follows:

(i) The glaciers in the Northern Xinjiang are receding due to global warming. According to the analysis in this paper, the glaciers in the Northern Xinjiang has declined by 6134.65 km^2, or 50.22% in the past decade.

(ii) There are differences in glacier evolution trends in various regions of Northern Xinjiang, but they all face the risk of glacier loss. According to the average annual decline area in 55 years, most glaciers in these areas may gradually disappear around 2100, while glaciers in the Southern Tianshan Mountains may even disappear in 2040. Even under the most ideal circumstances, glaciers in most areas are on the verge of disappearance.

(iii) In order to cope with the water shortages in the future, it is recommended to build reservoirs in the glacier area to reduce the flow of melting material into the glacier and reduce the melting rate of the glacier.

The expected results of this paper may deviate from the actual results; this may be attributed to the unreliability of the data sources and the uniqueness of forecasting methods. In future studies, elevation models and permanent snow cover data can be introduced to analyze and predict the changes of glaciers in northern Xinjiang.

CRediT authorship contribution statement

The concept was put forward by Xi-yong Sun, Jia-feng Liu and Shao-qiang Wang. The experiment was conducted by Xi-Yong Sun and Wen-chen Hu. The project was supervised by Xiao-min Du and Jing-hui Fan. All authors discussed the results and contributed to the final manuscript.

Declaration of conflicting interests

The authors declared no conflicts of interest.

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