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Spatial and temporal changes of glaciers and glacial lakes in the Northern Tianshan Mountains over the past 30 years

HU Jiayu, *YAO Xiaojun, ZHANG Cong, ZHANG Yuan, MA Yuxin

College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China

Abstract: Glaciers and glacial lakes are very sensitive to climate change, and studying their dynamics is important for revealing changes in global climate. In this study, we extracted the boundaries of glaciers and glacial lakes in the Northern Tianshan Mountains based on Landsat TM/ETM+/OLI and Sentinel 2A/2B MSI remote sensing images and analyzed their dynamics and impacts over the past 30 years. The findings indicate that in 2020, the Northern Tianshan region exhibited a total of 3254 glaciers, with an area of 1670.55 km^2 and a volume of 95.69 km^3. The corresponding numbers, areas, and volumes of glacial lakes were 281, 13.23 km^2 and 210.49×10^6 m^3, respectively. Over the past 30 years, glaciers and glacial lakes have exhibited opposite characteristics. The former decreased by 16, 332.64 km^2 (−0.60%·a^{-1}) and 18.36 km^3 (−0.58%·a^{-1}), respectively, and the latter increased by 56 and 2.48 km^2 (0.82%·a^{-1}) and 38.88×10^6 m^3 (0.79%·a^{-1}), respectively. Moreover, different glacier termination types cause differences in the glacier retreat rates. Lake-terminated glaciers retreated faster than land-terminated glaciers, and the type of glacier termination has a greater effect on the retreat rate than the size of the glacial area.

Keywords: glacier; glacial lake; climate change; Northern Tianshan Mountains

1 Introduction

The cryosphere is one of five major spheres of the global climate system (Qin and Ding, 2009). Glaciers and glacial lakes are essential parts of the cryosphere and are sensitive indicators of global and regional climate change (Deng *et al*., 2019; Yue *et al*., 2022). The Tianshan Mountains in Central Asia is one of the largest glacierized mountain systems in the world and is often referred to as the “Central Asian Water Tower” (Sorg *et al*., 2012). Glaciers and glacial lakes recharge many rivers, are crucial freshwater resources in arid zones

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Author: Hu Jiayu (1999–), Master Candidate, specialized in glacier and glacial lake change and climate change. E-mail: 2021212875@nwnu.edu.cn
***Corresponding author:** Yao Xiaojun (1980–), PhD and Professor, specialized in cryospheric remote sensing and climate change. E-mail: xj_yao@nwnu.edu.cn

(Zhang *et al*., 2017a; Du *et al*., 2022), and have great significance for the regulation of river runoff, regional agricultural irrigation, and hydropower generation (Gong *et al*., 2017; Hou *et al*., 2022). In the context of global warming, glaciers in the Tianshan Mountains have melted rapidly (Nie *et al*., 2010; Wang *et al*., 2011), resulting in large losses of water resources in some basins in this area (Zhang *et al*., 2017b). Climate change weakens glacier stability (Zhou *et al*., 2024), which in turn leads to a higher frequency of glacial hazards, expansion of glacial lake areas (Liu *et al*., 2014), and increased susceptibility to glacial lake outburst floods (Duan *et al*., 2020). This will have a greater impact on local oasis agriculture and the ecological and economic development of towns (Xu *et al*., 2020), and even threaten the lives and properties of local people (Yao *et al*., 2018). Therefore, monitoring changes in glaciers and glacial lakes has received considerable attention from local governments and academics (Grinsted, 2013; Ji *et al*., 2022). Owing to the complex topography and geomorphology of glaciers and glacial lake distribution areas, it is difficult to conduct field surveys. Currently, the continuous progress of remote sensing technology and easy access to multi-source remote sensing imagery provide technical and data support for monitoring glaciers and glacial lakes and mapping their current status (Nie *et al*., 2017; Hu *et al*., 2022).

In the context of global warming (Harris *et al*., 2014), climatic conditions in China, particularly in the mountainous regions of northwest China, have shifted from warm to warm wet in recent decades (Gou *et al*., 2019; Liu and Shi, 2023). The Tianshan Mountains range is situated in northwestern China and spans the central portion of Xinjiang Province, giving rise to a distinct regional climate (Chen *et al*., 2017). Numerous researchers have undertaken comprehensive investigations in this geographical area, leading to a consensus that the Northern Tianshan Mountains (hereafter Northern Tianshan) has experienced increased temperature and precipitation (Wang *et al*., 2013a; Guo and Li, 2015; Yin *et al*., 2020), with a distinct amalgamation of warm-dry and warm-wet conditions, characterized by a prevailing increase in average annual temperature and alterations in yearly precipitation. The intensification of westerly atmospheric currents originating from the Atlantic and Arctic Oceans has resulted in the influx of a substantial quantity of water vapor. This moisture underwent topographic uplift, leading to the formation of topographic precipitation and subsequently causing an increase in precipitation (Yuan *et al*., 2004). The retreat of glaciers in several parts of the Tianshan Mountains has been seen to be in accelerating decline to diverse extents over the past 50 years (Lan *et al*., 2007; Chen *et al*., 2016). From 1990 to 2015, there was a reduction in eight glaciers and a drop in volume of 26.14 km^3 in the Northern Tianshan region (Zhang *et al*., 2022a). Glacial ablation has depleted interim water resources. Thus, the depletion of water resources resulting from the reduction in glacial storage within the Kuytun River Basin amounted to 3.95 billion m^3 between the years 1964 and 2015 (Zhang *et al*., 2017b). From 2000 to 2016, the cumulative mass balance of glaciers in the Manas River Basin was recorded to be −9811.19 mm (Zhao *et al*., 2020). Liu *et al*. (2020) postulated that glaciers in the Tianshan Mountains region of Xinjiang will completely disappear from 2050 to 2150, assuming that the current global warming trend persists and leads to further increases in temperature. Over the past few decades, global glacial lake area has increased (Dou *et al*., 2022). Specifically, the glacial lakes area in the Tianshan Mountains region has expanded at an average rate of 0.689 $km^2 \cdot a^{-1}$ (equivalent to 0.8%$\cdot a^{-1}$) between 1990 and 2010. Glacial lake growth mitigates the depletion of regional glacial water resources in response to climate warming. According to Wang *et al*. (2013b), an estimated 0.006 Gt of glacial meltwater is preserved annually in glacial lakes, accounting for approximately 2 ‰ of the total annual glacial ablation in the Tianshan Mountains region.

The Third Xinjiang Scientific Expedition Program focuses on soil and water balances and water resource security and aims to solve current and future resource environment and green development problems. It also examines the resource, environment, ecological background and the carrying capacity to support economic and social development for the whole region of Xinjiang and proposes a future ecological construction and green development strategy and roadmap for Xinjiang. As a result of global warming, glaciers in the Northern Tianshan are swiftly melting and water resources are severely depleted. However, the spatial and temporal changes in glaciers and glacial lakes in recent years are unclear. Currently, most studies have only examined glaciers or glacial lakes over the Tianshan Mountains (Kääb *et al*., 2021; Zhou *et al*., 2021; Zhang *et al*., 2022b), lacking systematic and interactive analyses. Therefore, we constructed a glacier and glacial lake (>0.01 km^2) inventory for 1990, 2000, 2010, and 2020 using Landsat and Sentinel satellite remote sensing images. By combining climate data and ITS_LIVE glacier flow velocity data, we clarified the current status of glacier and glacial lake resources in the Northern Tianshan, investigated their changing patterns, and conducted a joint analysis of glacier and glacial lake reserves. This provides fundamental data for studying the water resource carrying capacity and water security of the Northern Tianshan.

2 Material and methods

2.1 Study area

The Tianshan Mountains range, situated in the interior of the Eurasian continent, occupies an average altitude exceeding 4000 m (Wang *et al*., 2017). With a length of approximately 2500 km, an average north-south width of 250–350 km, and over 800 km at its widest point, the Tianshan is further from an ocean than any other mountain system and is the largest in the arid regions of the world (Chen, 2014). The Tianshan Mountains traverses in an east-west direction, spanning approximately 1700 km across China. Encompassing an area of over 570,000 km^2, these mountains constitute approximately one-third of the total land mass of Xinjiang. Tomur Peak, at an elevation of 7443.8 m, is the loftiest summit within the Tianshan Mountains. The Syr Darya, Chu Darya, and Yili Darya rivers all have their sources in the Tianshan Mountains. The Tianshan Mountains is the only large mountain range in the world sandwiched between a huge desert and is the most typical representative of large mountain ecosystems in temperate arid zones globally. This study was undertaken on the northern slope of the Tianshan Mountains (42°–48°N, 79°–97°E), which was identified during the Third Xinjiang Scientific Expedition Program in China (Figure 1). According to the Chinese Glacier Inventory, the Northern Tianshan can be divided into five basins: Yiwu River Basin (5y71), Baiyang River Basin (5y72), Manas River Basin (5y73), Ebinur Lake Basin (5y74), and Ayding Lake Basin (5y81).

The northern section of the Tianshan Mountains exhibits the highest elevation and lowest temperatures of the entire range and has been subjected to a greater impact from the Siberian high-pressure system. The study region exhibits an average annual temperature of −0.71°C, and an average annual precipitation of 289 mm and summer precipitation constitutes 52% of the total annual precipitation, with a progressive decline from west to east. The Northern Tianshan region exhibits a significant extent of snow and ice cover, including 3257 glaciers and 300 glacial lakes in the region, across an area of 1789.24 km^2 and 11.77 km^2, respectively. The copious glaciers found in the Northern Tianshan region are a vital water resource in the arid areas of Central Asia. These glaciers not only determine the positioning of rivers in Central Asia, but also exert an influence on the quantity of water resources available in the region.

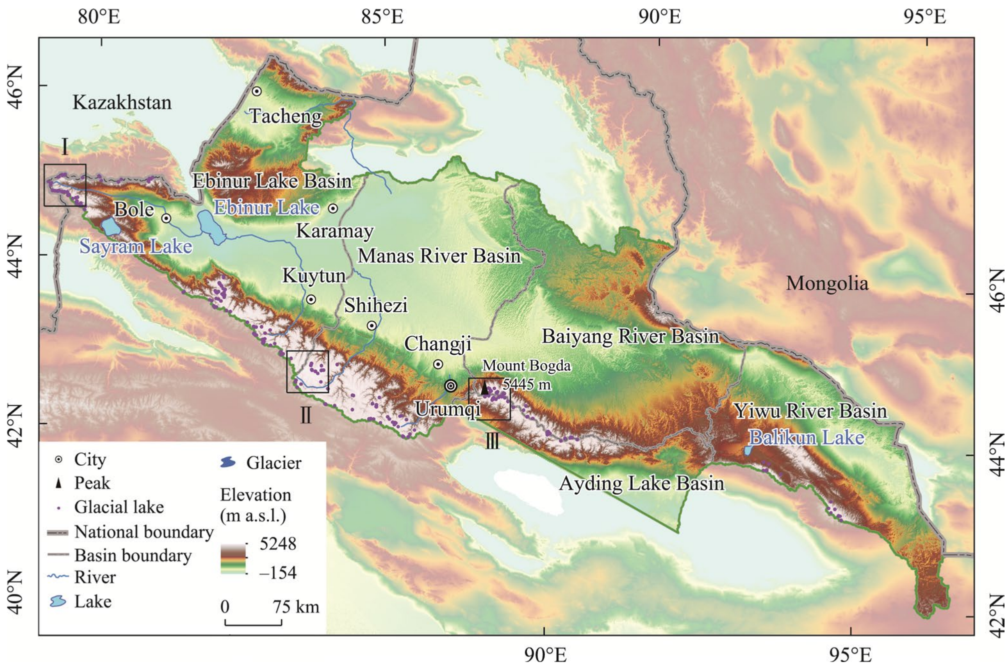

Figure 1 Study area overview map (Northern Tianshan Mountains in China)

2.2 Data

To enhance the precision of extraction of glacier and glacial lake data, we obtained China's Second Glacier Inventory Data V1.0, from the National Tibetan Plateau Data Center via the following website: http://data.tpdc.ac.cn/en/. This dataset was utilized as a reference point to accurately delineate and modify glacier boundaries across various years. Additionally, glacial lake datasets for 1990 and 2018, as published by Wang *et al.* (2020), were employed as benchmarks to revise glacial lake inventories for different time periods.

Satellite remote sensing images used for extracting glaciers and glacial lakes included Landsat TM/ETM+/OLI and Sentinel-2A/2B MSI images. Among them, 19 scenes used Landsat TM images from 1990, 11 scenes and 15 scenes used Landsat TM/ETM+ images from 2000, 23 scenes used Landsat TM images from 2010, 26 scenes used Landsat OLI, and 38 scenes used Sentinel-2A/2B MSI images from 2020 (Table 1). Landsat TM/ETM+/OLI images were downloaded from the United States Geological Survey (https://earthexplorer.usgs.gov/). The quality was Level-1, that is, they underwent preprocessing, including radiometric calibration and atmospheric correction. Sentinel-2A/2B MSI

Table 1 Remote sensing imagery information sheet

Row	Column	Number	Sensor	Date	Row	Column	Number	Sensor	Date
30	138	7	TM	1989/08/23	30	144	14	TM	1989/09/10
			ETM+	2000/07/12				TM	1993/08/28
			ETM+	2001/07/15				TM	1994/10/02
			TM	2008/07/10				ETM+	2000/08/07
			TM	2009/08/30				TM	1998/08/26
			TM	2010/10/04				TM	2011/07/13
			OLI	2020/07/27				TM	2011/07/29
30	139	6	TM	1991/08/20				OLI	2019/07/03
			ETM+	2002/08/26				OLI	2019/09/21
			TM	2009/10/08				OLI	2020/08/22
			TM	2010/09/25				OLI	2021/08/09
			OLI	2021/08/22				OLI	2021/09/26
			OLI	2021/09/07				OLI	2017/07/29
30	141	12	TM	1991/07/17				OLI	2021/07/24
			ETM+	1999/09/01	29	145	9	TM	1994/08/22
			ETM+	2001/08/21				ETM+	2002/09/21
			TM	2004/07/04				ETM+	2000/08/14
			TM	2003/07/18				TM	2008/07/27
			TM	2001/07/12				TM	2010/08/02
			TM	2000/08/26				TM	2010/10/05
			TM	2009/10/06				TM	2011/09/06
			TM	2011/08/25				OLI	2020/07/28
			OLI	2020/08/01				OLI	2019/08/27
			OLI	2020/09/18	30	145	5	TM	1994/08/22
			OLI	2021/09/05				ETM+	2002/08/20
30	142	9	TM	1992/07/26				ETM+	1999/10/15
			TM	1989/08/19				OLI	2020/07/28
			TM	1990/06/03				OLI	2019/08/27
			TM	1990/08/22	29	146	5	TM	1990/08/02
			ETM+	2001/07/11				ETM+	2001/08/08
			TM	2010/08/13				TM	2009/07/21
			TM	2011/10/03				TM	2011/09/13
			OLI	2019/09/23				OLI	2021/08/23
			OLI	2021/09/28	29	147	7	ETM+	2002/08/18
30	143	12	TM	1989/08/18				ETM+	2001/05/27
			TM	1991/09/01				ETM+	2000/08/28
			TM	1993/09/22				TM	2008/07/09
			TM	1994/08/24				TM	2009/10/16
			TM	2003/08/17				TM	2011/08/19
			TM	2000/10/11				OLI	2021/09/15
			TM	2010/08/04	29	148	2	TM	2011/09/11
			TM	2011/08/23				OLI	2021/09/06
			OLI	2019/08/13	44	TLQ	1	MSI	2021/08/20
			OLI	2021/09/19	44	TMQ	4		2020/07/13
			OLI	2021/07/01					2020/07/16
			OLI	2020/10/02					2021/07/26

(*To be continued on the next page*)

(*Continued*)

Row	Column	Number	Sensor	Date	Row	Column	Number	Sensor	Date
44	TMQ	4	MSI	2021/08/02	45	YUJ	5	MSI	2021/08/09
44	TMR	1		2021/08/02					2021/08/11
44	TNQ	1		2021/08/02	45	TVH	3		2020/10/20
44	TNR	1		2021/08/02					2021/08/11
44	TPP	2		2020/09/11					2021/08/21
				2021/08/02	45	TVJ	2		2020/07/17
44	TPQ	1		2021/08/02					2021/08/30
44	TQP	2		2020/07/05	45	TWH	2		2020/07/14
				2021/07/10					2021/08/23
45	TUH	5		2021/07/10	45	TWJ	2		2020/09/12
				2021/08/09					2021/08/23
				2021/08/11	45	TXJ	2		2020/06/09
				2021/09/15					2021/08/23
				2021/09/20	46	TEN	1		2021/08/22
45	YUJ	5		2020/07/15	46	TEP	1		2021/08/22
				2020/07/17	46	TFN	2		2021/08/22
				2021/07/10					2021/09/06

images were downloaded from the Copernicus Open Access Center (https://scihub.copernicus.eu/apihub/). The quality was Level-2A, that is, after radiometric calibration, geometric precision correction, and atmospheric correction. For preprocessing such as correction, the spatial resolution of the selected band was 10 m. The images were obtained from June to October of the same year. Because of the influence of clouds and mountain shadows, some images were replaced by images from similar months (4, 5, and 11) in the previous two years and the next four years. This study utilized images from path 146, row 029, to identify glaciers for 1990, 1988, and 1994. Using images from the first two years resulted in an overestimation of the glacier area, whereas using images from the latter four years leads to an underestimation of glacier area. However, the overall error remained within 5% and did not significantly affect the results.

The DEM data used to calculate the surface elevation of glacial lakes and to extract ridgelines for glacier segmentation were ASTER GDEM V2 products with a spatial resolution of 30 m obtained from the Geospatial Data Cloud website of the Chinese Academy of Sciences Computer Network Information Centre (http://www.gscloud.cn). Climatological and meteorological data from 1990 to 2020 used for the analysis of glacial lake changes were obtained from the National Meteorological Science Data Centre (http://data.cma.cn/). The 0.5°×0.5° gridded point dataset of monthly values of surface air temperature and precipitation in the study area (V2.0) was downloaded and obtained based on the information of national stations across the country and generated by spatially interpolating the data using the GTOPO30 DEM. The glacier flow rate data used in this study was the ITS_LIVE product, which contained flow rate data of the major glaciers in High Asia from 1985 to 2018, and is derived from NASA's MEa-SUREs project (https: //its-live. jpl.nasa.gov/). The product is based on Landsat TM/ETM+/OLI imagery and used the automatic crevasse feature tracking processing chain method proposed by Gardner *et al*. (2018) to extract glacier movement velocity. The ITS_LIVE product has been widely used in studies related to glacier movement in high Asia, and its reliability and accuracy have been fully verified (Dehecq *et al*., 2018; Huang *et al*., 2021). In this study, single-year streamflow and error data from 1990 to 2018 were selected with a spatial resolution of 240 m and the latest data version V01.

2.3 Methods

2.3.1 Glacier extraction and error analysis

In this study, the glacier boundary automatic extraction method was used to extract glaciers with an area ≥ 0.01 km^2. First, the band ratio method (R/SWIR) and manual interaction method were used to determine the threshold value, and the binary image after threshold segmentation was processed by median filtering and converted into a vector polygon by combining the morphological opening and closing operation method, and then referring to Google Earth and the glacier catalog data to manually revise the glacier vector boundary and check the data quality to ensure accurate identification of the glacier outlines. Finally, based on the SRTM DEM data and the ridgeline automatic extraction method, the ridgeline vector data of each glacier area were obtained, and the revised the glacier boundary was segmented to obtain the vector data of each glacier (Figure 2).

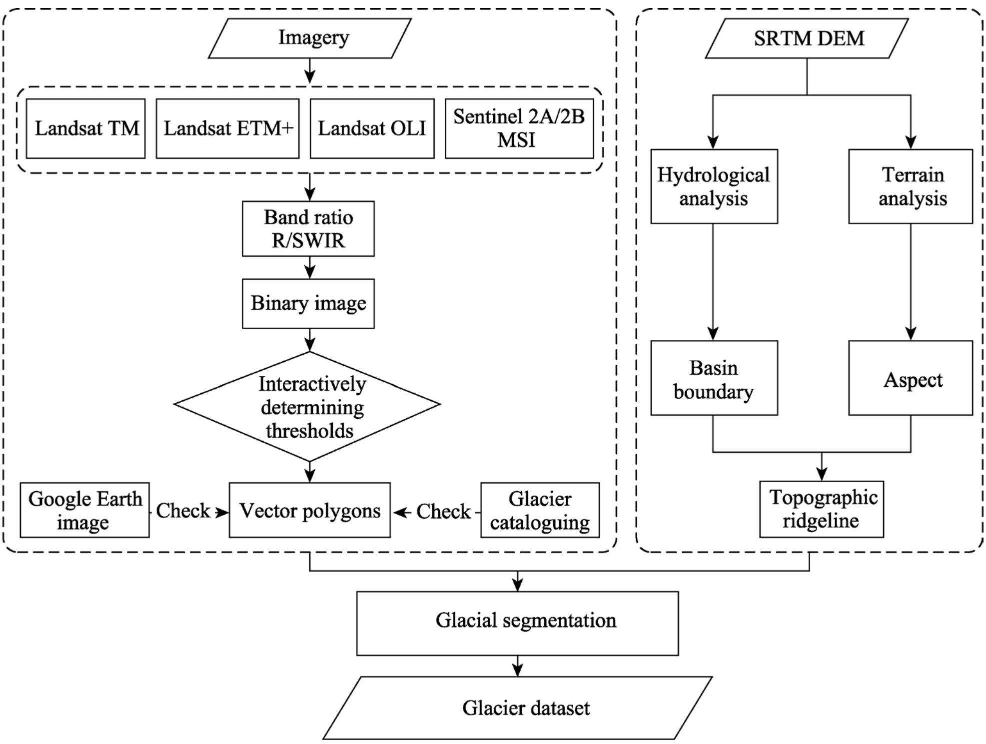

Figure 2 The process of glacier boundary extraction based on Landsat imagery

The accuracy of glacier boundary extraction is mainly affected by the errors in satellite sensors and image alignment. The results of remote sensing interpretation of glacier boundaries can be examined using the results of ground surveys or very high spatial resolution remote sensing data classification as reference data. Because glaciers in the study area are mostly located at remote areas at high altitudes, it is difficult to conduct field investigations. Therefore, this study only considered the errors caused by the spatial resolution of remote sensing images, which can be calculated by the following formula:

$$\varepsilon = N \times A \tag{1}$$

where ε is the glacier area error caused by the spatial resolution of the image; N is the perimeter of the glacier outline; A is the side length of half a pixel (Landsat TM is 15 m, Landsat ETM+/OLI is 7.5 m, Sentinel 2A/2B MSI is 5 m). Among them, the glacier area errors caused by the spatial resolution of Landsat TM/ETM+/OLI and Sentinel 2A/2B MSI remote sensing images were 162.14 km^2, 91.74 km^2, 118.11 km^2 and 71.55 km^2 in 1990, 2000, 2010 and 2020, respectively, each accounting for 8.1%, 4.85%, 6.6% and 4.28% of the glacier area in this period.

2.3.2 Glacial lake extraction

Lake boundaries were extracted using a combination of water body index and manual revisions. First, the normalized difference water index (Peppa *et al.*, 2020) was used to pre-extract the water bodies from Landsat TM images from 1990 and 2010, Landsat TM/ETM+ from 2000, and Sentinel 2A/2B MSI and Landsat OLI images from 2020. The Otsu algorithm was then applied to the calculated images to automatically determine the threshold (ranging from 0 to 0.3) and extract potential water body areas. Finally, manual visual interpretation was used to revise the boundaries of the glacial lakes, resulting in a glacial lake inventory. Limited by the spatial resolution of different remote sensing images, the Landsat OLI and Sentinel 2A/2B MSI images used in 2020 were suitable for extracting glacial lakes with an area ≥ 0.001 km^2, while the Landsat TM/ETM+ images used in 1990, 2000 and 2010 were suitable for extracting glacial lakes with an area ≥ 0.01 km^2. Therefore, this paper takes the area ≥ 0.01 km^2 as the minimum resolution when discussing the changes to glacial lakes.

2.3.3 Glacier volume calculation

Glacier volume is an important parameters of glaciers and is not only an important input parameter for the establishment of glacier hydrological, dynamical, and disaster models, but also an important indicator for assessing the impacts of glacier changes on glacier and river runoff, formulating proactive disaster prevention and mitigation measures, and an important prerequisite for the prediction of the future rise and fall of sea levels arising from changes in glacier volume (Xu *et al.*, 2020). Currently, the following volume-area empirical formula is used to calculate of glacier volume:

$$V = C \times A^{\gamma} \tag{2}$$

where V is the glacier ice storage (km^3); A is the area of the glacier (km^2); and C and γ are empirical coefficients. In this study, the values proposed by Liu *et al.*, Radic *et al.* and Grinsted were used to calculate glacier ice storage in the Northern Tianshan (Table 2); the average value calculated by the above three methods was used as a reference.

Table 2 Parameters related to empirical formulas for calculating ice reserves

ID	C	γ	Source
1	0.04	1.35	(Liu *et al*., 2017)
2	0.0365	1.375	(Radić and Hock, 2010)
3	0.0433	1.29	(Grinsted, 2013)

2.3.4 Glacial lake water storage

Most of the glacial lakes in the Northern Tianshan are located in highly mountainous areas, which makes it difficult to measure their water storage directly; therefore, estimates of water storage were obtained through indirect calculations. The water storage of glacial lakes is generally calculated by determining their geometric characteristics. In this study, the empirical formula proposed by Qi *et al*. (2022), which was used for the calculation:

$$V = \begin{cases} 40.67 \times A^{1.184} - 3.218 \times Ratio_{(mxw/mxl)} & A > 0.1\ \text{km}^2 \\ 557.4 \times A^{2.455} + 0.2005 \times Ratio_{(mxw/mxl)} & A < 0.1\ \text{km}^2 \end{cases} \quad (3)$$

where V is the water storage ($\times 10^6$ m^3) of the glacial lake, A is the area (km^2) of the glacial lake, and the $Ratio_{(mxw/mxl)}$ is the ratio of the width to the length of the smallest circumscribed rectangle of the glacial lake.

2.3.5 Glacier and glacial lake change calculation

The change in glacier area was defined as the difference in glacier area for different years. Owing to the time span of the data set, Sun *et al*. (2018) proposed two methods, the glacier area change rate and relative change rate, to compare glacier changes. This method is also applicable to changes to glacial lakes. The calculation method was as follows:

$$V_{GAC} = \frac{GA - GB}{Y} \quad (4)$$

$$PV_{GAC} = \left[\left(\frac{GA}{GB} \right)^{1/Y} - 1 \right] \times 100\% \quad (5)$$

where V_{GAC} is the rate of change of the glacier and glacial lake area and volume (km^2·a^{-1}), and PV_{GAC} is the relative change rate of glacier and glacial lake area and volume (%·a^{-1}); GA and GB are the glacier and glacial lake area (km^2) or volume (km^3 or 10^6 m^3) of the latter and the former periods, respectively. Y is the time interval (in years) between the two observations of the glacier and glacial lake.

3 Results

3.1 Glacier changes in the Northern Tianshan Mountains

In 2020, the Northern Tianshan region contained 3254 glaciers. These glaciers covered an area of approximately 1670.55 km^2 and contained an ice volume of approximately 95.69 km^3. The data indicated a consistent decline in the number, area, and volume of glaciers from 1990 to 2020 (Table 3). Specifically, there was a reduction of in 17 glaciers, accounting for 0.48% of the total glacier count. The area and volume of glaciers also decreased by 333.01 km^2 and 18.36 km^3, respectively. The rates of change observed were −0.6%·a^{-1} and −0.58%·a^{-1}. Temporal variations in glacier dynamics were non-uniform throughout the 30-year period. Specifically, the number of glaciers decreased by nine from 1990 to 2000, with a reduction of 111.47 km^2 in glacier area and 5.82 km^3 in glacier volume. The rates of change observed during this period were −0.19%·a^{-1} and −0.17%·a^{-1} for glacier area and volume, respectively. From 2000 to 2010, there was a reduction in both the area and volume of glaciers of 102.48 km^2 and 5.05 km^3, respectively. The corresponding relative rates of change were −0.18%·a^{-1} and −0.16%·a^{-1}, respectively. From 2010 to 2020, the area and volume of glaciers decreased by 119.06 km^2 and 7.49 km^3, respectively. These findings suggest that the rate of glaciers retreat in the Northern Tianshan region has intensified since 2000.

Table 3 The change of number, area and volume of glacier in the Northern Tianshan Mountains from 1990 to 2020

Year and change		Number	Area (km^2)	Glacier volume (km^3)
1990		3270	2003.19	114.05
1990–2000	Change	−9	−111.47	−5.82
	Relative change rate (%·a^{-1})	/	−0.19	−0.17
2000		3261	1891.72	108.23
2000–2010	Change	−4	−102.48	−5.05
	Relative change rate (%·a^{-1})	/	−0.18	−0.16
2010		3257	1789.24	103.18
2010–2020	Change	−4	−119.06	−7.49
	Relative change rate (%·a^{-1})		−0.23	−0.25
2020		3253	1670.55	95.69
1990–2020	Change	−17	−333.01	−18.36
	Relative change rate (%·a^{-1})	/	−0.60	−0.58

3.1.1 Changes of glaciers of different sizes

Glaciers in the Northern Tianshan are mainly small- and medium-sized (Figure 3), with an average glacier area of 0.52 km^2 in 2020. The number of glaciers is dominated by glaciers <0.5 km^2, with 2577 glaciers (79.22%), and the area of glaciers dominated by glaciers 0.2–10 km^2 were 1256.83 km^2 (75.23%).

During the period from 1990 to 2020, the number and area of glaciers in the <0.1 km^2 and 10–20 km^2 intervals increased, with the number of glaciers in these two classes increasing by 419 and 1 glacier respectively, and the area increasing by 9.88 km^2 and 20.54 km^2 respectively, while the number and area of glaciers in the other area classes showed a downward trend. The number of glaciers with areas ranging from 0.2 to 0.5 km^2 decreased the most, by 166. The largest decrease in glacier area occurred in glaciers with areas ranging from 1 to 2 km^2, with a reduction of 65.07 km^2. Glaciers with area 0.2–0.5 km^2 (with a decrease of 56.88 km^2), 0.5–1 km^2 (−63.82 km^2), 1–2 km^2 (−65.07 km^2), 2–5 km^2 (−57.05 km^2), and 5–10 km^2 (−58.29 km^2) were reduced more than 50 km^2. The relative rate of change in glacier area within each size category demonstrated that smaller glaciers had a more rapid rate of retreat. Glaciers with area of 0.2–2 km^2, exhibited the most rapid rate of retreat, with a relative rate of change of 0.76%·a^{-1}. Conversely, glaciers with area of 10–20 km^2 exhibited the smallest rate of retreat, with a relative change rate of 0.46%·a^{-1}.

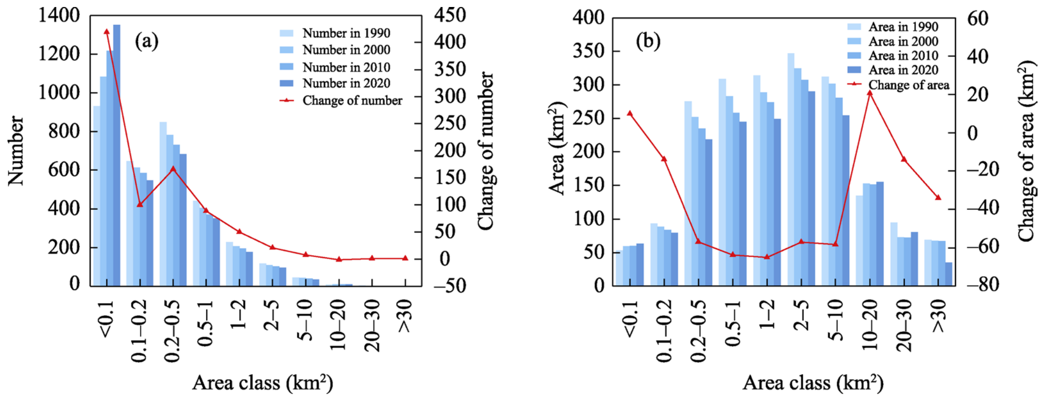

Figure 3 Changes in the number (a) and area (b) of glaciers of different sizes in the Northern Tianshan Mountains from 1990 to 2020

3.1.2 Differences in altitude among glaciers

The primary topographic factor governing glaciers dimensions is the absolute elevation of mountains or peaks (Gärtner-Roer *et al*., 2014). There were significant differences in glacier retreat rates at different elevations in the Northern Tianshan. In this study, the elevation of the glacier-covered area was counted at intervals of 200 m and this demonstrated that the glacier area in the Northern Tianshan was normally distributed with elevation (Figure 4a). From 1990 to 2020, glaciers in the Northern Tianshan were all developed at an elevation of 2500–5300 m, and the area was concentrated in the range of 3700–4300 m, with proportions of 90.34%, 90.41%, 90.81%, and 91.9%, respectively. Except for the glaciers at altitude of 4900–5100 m, glaciers at all other altitudes exhibited a decline in area. The relative rate of change in glacier area exhibited a discernible decline as altitude increased. It was impossible to calculate the relative rate of change because of the disappearance of all the glaciers below 2700 m (Figure 4b).

3.1.3 Glaciers changes in different orientations

Orientation is a key topographic element affecting heat gain and loss of glaciers. The glaciers in the Northern Tianshan region primarily occur on slopes facing north, northwest, and northeast (Figure 5). These orientations accounted for 75.58% and 77.47% of the overall quantity and surface area of glaciers in the Northern Tianshan, respectively. This was followed by the east-facing aspect, with an area and number of 136.29 km^2 and 282 glaciers, respectively, while the number and area of glaciers in the south-, southeast-, southwest-, and west-aspects were smaller, with an area < 100 km^2. From 1990 to 2020, in terms of number, only a slight increase in the number of glaciers oriented in the east-, southeast-, and west-aspects, which increased by 2, 2, and 1, respectively. The glaciers oriented towards the north-east exhibited a pattern characterized by initial growth followed by subsequent

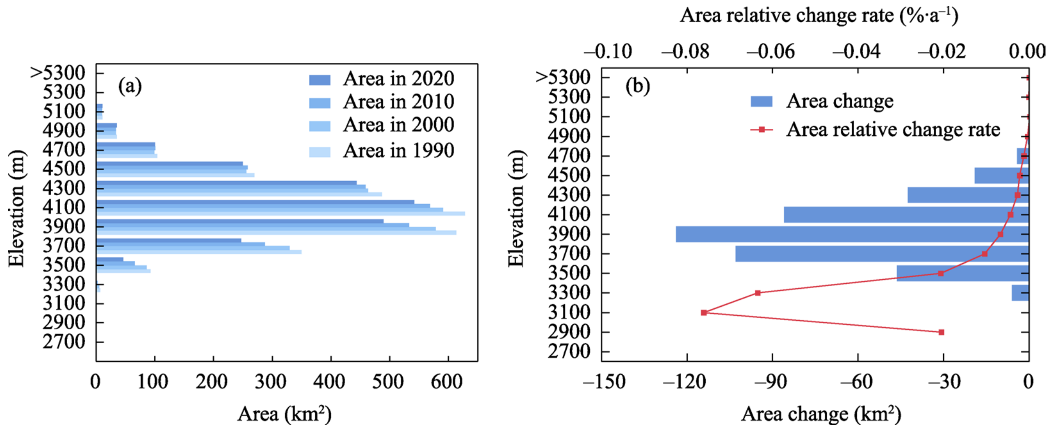

Figure 4 Changes of glaciers with different elevations in the Northern Tianshan Mountains from 1990 to 2020 (a. Glacier area in different years; b. Glacier changes)

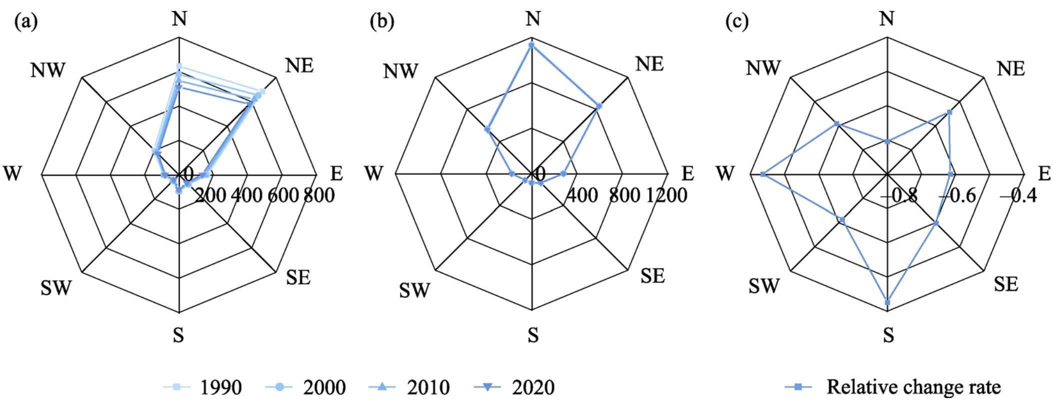

Figure 5 Changes of glaciers with different orientations in the Northern Tianshan Mountains from 1990 to 2020 (a. Glacier area changes; b. Glacier number changes; c. Glacier area relative change rate

shrinkage, decreasing from 844 to 840 from 1990 to 2000, continuing to decrease by 2 to 838 from 2000 to 2010, and increasing by 5 to 843 by 2020. The number of glaciers in the rest of the directions showed a decreasing trend. Glaciers in all directions showed a decreasing areal extend, among which the glaciers with a northly aspect exhibited the largest decline in area of 121.76 km^2, followed by the northeast direction with a decline area of 104.59 km^2, the southwest with a decline of 33.77 km^2, and glaciers in the remaining directions declined less than 30 km^2. The relative rate of glacier area change in each direction was fastest in the north (−0.71%·a^{-1}), east (−0.62%·a^{-1}), and southwest (−0.61%·a^{-1}) aspects, and slowest in the south (−0.43%·a^{-1}).

3.1.4 Changes in glaciers in different basins

The numbers and areas of glaciers in each basin in Northern Tianshan differed from each other (Table 4). The Manas River Basin contained the largest number and total area: 1583 and 781.18 km^2, respectively. The second largest was the Ebinur Lake Basin, with 1216 and 705.32 km^2 respectively. The area of glaciers in the other three basins was less than 100 km^2, and the distribution of glaciers in the Yiwu River Basin was the lowest, with 97 glaciers and 49.88 km^2 in area. From 1990 to 2020, glaciers in the Northern Tianshan declined in all basins, but there were significant regional differences. The number of glaciers in each basin did not change by more than 10, and the number of glaciers in the Yiwu River Basin increased by 2 in 30 years, from 95 in 1990, 2000 and 2010 to 97 in 2020 because two glaciers split. The number of glaciers in other basins declined. The area of glaciers in the Manas River Basin decreased the most (−149.29 km^2), followed by the Ebinur Lake Basin (−142.73 km^2), the Baiyang River Basin (−15.79 km^2) and the Yiwu River Basin (−14.31 km^2), The Ayding Lake basin exhibited the smallest (−11.16 km^2). The Yiwu River Basin exhibited the fastest glacier retreat (−0.83%·a^{-1}), followed by the Baiyang River Basin (−0.72%·a^{-1}), and the Manas River Basin and Ebinur Lake Basin were basically the same (−0.58%·a^{-1} and −0.61%·a^{-1}, respectively). The Aydin Lake Basin was the slowest (−0.49%·a^{-1}).

Table 4 The change of number and area of glaciers in different basin in the Northern Tianshan Mountains from 1990 to 2020

Basin	1990		2000		2010		2020		Relative change rate (%·a^{-1})
	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	
Yiwu River	64.19	95	57.85	95	55.89	95	49.88	97	–0.83
Baiyang River	80.42	179	76.33	179	70.72	179	64.63	177	–0.72
Manas River	930.47	1593	869.98	1584	831.51	1580	781.18	1583	–0.58
Ebinur Lake	848.05	1222	809.11	1222	757.38	1222	705.32	1216	–0.61
Ayding Lake	80.07	181	78.47	181	73.75	181	68.91	180	–0.49

3.2 Glacial lake changes in the Northern Tianshan Mountains

Between 1990 and 2020, the number and area of glacial lakes in the Northern Tianshan region increased. However, the pace at which the areas of these glacial lakes expanded consistently declined during this period. Over the past 30 years, the number of glacial lakes with an area of ≥0.01 km^2 increased from 190 to 246, a 29.47% increase. The area of glacial lakes expanded from 8.83 km^2 to 11.31 km^2, with a change rate of 0.86% (Table 5). The volume of

Table 5 The change of number, area and volume of glacial lake in the Northern Tianshan Mountains from 1990 to 2020

Year and change		Number	Area (km^2)	Water storage (10^6 m^3)
1990		190	8.83	142.60
1990–2000	Change	18	1.28	19.33
	Relative change rate (%·a^{-1})	/	0.45	0.42
2000		208	10.11	161.93
2000–2010	Change	24	0.88	18.76
	Relative change rate (%·a^{-1})	/	0.28	0.36
2010		232	10.99	180.69
2010–2020	Change	14	0.32	0.79
	Relative change rate (%·a^{-1})	/	0.09	0.01
2020		246	11.31	181.48
1990–2020	Change	56	2.48	38.88
	Relative change rate (%·a^{-1})	/	0.86	0.82

glacial lakes increased from 142.60×10^6 m^3 to 181.48×10^6 m^3, with a relative change rate of 0.82%·a^{-1}. The number of glacial lakes from 1990 to 2000 increased from 190 to 208, and the area expanded from 8.83 km^2 to 10.11 km^2, with a relative change rate of 0.45%·a^{-1}, and the volume of glacial lakes increased by 19.33×10^6 m^3. From 2000 to 2010, there was a 24% rise in the number of glacial lakes. The rate of expansion of the area had a slightly diminished pace compared to the preceding decade, expanding from 10.11 km^2 to 10.99 km^2, with a relative change rate of 0.28%·a^{-1}, and the volume of glacial lake increasing by 18.76×10^6 m^3. The increase in the number of glacial lakes from 2010 to 2020 decreased to nine, and the relative expansion rate of area continued to decrease to 0.09%·a^{-1}.

3.2.1 Changes of glacial lakes of different sizes

Glacial lakes in the Northern Tianshan are mainly dominated by small glacial lakes, with an average area of 0.046 km^2 in 2020. The number of glaciers was dominated by glaciers <0.02 km^2, which were 105, and the area was dominated by glacial lakes >0.1 km^2, which was 4.97 km^2.

The area of glacial lakes of all size classes in Northern Tianshan increased from 1990 to 2020 (Figure 6). However, the pattern of change in the number of glacial lakes of different size classes was quite different. There was a consistent increase in the number of glacial lakes between the range of 0.01–0.02 km^2 and those exceeding 0.2 km^2, but the number of glacial lakes falling within other area categories exhibited a variable pattern of growth. From 1990 to 2000, there was a decline in both the number and extent of glacial lakes between 0.02–0.04 km^2 and 0.1–0.2 km^2. However, after 2000, there was a consistent increase in the numbers and areas of these lakes. The number and area of glacial lakes with an area of 0.06–0.1 km^2 increased between 1990 and 2000, but decreased after 2000. The number of glacial lakes with an area of 0.04–0.06 km^2 exhibited fluctuations between 1990 and 2020. Initially there was increase from 1990 to 2000, followed by a subsequent decrease from 2000 to 2010, followed by another increase from 2010 to 2020. In contrast, the overall trend for these glacial lakes initially increased from 1990 to 2000, followed by a decrease from 2000 to 2020. Glacial lakes in the area intervals of 0.01–0.02 km^2 and 0.1–0.2 km^2 had the fastest change in area (1.11%·a^{-1}, 1.08%·a^{-1}), glacial lakes with the area of 0.08–0.1 km^2

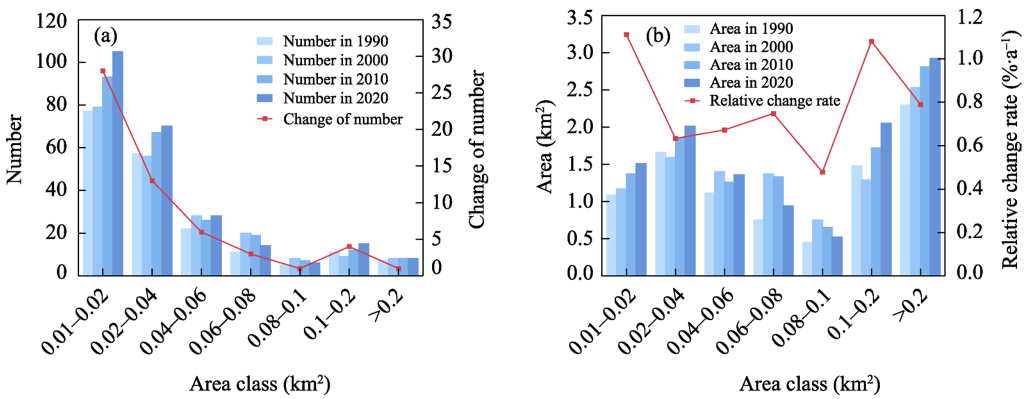

Figure 6 Changes in the number (a) and area (b) of glacial lakes of different sizes in the Northern Tianshan Mountains from 1990 to 2020

had the slowest change in area (0.48%·a^{-1}), and the remaining area intervals of 0.02–0.04, 0.04–0.06, 0.06–0.08 and >0.2 km^2 had relative rates of change of 0.63%·a^{-1}, 0.67%·a^{-1}, 0.75%·a^{-1} and 0.79%·a^{-1}, respectively.

3.2.2 Altitude variation of glacial lakes

The glacial lakes in the study region were mostly distributed between 2200–4100 m and the majority (85.37%) were located within the range 3100–3700 m. The corresponding area occupied by these lakes accounted for approximately 86.47% of the total. From 1990 to 2020, there was an increase in the number of glacial lakes located at different altitudes, and the total area also increased. However, there were significantly different trends in the area and number of glacial lakes at different altitudes (Figure 7). During this period, the glacial lakes in the Northern Tianshan changed little in low-altitude and high-altitude areas. The number of glacial lakes located at elevations below 3100 m increased by 4 and the total area expanded by 0.25 km^2. The number of glacial lakes at an altitude >4000 m increased by 2, and the area increased by 0.04 km^2. The changes in glacial lakes were mainly concentrated in the 3100–4000 m elevation, and the number and area increased by 50 and 2.19 km^2, respectively. From the perspective of the relative rate of increase in the area of glacial lakes, the area of glacial lakes between 3700–4000 m increased fastest (3.48%·a^{-1}), followed by glacial lakes in the range of 3400–3700 m (1.16%·a^{-1}), the slowest growth rate was observed in the glacial lakes of 3100–3400 m, with a rate of 0.25%·a^{-1}, which was also the relative change rate between low-altitude areas and high-altitude areas was small. Glacial lakes increased from 0 above an elevation of 4000 m, so the relative rate was not calculated.

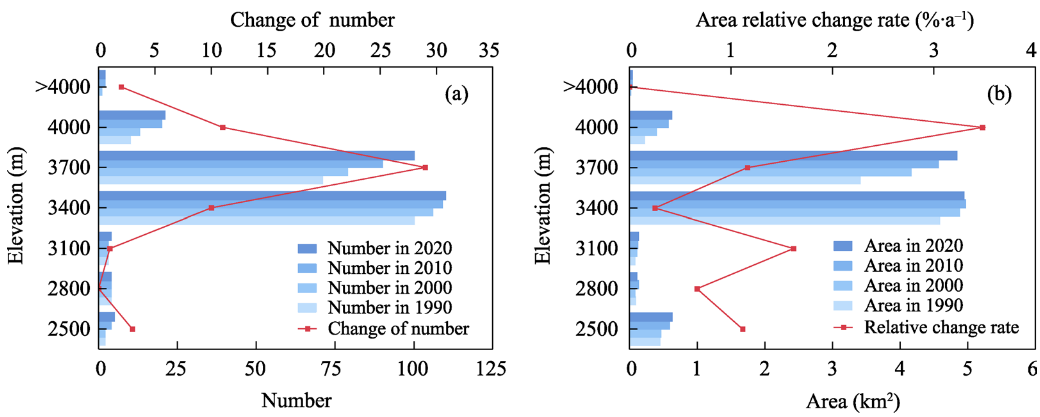

Figure 7 Changes of glacial lakes with different elevations in the Northern Tianshan Mountains from 1990 to 2020 (a. Glacial lakes number in different year; b. Glacial lakes area in different years)

3.2.3 Changes in glacial lakes in different basins

The Ebinur Lake Basin had the largest share of glacial lakes in 2020, with 125 (50.81%) and 5.65 km^2 (49.96%), while the Yiwu River Basin had the smallest share of glacial lakes, with 17 (6.91%) and 0.56 km^2 (4.95%) (Table 6). The number and area of glacial lakes in each basin from 1990 to 2020 generally increased, but there were large differences in the changes during different periods. The area and number of glacial lakes in the Yiwu River Basin, Manas River Basin, and Ebinur Lake Basin increased continuously during the 30-year period.

The Baiyang River Basin exhibited increases in area and number from 1990 to 2000, a decline in area and constant number from 2000 to 2010, and an increase area and constant number from 2010 to 2020. The Ayding Lake Basin showed the same trend in area and number as the Baiyang River Basin from 1990 to 2000, but the number of glacial lakes in the basin did not change from 2000 to 2020, while the area showed a continuous decline. The Yiwu River Basin had the fastest relative change rate (1.38%·a^{-1}), the Ayding Lake Basin had the slowest relative change rate (0.05%·a^{-1}), and the Baiyang River Basin, the Manas River Basin, and the Ayding Lake Basin had relative change rates 0.73%·a^{-1}, 1.01%·a^{-1}, and 0.82%·a^{-1}, respectively.

Table 6 The change of number and area of glacial lakes in different basin in the Northern Tianshan Mountains from 1990 to 2020

Basin	1990		2000		2010		2020		Relative change rate (%·a^{-1})
	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	
Yiwu River	0.37	13	0.38	14	0.50	14	0.56	17	1.38
Baiyang River	1.43	30	1.74	32	1.68	32	1.78	32	0.73
Manas River	1.94	33	2.19	36	2.62	52	2.63	53	1.01
Ebinur Lake	4.41	97	4.89	106	5.45	118	5.65	124	0.82
Ayding Lake	0.68	17	0.92	20	0.74	20	0.69	20	0.05

4 Discussion

4.1 Glacier and glacial lake response to climate change

The development of glaciers and glacial lakes is strongly linked to changes in climate, and the primary meteorological factors involved are temperature and precipitation. From 1990 to 2020, temperature in most areas of the Northern Tianshan increased, with the gradient rising from the northwest to southeast (Figure 8a). The largest relative change rate in temperature

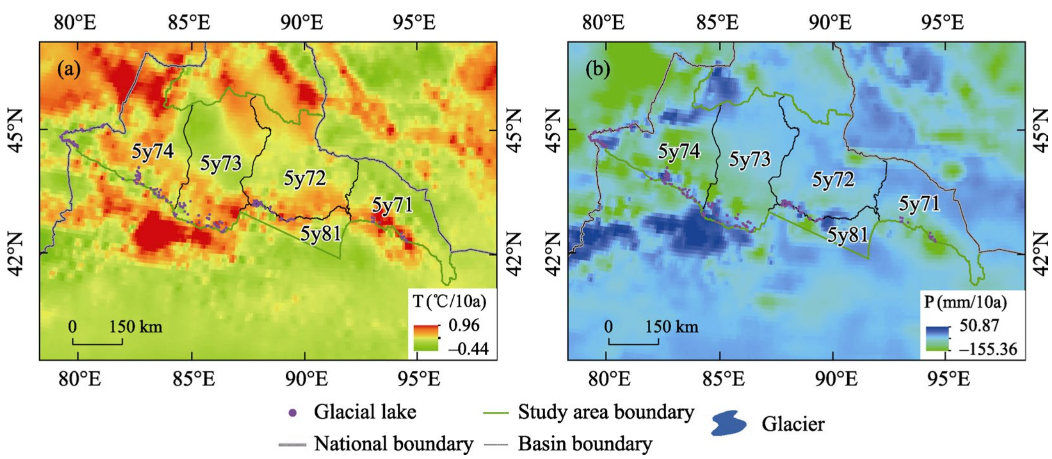

Figure 8 Changes in mean annual temperature (a) and cumulative annual precipitation (b) in the Northern Tianshan Mountains from 1990 to 2020

occurred in the northern part of the Yiwu River Basin, with a maximum rate of warming of 0.74℃ per decade. Conversely, the largest rate of decline in temperature occurred in the northern part of the Manas River Basin, with a maximum cooling rate of −0.15℃ per decade. The spatial variation in annual precipitation rate was opposite pattern to that of temperature, decreasing from northwest to southeast. The most significant reduction in precipitation occurred in the eastern part of the Northern Tianshan, in the Yiwu River Basin, with a maximum rate of decline of −101.97 mm per decade. However, increases in precipitation were primarily concentrated in the Manas River Basin, Baiyang River Basin, and Ayding Lake Basins, with a maximum of 24.88 mm per decade (Figure 8b).

The spatial distribution of temperature changes contrasted with that of precipitation changes. In the Yiwu River Basin, the relative rate of glacier area change was the highest at −0.83%·a^{-1}. In contrast, the Manas River Basin exhibited relative rate of glacier area change at −0.58%·a^{-1}, and the Ayding Lake Basin exhibited the smallest relative rate of change, at −0.49% a^{-1}. The trend in changes in glacial lakes was similar to that of glacier changes. The Yiwu River Basin had the highest relative rate of glacial lake area change at 1.38/%·a^{-1}, while the Ayding Lake Basin has the smallest rate of change at 0.05/%·a^{-1}. An increase of 1℃ in average summer temperature will lead to an increase of 100–160 m in the glacier equilibrium line, and the material loss caused by this will require an increase of 40%–50% in precipitation maintain material balance (Raper *et al.*, 2000). It is evident that the impact of rising temperatures on glacier mass balance cannot be compensated for by an increase in annual precipitation. Consequently, in the Yiwu River Basin, where temperatures are rising and precipitation is decreasing, the glacier retreat rate is the highest. This results in an overall retreat trend of glaciers in the Northern Tianshan, at a rate of −0.60/%·a^{-1}. The retreating trend was more pronounced in the central and eastern regions than the western regions. The relative rates of glacier area change in the Baiyang River Basin and the Yiwu River Basin in the central and eastern regions were −0.72%·a^{-1} and −0.83%·a^{-1}, respectively, whereas the glacier area relative change rate in the Ebinur Lake Basin in the western region was −0.61%·a^{-1}. This is largely consistent with the conclusion of this study that most areas of the Northern Tianshan exhibit an increasing lake area.

4.2 Influence of glacial lakes on glaciers change

According to the research conducted by Chen *et al*. (2017) and Zhang *et al*. (2022a), there has been a notable increase in the rate of glaciers retreat in the Tianshan Mountains region over the last 50 years, resulting in a decrease in both the total area and mass of these glaciers. Approximately 97.52% of glaciers in the Tianshan Mountains region are retreating (Chen *et al*., 2016). This retreat is further accompanied by a reduction in glacier volume, estimated to be around 27%±15% (Farinotti *et al*., 2015). It is anticipated that these glaciers will continue to retreat in the future. Although all glaciers show a continuous retreat trend, Carr *et al*. (2017) and Ali *et al*. (2023) found that different types of glacier terminations cause differences in the rate of glacier retreat, with marine- and lake-terminating glaciers retreating faster than land-terminating glaciers (Li *et al*., 2023). To investigate whether glaciers in the Northern Tianshan have the same change trend, eight glaciers in the Northern Tianshan with different size were selected for area change analysis (Figure 9): glaciers with the area <0.5 km^2 (G080548E44736N, G086065E43383N), glaciers with the area of 0.5–2 km^2 (G080203E44831N, G088477E43831N G088477E43836N), 2–4 km^2 (G080476E44760N, G085430E43485N), and > 4 km^2 (G088313E43812N, G094361E43094N), with 4 glacial lake terminating glaciers and 4 land terminating glaciers.

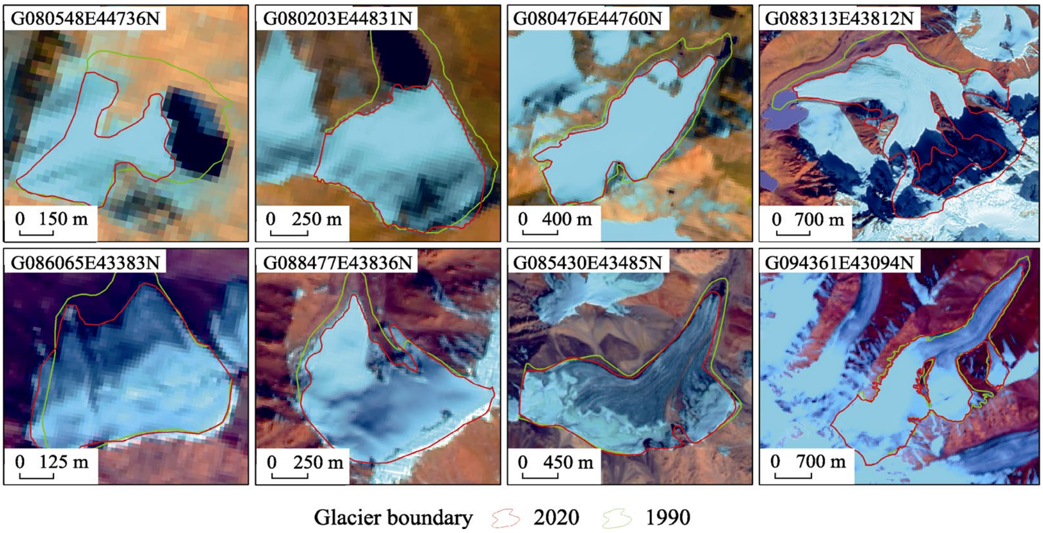

Figure 9 Changes in area of eight glacial lakes with different termination types (all base maps are 2020/2021 Landsat OLI Bnad6548 30 m)

Glaciers with an area <0.5 km^2, exhibited a rate of retreat of −2.06% for glaciers terminating at a lake, and for land termination glaciers the rate of retreat was −1.71%. For glaciers with an area of 0.5–2 km^2, the rate of retreat was −0.91% and −0.44% for land termination glaciers. Glaciers with an area of 2–4 km^2 exhibited rates of retreat of −0.79% and −0.23%, and that of glaciers with an area of >4 km^2 the rate of retreat was −0.40% and −0.38% for lake and land terminating glaciers, respectively (Table 7). In summary, the recession rate of glacial lake-terminated glaciers is higher than that of land-terminated glaciers across all four size classes. This may be because the specific heat capacity of glacial lakes is larger than that of land, and the heat absorbed by the end of the glacier in contact with a glacial lake is generally higher than that in contact with land. Consequently, the recession rate of glacial lake-terminated glaciers is higher than that of land-terminated glaciers. Furthermore, we demonstrated that the larger the area of the glacier, the more stable it was, and its retreat rate was lower than that of the glaciers with a smaller area. However, this relationship can be changed by the type of glacier termination: the area of glacier G080476E44760N was 2.07 km^2 in 1990, with a retreat rate of −0.79%, and the area of glacier G088477E43836N was 1.03 km^2, with a retreat rate of only −0.44%. This relationship also applies in the range of intervals with an area of >4 km^2, G088313E43812N glacier area was 8.28 km^2 in 1990, and the retreat rate was −0.40%, G094361E43094N glacier area was only 4.98 km^2, and the retreat rate was −0.38%. Therefore, this study concludes that the effect of glacier termination type on the retreat rate is greater than the influence of size of the glaciers.

Table 7 Changes in area and rate of glaciers of different termination types

Termination type	Glacier ID	Area (km^2)				Change rate (%)
		1990	2000	2010	2020	
Lake-terminating	G080548E44736N	0.42	0.39	0.27	0.21	−2.06
	G080203E44831N	1.07	0.97	0.85	0.79	−0.91
	G080476E44760N	2.07	1.91	1.69	1.59	−0.79
	G088313E43812N	8.28	8.26	7.84	7.24	−0.40
Land-terminating	G086065E43383N	0.35	0.26	0.23	0.32	−0.01
	G088477E43836N	1.03	0.98	0.93	0.89	−0.44
	G085430E43485N	3.14	3.03	3.02	2.91	−0.23
	G094361E43094N	4.98	4.88	4.85	4.39	−0.38

4.3 Changes in glaciers flow velocity

Glaciers are sensitive to changes in climate (Kaushik *et al*., 2019). The redistribution of material owing to changes in glacier movement is the main feature that distinguishes glaciers from other natural ice bodies and is one of the main components of glaciological research (Yan *et al*., 2017). Owing to the gravity-driven displacement of ice and meltwater within a glacier or ice gap downslope, the downward movement of a glacier consists of sliding along the bedrock and movement due to deformation of the sedimentary layers at the bottom (Iverson and Zoet, 2015). The study of glacier motion improves our understanding of glacier change, analyze the driving mechanism of atmospheric circulation, and provides a scientific basis for the comprehensive investigation of glaciers and the rational use of glacier resources (Kelly *et al*., 2023). In this study, the single-year glacier flow rate and error product (ITS_LIVE) from 1990 to 2018 was used to analyze flow velocity in the Northern Tianshan during the observation period in the Bortala River source area (I), the Manas River source area (II) and the Baiyang River source area (III) (Figure 1). The flow velocity of the glaciers in these three regions was more evident in the Northern Tianshan.

The flow velocity of the large glacier was significantly higher than that of the small glacier (Figure 10). This is because the longitudinal movement of a glacier depends on surface accumulation or ablation, and the accumulation and ablation on the surface of the large glacier is much larger relative to the small glacier. In the accumulation zone there is a net accumulation of material each year, and the velocity of the movement has a vertically downward component under the pressure of the new overlying snow-ice layer. However, the velocity also has an upward component in the ablation zone, as the old ice continues to ablate and ice from upstream comes in to compensate (Benn *et al*., 2019). In the vertical direction within the glacier and horizontally across the glacier, the flow velocity is greatest in the middle because for the same cross-section, the edge has a slower flow velocity owing to high friction with the valley wall (Huang *et al*., 2015; Yan *et al*., 2017). However, at a glacier bend, the location of the maximum velocity is biased towards the outer edge of the bend because of the larger centrifugal force on the outer ice body compared to the inner ice body, which accelerates flow (Li, 1992; Bhushan *et al*., 2017). To further analyze the change of glacier movement, we calculated the average flow rate of the three river source areas, The highest average flow rate was in the Manas River source area, followed by Baiyang river source area, and the smallest glacier flow rate was found in the Bortala River source area (Table 8), Overall, glacier flow rates in the study area were relatively stable, but with a slow

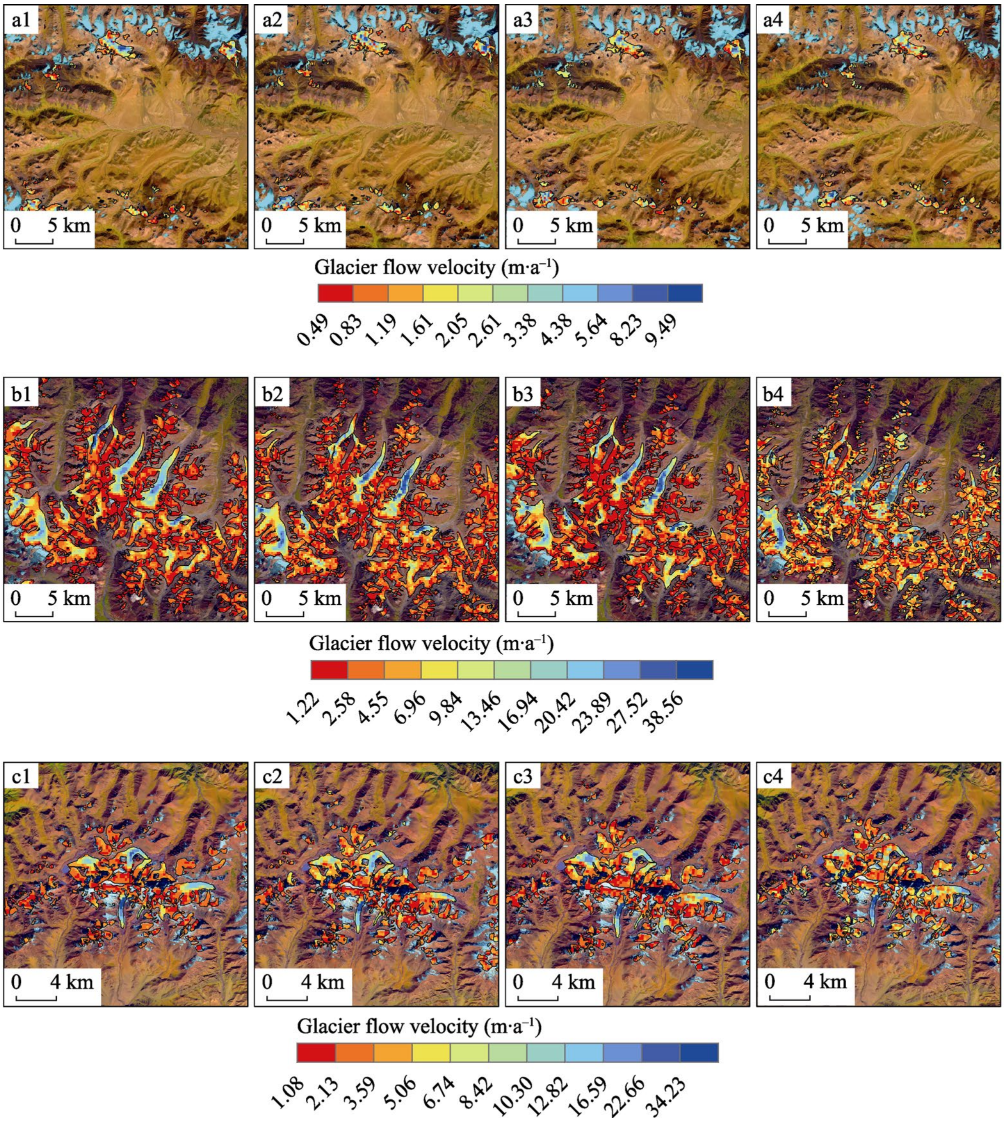

Figure 10 The derived two-dimensional glacier flow velocity in the Northern Tianshan Mountains during 1990–2018. The black curves are glacier boundaries. a1, b1, and c1 are glacier flow velocity in 2018; a2, b2, and c2 are glacier flow velocity in 2010; a3, b3, and c3 are glacier flow velocity in 2000; a4, b4, and c4 are glacier flow velocity in 1990. The background of maps is the Landsat OLI image acquired in 2020 and 2021.

Table 8 Average glacier flow velocity in 1–3 in the Northern Tianshan Mountains from 1990 to 2018

Area	Glacier flow velocity ($m \cdot a^{-1}$)			
	1990	2000	2010	2018
a	3.21	1.49	1.66	1.07
b	6.09	4.08	2.66	3.09
c	2.85	2.48	2.19	2.29

decline in the period 1990–2018. This result is similar to that reported by Dehecq *et al*. (2018).

5 Conclusions

(1) In 2020, the number, area, and storage of glaciers in the Northern Tianshan were 3254, 1670.55 km^2 and 95.69 km^3, respectively. The number (1167) and area (1042.27 km^2) of north-facing glaciers were the largest (big). In 2020, the number, area, and water storage of glacial lakes with an area ≥0.01 km^2 were 246, 11.31 km^2 and 181.48×10^6 m^3, respectively. The number of glacial lakes was mainly <0.02 km^2, and the area of glacial lakes was mainly >0.1 km^2, of which the Lake Ebinur Lake Basin has the largest number of lakes (124) and the largest area (5.65 km^2).

(2) From 1990 to 2020, glaciers in the Northern Tianshan showed a decreasing trend, whereas glacial lakes showed an expanding trend. Over the past 30 years, because of climate warming and humidification in Northwest China, the number of glaciers, glaciers area, and glacier volume in the Northern Tianshan have decreased by 16, 332.64 km^2 and 18.36 km^3 respectively, and the elevation of the glacier at the end of the glacier has increased from 2699 to 2805 m as the termini of glaciers retreated. The number of glacial lakes, area, and glacial lake water storage in the Northern Tianshan increased by 56, 2.48 km^2 and 38.88×10^6 m^3, respectively. The changes of glaciers and glacial lakes in the Northern Tianshan exhibited spatial heterogeneity, and the rate of glacier retreat in the eastern region was faster than that in the western region, in which the glacier area in the Yiwu River Basin retreated the fastest ($-0.83\%\cdot a^{-1}$), and the Ayding Lake Basin was the slowest ($-0.49\%\cdot a^{-1}$). The changes of glacial lakes were similar to those of the glacier, the rate of glacial lake expansion was faster in the east-central region than in the western region, with the fastest rate of change in the Yiwu River Basin ($1.38\%\cdot a^{-1}$) and the slowest in the Ayding Lake Basin ($0.05\%\cdot a^{-1}$).

(3) The glacier change characteristics of the Northern Tianshan were similar to those of the Himalayan region, and different glacier termination types resulted in different rate of glacier retreat. Compared to the land termination of the glacier, the glacial lake termination-type glacier rate of retreat was relatively fast, and the glacier termination type had a greater impact on the rate of retreat than the size of the glacier. The flow velocity of large glaciers was significantly higher than that of small glaciers, and the flow velocity of the part with a large slope was relatively larger. The flow velocity of the glacier in the central part of the Northern Tianshan was the largest, followed by the eastern part, and the flow velocity of the glacier in the western part of the glacier was the slowest.

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