Spatiotemporal changes of typical glaciers and their responses to climate change in Xinjiang, Northwest China (Postprint)

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Abstract

Abstract: Glaciers are highly sensitive to climate change and are undergoing significant variations in mid-latitude regions. This study analyzed the spatiotemporal changes of typical glaciers and their responses to climate change during 1990–2015 across four distinct mountainous sub-regions in the Xinjiang Uygur Autonomous Region of Northwest China: the Bogda Peak and Karlik Mountain sub-regions in the Tianshan Mountains; the Yinsugaiti Glacier sub-region in the Karakorum Mountains; and the Youyi Peak sub-region in the Altay Mountains. The normalized snow cover index (NDSI) and correlation analysis were employed to reveal glacier area changes in the four sub-regions from 1990 to 2015. Glacier areas in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions decreased by 57.7, 369.1, 369.1, and 170.4 km^2, respectively, during 1990–2015. Analysis of the glacier area center of gravity indicated that quadrant changes of glacier areas in the four sub-regions shifted toward the origin. Glacier area on the south aspect of the Karlik Mountain sub-region was larger than that on the north aspect, whereas glacier areas on the north aspect of the other three sub-regions were larger than those on the south aspect. Increased precipitation in the Karlik Mountain sub-region inhibited glacier retreat to a certain extent. However, glacier area changes in the Bogda Peak and Youyi Peak sub-regions were not sensitive to increased precipitation. On a seasonal timescale, glacier area changes in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions were primarily driven by accumulated temperature during the wet season; on an annual timescale, the correlation coefficient between glacier area and annual average temperature was -0.72 and passed the significance test at the $P<0.05$ level in the Karlik Mountain sub-region. The findings of this study can provide a scientific basis for water

resources management in the arid and semi-arid regions of Northwest China under the context of global warming.

Full Text

Preamble

Spatiotemporal Changes of Typical Glaciers and Their Responses to Climate Change in Xinjiang, Northwest China

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Abstract

Glaciers are highly sensitive to climate change and are undergoing significant changes in mid-latitudes. In this study, we analyzed the spatiotemporal changes of typical glaciers and their responses to climate change during 1990–2015 in four mountainous sub-regions of Xinjiang Uygur Autonomous Region, Northwest China: the Bogda Peak and Karlik Mountain sub-regions in the Tianshan Mountains, the Yinsugaiti Glacier sub-region in the Karakorum Mountains, and the Youyi Peak sub-region in the Altay Mountains. The normalized snow cover index (NDSI) and correlation analysis were used to reveal glacier area changes in these four sub-regions from 1990 to 2015. Glacier areas in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions decreased by 57.7 km^2, 369.1 km^2, 369.1 km^2, and 170.4 km^2, respectively, during 1990–2015. Analysis of glacier area center of gravity showed that quadrant changes of glacier areas in all four sub-regions moved toward the origin. Glacier area on the south aspect of the Karlik Mountain sub-region was larger than that on the north aspect, while glacier areas on the north aspect of the other three sub-regions were larger than those on the south aspect.

Increased precipitation in the Karlik Mountain sub-region inhibited glacier retreat to a certain extent. However, glacier area changes in the Bogda Peak and Youyi Peak sub-regions were not sensitive to increased precipitation. On a seasonal time scale, glacier area changes in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions were mainly caused by accumulated temperature in the wet season. On an annual time scale, the correlation coefficient between glacier area and annual average temperature was -0.72 and passed the significance test at $P<0.05$ level in the Karlik Mountain sub-region. These findings provide a scientific basis for water resources management in the arid and semi-arid regions of Northwest China under global warming.

Keywords: glacier area change; normalized snow cover index (NDSI); climate change; remote sensing; Altay Mountains; Tianshan Mountains; Karakorum Mountains

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1. Introduction

Glaciers, as vital water reservoirs, play an important role in the global water cycle [?]. They are not only the source of many rivers and lakes but also constitute the main water source in arid and semi-arid regions. As stable suppliers of river flow, glaciers significantly influence the regulation of annual runoff and thus maintain regional ecological balance [?, ?, ?, ?, ?, ?, ?].

Studies of global glacier area changes over the last 40 years have demonstrated that different geographical locations have experienced varying temperature and precipitation changes, resulting in different glacier responses [?, ?, ?]. From a global perspective, glacier area change and climate change are closely related [?, ?, ?, ?, ?, ?, ?, ?].

The size of a glacier determines its sensitivity to climate change and its response time to key meteorological factors. According to Ding [?], glaciers longer than 5 km have an 8-year response time, while those shorter than 5 km have a 2-year response time. Wang [?] showed that mountain glaciers in the Northern Hemisphere require 12–13 years to respond to climate change. Mountain glacier area in the Northern Hemisphere is retreating as a result of global warming [?]. Zhang et al. [?] found that small-area glaciers at low latitudes in the Northern Hemisphere are more sensitive to climate change.

The Xinjiang Uygur Autonomous Region in Northwest China contains the largest number of mountain glaciers in the middle- and low-latitude regions of the world [?]. Xinjiang has approximately 19,374 glaciers covering an area of 0.26×10^{6} km^2 with total ice reserves of 0.27×10^{12} m^3. These glaciers are unevenly distributed, mainly concentrated in the western half of the region. Ice storage capacity is about 29 times that of surface runoff, providing 0.20×10^{12} m^3 of meltwater annually, which constitutes the main water source for oasis irrigation in Xinjiang [?]. Mountain glacier meltwater is also an important component of the water resource cycle in Xinjiang. For example, glaciers in the Karakorum Mountains are the sources of the Hotan River and the Yarkant River.

Glacier accumulation and melting are of great significance to the sustainable development of Xinjiang and even the entire northwestern region of China [?]. The continuous retreat of mountain glaciers in middle and low latitudes provides the most powerful and direct evidence of global climate warming [?]. The intensity of glacier accumulation and melting is mainly affected by precipitation and temperature, with temperature determining melting and precipitation determining accumulation [?]. Therefore, understanding the variations of the driving forces affecting glaciers in Xinjiang is crucial.

The Altay Mountains in the north, the Karakorum Mountains in the south, and the Tianshan Mountains in the center constitute the three major mountain ranges in Xinjiang. The Bogda Peak sub-region contains the largest glacier area in the eastern Tianshan Mountains, while glaciers in the Karlik Mountain sub-region in the eastern Tianshan Mountains are relatively well-developed and have been extensively studied [?, ?, ?, ?]. The Yinsugaiti Glacier is a typical large moraine-covered glacier located in the Karakorum Mountains. The Youyi Peak sub-region lies on the northern side of the central Altay Mountains and represents the highest-latitude modern glacier distribution area in China [?].

In this study, we used high-spatial-resolution Landsat data with long time series to analyze glacier area changes in four different mountainous sub-regions from 1990 to 2015. By comparing glacier area changes across these four typical sub-regions, we explained the change trends. Furthermore, we employed correlation analysis to examine temperature and precipitation changes from 1960 to 2014, aiming to provide a scientific foundation for water resources management in Xinjiang under global warming.

2.1 Study Sites

Xinjiang Uygur Autonomous Region in Northwest China is situated in the arid region of Central Asia and has a continental climate characterized by long sunshine duration, low precipitation, high winds often carrying sand, and large daily and annual temperature ranges at low altitudes [?]. In this study, four sub-regions in Xinjiang's three major mountain ranges were selected: the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions (Fig. 1).

Bogda Peak is the main peak of the Bogda Mountains, located in the eastern Tianshan Mountains between 87°50 -88°30 E and 43°33 -43°54 N. The high and steep terrain provides favorable conditions for glacier development. Modern glaciers distributed in the Bogda Peak sub-region are the sources of many rivers [?]. According to Niu et al. [?], the average glacier scale in the Bogda Peak sub-region was 0.78 km^2 in 2001. This sub-region contains many small glaciers that are sensitive to climate change [?].

Karlik Mountain is located between 93°41 -95°07 E and 42°50 -43°35 N, representing the easternmost section of the Tianshan Mountains. The sub-region has an area of 100.54 km^2 [?] and is characterized by a dry continental climate influenced by westerly winds [?]. Glaciers are well-developed in the Karlik Mountain sub-region.

The Yinsugaiti Glacier sub-region lies between 75°55 -76°21 E and 35°55 -36°15 N. Due to recharge from accumulation areas in the north, west, and south, a massive valley glacier developed with branches formed by the confluence of four rivers.

The Youyi Peak sub-region is located on the northern side of the central Altay Mountains between 87°00 -88°00 E and 48°40 -49°10 N. It is the highest-latitude region where modern glaciers are distributed in China.

2.2.1 Remote Sensing Data and Digital Elevation Model (DEM)

Landsat TM and ETM+ images were downloaded from the United States Geological Survey (USGS) (http://www.glovis.usgs.gov). The downloaded remote sensing data had undergone system radiometric correction and ground control point geometric correction, and were processed with DEM correction. To facilitate analysis, we unified the coordinate system of the remote sensing data (images, DEM, and glacier catalog data) for each period. The spatial resolution of Landsat TM and ETM+ images was 30 m. To reduce errors caused by glacier changes over time and minimize the influence of snow on glacier boundary extraction, we selected the smallest glacier boundary in July–September for every 3-year interval during 1990–2015 as the base map. All image details are summarized in Table 1.

Gaofen-1 images were also used in this study. Gaofen-1 was China' s first low-earth-orbit remote sensing satellite with a design life of more than 5 years (http://www.cresda.com). It adopted CAST2000 small satellite platform technology and carried six high-resolution cameras as well as multispectral wide-range cameras (China Great Wall Industry Corporation, Beijing, China) with different bands and resolutions. The satellite has an orbital altitude of 645 km, and the visibility range of the high-resolution camera with 25° sideways tilt was 700 km, allowing for a 4-day revisit. When the side-swing function was not used, the coverage interval was 41 days. For the wide-angle camera, the satellite could achieve 4 days of global coverage without pendulum measurement.

DEM data were primarily used for extracting glacier boundary data and performing glacier change analysis. The data were downloaded from the China International Scientific Data Service Platform (http://datamirror.csdb.cn/index.jsp). We selected ASTER Global Digital Elevation Model (GDEM) with a spatial resolution of 30 m × 30 m and Shuttle Radar Topography Mission (SRTM) 4.1 product with a spatial resolution of 90 m × 90 m.

2.2.2 Meteorological Data

Precipitation, temperature, and their combination are critical climatic factors affecting glacier development. Precipitation determines glacier accumulation, while temperature affects glacier melting [?]. Their combined influence determines the nature, development, and evolution of glaciers [?, ?, ?]. Since meteorological stations are all located far from the sub-regions, it was challenging to obtain relevant meteorological data. Therefore, gridded monthly temperature and precipitation data were used in this study. The grid point dataset (v2.0), with a resolution of 0.5° × 0.5° covering the period from 1961 to 2014, was downloaded from the China Meteorological Data Service Centre (http://data.cma.cn/en). These data accurately describe the spatial characteristics of precipitation near mountainous terrain in Xinjiang [?, ?] and can be used to explore the relationship between glacier area change and climate change. Temperature and precipitation values were calculated as the average of the grid data across the four sub-regions.

2.2.3 Other Data

The National Cryosphere Desert Data Center (http://www.ncdc.ac.cn/portal/) provides the first and second glacier inventory datasets of China (v1.0). These glacier inventory data were mainly used to extract glacier boundaries for the four sub-regions.

2.3.1 Normalized Snow Cover Index (NDSI)

The NDSI method, which detects strong reflectivity in the red band of visible light and strong absorption characteristics in the short-wave infrared radiation band, was used to distinguish ice and snow from surrounding ground. The specific equation used is as follows:

NDSI=-+nmnmCHCHCHCH

where CHn and CHm are the visible band number and near-infrared band number, respectively. The grayscale value of NDSI ranges from -1 to 1. An appropriate threshold can be set to obtain more accurate results.

2.3.2 Glacier Boundary Extraction and Verification

Sensor error and image alignment error are the main sources affecting the accuracy of glacier boundary extraction. This study selected the smallest glacier boundary to estimate glacier area every 3 years, and this area was used to analyze glacier area change.

For the first verification method, we compared the Landsat image from September 1, 2014 with the high-resolution Gaofen-1 image from September 6, 2014 for glacier areas in the Bogda Peak sub-region (Fig. 2). Glacier boundaries on the Gaofen-1 image were extracted using visual interpretation. Using the ArcGIS platform, we randomly generated 50 points along the glacier boundaries delineated on the Landsat image and superimposed these points on the Gaofen-1 image with their visually defined boundaries. The error between the two images was found to be about 2.0%.

The second verification method was the ratio of the calculated glacier area from the Gaofen-1 satellite image to the extracted glacier area from the Landsat image [?]. For this method, the error was found to be about 0.6%.

2.3.3 Glacier Area Change Rate

The glacier area change rate is a common index used to evaluate the degree of glacier area change. This index can unify and compare results of glacier area change at different time scales. The index was calculated as follows [?]:

0100%APACsAts

where AAPAC is the glacier area change rate (%/a), Δs is the glacier area change (km^2), Δt represents the time interval of the study period (a), and s_0 represents the initial glacier area (km^2).

2.3.4 Extraction of Glacier Attributes

Three glacier attributes were used to further document glacier changes: glacier area, glacier aspect, and glacier area center of gravity. Glacier structure is an important factor in glacier research, as different glacier types have different responses to meteorological factors. Moreover, studying changes in the glacier area center of gravity has predictive value for future glacier morphological changes. The glacier area center of gravity represents the geometric center of glacier area in each sub-region and can be derived from ArcGIS. Each of the four sub-regions was divided into four quadrants using the glacier area center during 1990–1992 as the origin. A horizontal axis was defined east–west from the center, while a vertical axis was defined north–south from the center. We defined the northeast quadrant as the first quadrant, northwest as the second, southwest as the third, and southeast as the fourth.

The size of the abscissa represented the change in area relative to the area in the quadrant from 1990 to 1992, and the angle with the x-axis represented the direction of change relative to the glacier area center of gravity. This analysis aimed to explore changes in the glacier area center of gravity across different sub-regions.

Glacier aspect is another principal factor affecting glacier area change [**?**]. Due to the influence of topography, solar radiation, and other factors, glacier area change varies depending on aspect direction. The aspect direction of each glacier area was analyzed using DEM data and ArcGIS. Glacier areas in the four sub-regions were classified into eight aspect directions: north, south, west, east, northeast, northwest, southeast, and southwest. Then, glacier areas in different aspect directions were calculated for each sub-region.

3.1 Changes of Glacier Area

Glacier boundaries of the four sub-regions in different periods are presented in Figure 3. Glacier areas in all four sub-regions showed varying decreasing trends throughout the study period. Glacier areas in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions decreased by 57.7 km^2, 369.1 km^2, 369.1 km^2, and 170.4 km^2, respectively, during 1990–2015. Notably, they showed increasing trends from 2002 to 2004 (Fig. 4). In the Bogda Peak sub-region, the periods of maximum and minimum glacier area retreat rates were 1996–1998 and 2002–2004, respectively. The overall glacier area retreat rate was 4.58% during 2005–2015.

In the Karlik Mountain sub-region, the periods of maximum and minimum glacier area retreat rates were 2005–2007 and 2011–2013, respectively. The overall glacier area retreat rate was 17.78% during 2005–2015. In the Yinsugaiti Glacier sub-region, the periods of maximum and minimum glacier area retreat rates were 1993–1995 and 2002–2004, respectively. From 2005 to 2015, the glacier area retreat rate of the total area was 2.20%. In the Youyi Peak sub-region, the periods of maximum and minimum glacier area retreat rates were 1996–1998 and 2002–2004, respectively. From 2005 to 2015, the glacier area retreat rate of the whole sub-region was 13.79%. During 2005–2015, the glacier area retreat rate in all four sub-regions slowed.

In general, glacier areas in the four sub-regions showed large-scale retreat trends in the 1990s, then exhibited different downtrends followed by an expansion trend from 2002 to 2004. During 2005–2015, the glacier area retreat rate in the four sub-regions showed decreasing trends. Compared to the average annual glacier area retreat rate across the four sub-regions, the retreat rate was highest in the

Youyi Peak sub-region, followed by the Bogda Peak sub-region, the Yinsugaiti Glacier sub-region, and the Karlik Mountain sub-region.

3.2 Changes of the Glacier Area Center of Gravity

The glacier area center of gravity in the four sub-regions showed a tendency to approach the origin in each sub-region (Fig. 5), indicating glacier area retreat from 1992 to 2015. Changes in the glacier area center of gravity in each quadrant of the four sub-regions from 1990 to 1995 were generally larger than those after 2005, corresponding to significant glacier area fluctuations after 1990. Except for the Youyi Peak sub-region, glacier areas in the Bogda Peak, Karlik Mountain, and Yinsugaiti Glacier sub-regions exhibited obvious changes in the glacier area center of gravity in all four quadrants. The Youyi Peak sub-region only showed obvious changes in the glacier area center of gravity in the second and third quadrants, as well as noticeable changes in the east-west horizontal direction in the second quadrant (Fig. 5).

3.3 Changes of Glacier Aspect

Glacier areas in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions are unevenly distributed [?]. In this study, glacier areas on the east aspect were significantly greater than those on other aspect directions (Fig. 6). Glaciers were more uniformly distributed in the Yinsugaiti Glacier sub-region than in the other three sub-regions, with more glaciers on each aspect direction. In contrast to the Karlik Mountain sub-region, glacier areas on the north aspect of the Bogda Peak, Yinsugaiti Glacier, and Youyi Peak sub-regions were greater than those on the south aspect (Fig. 6).

In the Bogda Peak sub-region, the fastest glacier area retreat rate occurred on the southwest aspect (52.66%), followed by the northwest aspect (44.40%), while the lowest retreat rate was on the east aspect (22.62%). In the Karlik Mountain sub-region, the fastest retreat rate was on the northwest aspect (44.40%), followed by the north aspect (42.40%), and the smallest retreat rate was 19.50% on the east aspect. These variations were consistent with retreat rates of glaciers in the eastern, middle, and western parts of the Tianshan Mountains. Generally, in the Tianshan Mountains, the glacier area retreat rate was fastest in the western part, second fastest in the middle part, and slowest in the eastern part. Moreover, the northern part shrank faster than the southern part, consistent with previous studies [?, ?]. In the Yinsugaiti Glacier sub-region, glacier area on the east aspect shrank the most, reaching 58.16%, followed by the south aspect (39.11%) and the north aspect (26.62%). The east aspect of the Youyi Peak sub-region experienced the fastest glacier area retreat rate (22.37%), followed by the southeast aspect (20.64%) and the north aspect (0.33%).

Generally, glaciers in the Bogda Peak, Karlik Mountain, and Yinsugaiti Glacier sub-regions all showed retreat trends on each aspect direction. However, in the Youyi Peak sub-region, the glacier area retreat rate showed an increasing trend on the northwest aspect direction while exhibiting retreating trends on other aspect directions. In the Bogda Peak and Karlik Mountain sub-regions, the glacier area retreat rate was fastest on the northwest aspect and slowest on the east aspect. In the Yinsugaiti Glacier and Youyi Peak sub-regions, the glacier area retreat rate was fastest on the east aspect and slowest on the north aspect (Fig. 7).

4.1 Inter-Annual Changes of Precipitation and Temperature

From 1961 to 2014, annual precipitation in the four sub-regions showed an increasing trend. Specifically, annual precipitation in the Karlik Mountain sub-region clearly increased (0.05 significance level). Linear trend analysis showed that from 1961 to 2014, annual precipitation values in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions were 610.0 mm, 212.3 mm, 109.1 mm, and 526.7 mm, respectively, with increasing rates of 14.6 mm/10a, 9.1 mm/10a, 2.6 mm/10a, and 15.4 mm/10a, respectively (Figs. 8–11).

From 1961 to 2014, annual average temperature in the four sub-regions showed warming trends, with the Bogda Peak and Karlik Mountain sub-regions exhibiting significant increasing trends ($P<0.05$). Linear trend analysis showed that from 1961 to 2014, annual average temperature values in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier (after excluding abnormal values), and Youyi Peak sub-regions were -2.5°C, 1.7°C, 5.1°C, and -4.8°C, respectively, with increasing rates of 0.2°C/10a, 0.3°C/10a, 0.3°C/10a, and 0.2°C/10a, respectively (Figs. 8–11).

From this information, we conclude that the sub-regions with the highest increasing temperature rates, in descending order, were Karlik Mountain, Yinsugaiti Glacier, Bogda Peak, and Youyi Peak. The sub-regions with the highest increasing precipitation rates, in descending order, were Youyi Peak, Bogda Peak, Karlik Mountain, and Yinsugaiti Glacier. The Youyi Peak sub-region had the fastest glacier area retreat rate, followed by the Bogda Peak sub-region, the Yinsugaiti Glacier sub-region, and finally the Karlik Mountain sub-region. This suggests that the response of the Youyi Peak sub-region to key meteorological factors was greater than those of the Bogda Peak, Yinsugaiti Glacier, and Karlik Mountain sub-regions. Moreover, increased precipitation in the Youyi Peak and Bogda Peak sub-regions had little effect on glacier area retreat, while increased precipitation in the Karlik Mountain sub-region had a certain inhibitory effect on glacier area retreat.

From the spatial distribution of change rates of precipitation and temperature, we conclude that areas with higher increasing rates of precipitation and temperature were mainly distributed along the edges of the four sub-regions (Figs. 8–11).

To better understand the rapid change of glacier areas in the 1990s, we calculated mean values of temperature and precipitation for 10-year intervals (Fig. 12). The results revealed that temperature in the Bogda Peak, Karlik Mountain, Yinsugaiti Glacier, and Youyi Peak sub-regions increased significantly in the 1990s, while precipitation decreased significantly in the Bogda Peak and Yinsugaiti Glacier sub-regions and increased slightly in the Karlik Mountain sub-region. Glaciers in the Youyi Peak sub-region were sensitive to temperature, and the increase in precipitation could not compensate for glacier ablation caused by temperature rise, which explains the rapid change of glacier areas in the 1990s.

4.2 Seasonal Changes of Precipitation and Temperature

To investigate the different impacts of climate change on glaciers across seasons, this study divided a year into two seasons: (1) April–October as the wet season and (2) November–March as the dry season. This division was largely based on research on Glacier No. 1 at the source of the Urumqi River in the Tianshan Mountains [**?**, **?**]. Annual average temperature in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions exhibited increasing trends in the wet season ($P<0.05$; Fig. 13a and b). Annual precipitation in those sub-regions also increased in the wet season, though it decreased insignificantly in the Youyi Peak sub-region. Variation of annual precipitation in the Karlik Mountain sub-region passed the significance test ($P<0.05$), while it failed to pass in the Bogda Peak and Youyi Peak sub-regions. In the dry season (Fig. 13c and d), annual precipitation in the Bogda Peak and Youyi Peak sub-regions increased significantly and passed the significance test ($P<0.05$), while annual precipitation in the Karlik Mountain and Yinsugaiti Glacier sub-regions remained relatively stable with slight variations.

Accumulated temperature indicated an upward trend in all four sub-regions. However, it did not increase significantly in the Bogda Peak, Yinsugaiti Glacier, and Youyi Peak sub-regions, failing to pass the significance test at $P<0.05$ level. In the Karlik Mountain sub-region, accumulated temperature increased significantly throughout the dry season, passing the significance test at $P<0.05$ level. Moreover, Table 2 shows a strong negative correlation between accumulated temperature in the wet season and glacier area in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions, with correlation coefficient values of -0.87, -0.85, and -0.67, respectively, all passing the significance test at $P<0.05$ level. This is consistent with the findings of Gao et al. [**?**]. When temperature change exceeded 0.5°C, glacier area change mainly depended on temperature, consistent with the fact that precipitation no longer plays a major role in affecting glacier area change [?].

In summary, glaciers in all sub-regions showed retreating trends in terms of slope aspect and glacier area center of gravity, and accumulated temperature in the wet season played a major role in glacier area retreat in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions [?, ?, ?]. However, the different glacier area retreat rates across sub-regions were also mainly attributed to the size and morphology of the glaciers themselves.

4.3 Response Time of Glacier Area to Changes in Precipitation and Temperature

The response time of glacier area change to precipitation and temperature changes in the Bogda Peak sub-region was relatively short (Fig. 14a and b). For example, when precipitation began to decrease in 1993, glacier area started to decrease around 1994, and when precipitation began to decrease in 2003, glacier area started to decrease around 2004 (Fig. 14a). Comparison of annual average temperature and glacier area showed that in the Bogda Peak sub-region, when temperature began to decrease in 1997, glacier area began to increase around 1998, and when temperature increased in 2003, glacier area started to decrease around 2004 (Fig. 14b). These results support the conclusion of Niu et al. [?] that the Bogda Peak sub-region is dominated by small glaciers and responds faster to climate change.

A response analysis of key meteorological factors in the Karlik Mountain sub-region is presented in Figure 14c. Since about 1981, the precipitation trend has been rising then falling, while glacier area change has been slowing then accelerating responsively. The relationship between glacier area and annual average temperature in the Karlik Mountain sub-region is presented in Figure 14d, showing considerable consistency between the two factors. The correlation coefficient between glacier area and annual temperature was -0.72, which passed the significance test at $P<0.05$ level (Table 3).

The response analysis of climate change in the Yinsugaiti Glacier sub-region is presented in Figure 14e and f. Precipitation changes showed continuous decrease and increase trends around 1983, and glacier area changed rapidly, showing a good relationship between glacier area change and precipitation change. Around 1984, temperature change trends were rapid increase, increase, slow increase, and decrease, and the corresponding glacier area change rate trends were rapid increase, increase, slow increase, and decrease, respectively. There was good response correspondence between glacier area change and temperature change in the Youyi Peak sub-region (Fig. 14g and h). These findings agree with the research results of Yang [?], Zhang et al. [?], and Jiang et al. [?].

The status of glacier area changes in Xinjiang has been investigated by many previous studies [?, ?, ?, ?]. For example, Niu et al. [?] concluded that glaciers in the Bogda Peak sub-region were in an accelerated retreat status, with glacier shrinkage closely related to rapid temperature rise in the area, and glacier ablation caused by temperature rise has offset glacier recharge from increased precipitation to a certain extent. Wang [?] showed that glacier ablation was strong in the Karlik Mountain sub-region from 1972 to 2011, and the continuous increase in glacier meltwater runoff in recent years was a direct response to climate warming. Jiang et al. [?] pointed out that the overall thickness of the Yinsugaiti Glacier was thinning from 2000 to 2014. The results of Luo et al. [?] indicated that in the Youyi Peak sub-region, although glaciers with area smaller than 1.00 km^2 accounted for 67.00% of the total number, the area and reserves were mainly concentrated in glaciers larger than 1.00 km^2, and changes in thickness and reserves of several larger glaciers determined the change trend of glaciers in the region. They also suggested that small glaciers have small absolute changes but large relative change rates, and are sensitive to climate change.

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5 Conclusions

Based on Landsat TM and ETM+ images from 1990 to 2015, we compared and analyzed glacier area changes in the Bogda Peak and Karlik Mountain sub-regions in the Tianshan Mountains, the Yinsugaiti Glacier sub-region in the Karakorum Mountains, and the Youyi Peak sub-region in the Altay Mountains. Glacier areas in each of the four sub-regions showed a general shrinking trend, though with different changes across periods.

Glaciers in all sub-regions showed retreating trends in terms of slope aspect and glacier area center of gravity. From 1961 to 2014, annual precipitation in the four sub-regions showed an increasing trend, while annual average temperature showed a warming trend. On a seasonal time scale, glacier area changes in the Bogda Peak, Karlik Mountain, and Youyi Peak sub-regions had strong relationships with accumulated temperature in the wet season. Increased precipitation during both dry and wet seasons had not slowed the overall retreat of glacier areas. On an annual time scale, the correlation coefficient between glacier area and annual average temperature was -0.72 and passed the significance test at $P<0.05$ level in the Karlik Mountain sub-region.

Compared with similar studies in this region, the time series in this study are more intensive and can capture glacier changes from a more detailed perspective. Therefore, this study is important for research on glacier changes and water resources in Xinjiang.

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