Climate change and its impacts on mountain glaciers during 1960-2017 in western China postprint

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Abstract

Mountain glaciers are highly sensitive to climate change. In this paper, we systematically analyzed and discussed the responses of glaciers to climate change during 1960-2017 in western China by the methods of least squares and correlation analysis. Results show that the maximum temperature, minimum temperature, average temperature, and precipitation significantly increased in western China at the rates of 0.32°C/10a, 0.48°C/10a, 0.39°C/10a, and 11.20 mm/10a, respectively. However, the wind speed, hours of sunshine, snowfall, and snowy days displayed decreasing trends at the rates of -0.53 m/(s • 10a), 3.72 h/10a, -2.90 mm/10a, and -0.10 d/10a, respectively. The annual percentage of glacier area decreased by approximately 0.42%, and the average glacier area decreased by 2.76 km2/a. Meanwhile, glacial shrinkages were greater in the Altay Mountains, Tanggula Mountains, and Qilian Mountains than in the other mountainous regions. Glacier accumulation decreased while melt volume increased at a rate of 2.7$×$104 m3/a. The area of melt volume was 1.3 times that of the glacier accumulation area. The glacier mass balance (GMB) decreased substantially at a rate of -14.0 mm/a, whereas the equilibrium line altitude (ELA) showed an increasing trend at a rate of 0.5 mm/a. After 1997, the mass was smaller than -500.0 mm, indicating a huge loss in glaciers. Furthermore, relationships between ELA and GMB and various climatic factors were established. Temperature and precipitation demonstrated a significantly negative correlation, whereas wind speed and snowy days had significantly positive correlations with GMB. Snowy days also exhibited a remarkably negative correlation with ELA. The strong warming trend and less snowy days were thought to be the main factors leading to glacial melting, whereas the increase in precipitation, and reductions of sunshine hours and wind speed might slow glacial melting.

Full Text

Preamble

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Climate change and its impacts on mountain glaciers during 1960-2017 in western China

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Abstract

Mountain glaciers are highly sensitive to climate change. In this paper, we systematically analyzed and discussed the responses of glaciers to climate change during 1960-2017 in western China using least squares and correlation analysis methods. Results show that maximum temperature, minimum temperature, average temperature, and precipitation increased significantly in western China at rates of 0.32°C/10a, 0.48°C/10a, 0.39°C/10a, and 11.20 mm/10a, respectively. However, wind speed, sunshine hours, snowfall, and snowy days displayed decreasing trends at rates of -0.53 m/(s • 10a), 3.72 h/10a, -2.90 mm/10a, and -0.10 d/10a, respectively. The annual percentage of glacier area decreased by approximately 0.42%, with the average glacier area shrinking by 2.76 km^2/a. Glacial shrinkage was more pronounced in the Altay Mountains, Tanggula Mountains, and Qilian Mountains than in other mountainous regions. Glacier accumulation decreased while melt volume increased at a rate of 2.7$\times10^{4}$ m^3/a, with the melt area being 1.3 times that of the accumulation area. Glacier mass balance (GMB) decreased substantially at a rate of -14.0 mm/a, whereas the equilibrium line altitude (ELA) showed an increasing trend at a rate of 0.5 mm/a. After 1997, the mass balance fell below -500.0 mm, indicating massive glacier loss. Furthermore, relationships between ELA, GMB, and various climatic factors were established. Temperature and precipitation demonstrated significantly negative correlations with GMB, whereas wind speed and snowy days showed significantly positive correlations. Snowy days also exhibited a remarkably negative correlation with ELA. The strong warming trend and reduced snowy days appear to be the main factors driving glacial melting, while increased precipitation and reductions in sunshine hours and wind speed may

have slowed this melting process.

Keywords: temperature; precipitation; climate trend; glacier variation; impacts; western China

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1 Introduction

Glaciers and snow constitute the main components of the cryosphere, and mountain glaciers are highly sensitive to climate elements such as temperature, precipitation, and wind [?, ?, ?, ?]. Global warming exerts significant impacts on glacier mass accumulation and ablation intensity, causing advances or retreats in glacier area [?, ?, ?, ?, ?]. The modern glacier area worldwide is estimated to cover approximately 29$\times10^{6}$ km^2, of which 4.6377$\times10^{4}$ glaciers with a total area of 5.9425$\times10^{4}$ km^2 are distributed in China [?, ?, ?, ?]. Accelerating glacier shrinkage can affect solid water resources and sea level change [?, ?, ?, ?, ?, ?, ?]. Consequently, scholars worldwide have paid considerable attention to glacier variation [?, ?, ?].

In recent years, remote sensing imagery and satellite data [?, ?, ?] as well as glacier survey catalog data [?, ?, ?] have been widely used in research on glacier area change and glacier mass balance (GMB). The impact of climate change on glaciers has been simulated using different methods [?, ?, ?, ?]. For example, numerous observations have demonstrated that global glaciers are retreating in many regions, such as the northern Tianshan Mountains (Kazakhstan/Kyrgyzstan) [?], the western Himalaya Mountains [?], and mountain areas of Central Asia [?], resulting in reduced glacier volume worldwide [?]. Glaciers in China are also experiencing varying degrees of rapid shrinkage and melting [?, ?, ?, ?, ?, ?, ?, ?, ?]. Some studies have examined the relationship between climate change and GMB along with changes in glacier length during the 1970s–1990s; for instance, Klok and Oerlemans [?] used 17 length records of glaciers in Europe to retrieve climate reconstructions. Other researchers studied glacier sensitivity to climate warming [?, ?, ?, ?], while Pederson et al. [?] analyzed the driving force of decadal-scale climate on glaciers.

Although considerable research has investigated climate change and glacier variation with valuable results, most studies have focused on short-term data from single glaciers using simple methods, limiting the generalizability of their findings. Furthermore, much scholarship has addressed the impact of climate change on individual glaciers and tributary glaciers, qualitatively explaining glacial responses to climate. By comparison, comprehensive studies of glaciers and climate across broader regions remain limited. The impact of multiple meteorological factors on glaciers is particularly poorly understood, and the relationships between glacier variation and climate change require further investigation. Therefore, this paper selects long-term meteorological data (since the 1960s) and different glacier sequences using least squares, permutation, and correlation regression methods to present longitudinal changes in climate and the response of typical glaciers in western China. This study may serve as a basis for further evaluation of climate change and glacier variation.

2.1 Meteorological data

Western China is located between 26°00 12 N–47°51 36 N and 73°18 52 E–104°46 59 E, extending from the Pamir Plateau in the west to the Hengduan Mountains in the east, and from the southern margin of the Himalaya Mountains in the south to the Kunlun Mountains and Qilian Mountains in the north. Daily meteorological data used in this study were obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). Eight meteorological parameters were selected: maximum temperature, minimum temperature, average temperature, precipitation, snowfall, wind speed, sunshine hours, and snowy days in western China from 1960 to 2017. The annual average values of these eight parameters during 1960–1990 were used as standard values to calculate annual anomalies. To enhance reliability, we selected 78 weather stations (Fig. 1 [Figure 1: see original paper]) near glacier regions in western China for comparison.

Monthly data were derived from daily data, and annual averages were calculated from monthly means. Using anomalies avoided potential biases caused by missing data. The least squares method was applied to calculate linear trends in meteorological parameters, where a positive value indicates an increasing rate, a negative value represents a decreasing rate, and the absolute value denotes the intensity of change. Meteorological parameters often exhibit rising or falling trends with changing spatial distribution patterns, which can generally be considered as linear regression over time. The linear trend value was estimated by least squares: where xi is the individual climatic factor; ti is time (year); n is the number of samples; and Q is the trend value, with Q>0 indicating an increasing trend and Q<0 indicating a declining trend.

2.2 Glacier data

Mountain glaciers are widely distributed in western China [?, ?, ?]. Small glaciers (area <1 km^2), large glaciers (area >10 km^2), and huge glaciers (area >100 km^2) account for 20.0%, 37.6%, and 10.4% of the total glacier area, respectively [?]. In this study, data covering 2.4$\times$10^{4}$ km^2 of typical glaciers were collected, representing 45.3% of the total glacier area in western China. The research focuses on seven typical glacier regions: Altay Mountains (AMG), Tianshan Mountains (TMG), Qilian Mountains (QMG), west Kunlun Mountains (WKMG), east Kunlun Mountains (EKMG), Tanggula Mountains (TGMG), and Himalaya Mountains (HMG) (Fig. 1). Glacier area data were obtained from long-term ground observations, glacier inventories, and remote sensing data during 1960–2009, along with related documents published from the 1960s–1970s through the 2000s (Table 1). Long-term detailed observation data for equilibrium line altitude (ELA) were available, and glacier mass balance (GMB) data were obtained from Urumqi Glacier No. 1 in the Tianshan Mountains. Although glaciers are not evenly distributed across drainage basins, data from different spatial and temporal scales help estimate large-scale glacier variation. An area-based weighted method [?] was used to estimate glacier area changes. The study period was unified via interpolation for variation in glacier area per unit time to ensure stable references. The permutation method was used to calculate glaciers for each subsequent period, while correlation regression analysis explored glacier responses to climatic factors. Annual variation of glacier area is defined as follows:

AAC = where AAC is the annual variation of glacier area (%); n is the number of samples; i is the number of 2nd-grade drainage basins; W is the weight of glacier area; j is the number of 3rd-grade drainage basins; Aoij is the initial glacier area (km^2); ΔAij is the variation in glacier area (km^2); Δtij is the number of years; to and toij are the initial and end years, respectively; iA is the glacier area in the drainage basin (km^2); and A' is the total glacier area (km^2).

3.1 Climate trends

Seven, 32, 21, 9, 24, 10, and 19 meteorological stations were selected in the AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas, respectively, to calculate climate data and analyze climate change, anomalies, and linear trends. Figure 2 [Figure 2: see original paper] displays anomaly variations of climatic factors in seven typical glacier regions of western China. Annual average temperature and precipitation generally increased over the past 57 years. Temperature increase rates in the AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas were 0.38°C/10a, 0.31°C/10a, 0.33°C/10a, 0.26°C/10a, 0.37°C/10a, 0.63°C/10a, and 0.47°C/10a, respectively. Precipitation increased at rates of 12.80, 12.90, 10.39, 17.84, 8.09, 5.33, and 21.70 mm/10a, respectively. Average temperature initially decreased during 1960–1969, then showed a steady increase during 1970–1984, followed by a remarkable rise after 1985. Precipitation increased slightly during 1960–1971, fluctuated substantially before 2000, and exhibited an obvious increase after the 21st century began. However, before 1984 in the AMG area, precipitation trends opposed temperature changes, and after 1999 in the TMG area, precipitation showed a significantly decreasing trend.

Maximum temperature in the AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas increased markedly at rates of 0.32°C/10a, 0.12°C/10a, 0.29°C/10a, 0.21°C/10a, 0.29°C/10a, 0.59°C/10a, and 0.37°C/10a, respectively. Minimum temperature increase rates were 0.54°C/10a, 0.35°C/10a, 0.34°C/10a, 0.37°C/10a, 0.45°C/10a, 0.68°C/10a, and 0.65°C/10a, with the largest increases in AMG, TGMG, and HMG areas and the smallest variations in QMG. Maximum and minimum temperatures decreased during 1960–1970, then showed steady increases before 2000 and obvious increases thereafter.

Wind speed and snowy days each showed generally decreasing trends. Wind speed trend rates in AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas were -0.19, -0.06, -0.06, -0.02, -0.04, -0.28, and -0.06 m/(s • 10a), respectively. Wind speed increased during 1960–1975, decreased considerably during 1976–1990, and fluctuated slightly thereafter. Snowy days trend rates were -1.69, -1.58, -3.35, -3.65, -0.66, -6.22, and -7.37 d/10a, respectively. Sunshine hours decreased at rates of -9.58, -5.41, -0.87, -5.59, and 26.51 h/10a in AMG, TMG, QMG, TGMG, and HMG areas, but increased at rates of 12.02 and 10.29 h/10a in EKMG and TGMG areas, respectively. Conversely, snowfall showed fluctuating variations with rates of 4.81, 0.54, -0.47, -5.27, 0.49, -13.75, and 3.23 mm/10a in AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas, respectively. Snowfall increased in AMG, TGMG, and EKMG areas but decreased in the other three regions.

Overall, temperature and precipitation showed substantially increasing trends, especially in AMG and HMG areas, whereas other meteorological parameters including wind speed, sunshine hours, snowy days, and snowfall showed slight decreasing trends. Over the past 57 years, average temperature, maximum temperature, minimum temperature, and precipitation in northwestern China increased at rates of 0.39°C/10a, 0.32°C/10a, 0.48°C/10a, and 11.2 mm/10a, respectively. Snowfall, wind speed, sunshine hours, and snowy days declined at rates of -2.09 mm/10a, -0.30 m/(s • 10a), -3.72 h/10a, and -0.10 d/10a, respectively. Compared with national averages, temperature and precipitation increases were higher in western China than in China as a whole [**?**, **?**, **?**], indicating that climate conditions in the five glacier regions experienced a wetting and warming process over the past 57 years.

The standardized index of climatic factors is presented in Figure 3 [Figure 3: see original paper]. Temperature and precipitation exhibited substantial increasing variability, whereas other meteorological parameters (e.g., snowy days and snowfall) showed slight declines. The greatest increases in minimum temperature and wind speed occurred in the TGMG area, while precipitation and snowy days showed the greatest variability in TMG and TGMG areas, respectively. Snowfall and sunshine hours had relatively large ranges in TGMG and HMG areas, as did wind speed in AMG.

3.2 Glacier variation and response to climate change

The calculated variation rates of average glacier area in AMG, TMG, TGMG, QMG, and HMG areas were -2.30, -4.70, -0.44, -2.75, and -3.61 km^2/a, respectively. The average glacier area in these five regions retreated by 0.56%/a or 2.76 km^2/a overall during 1960–2009. As shown in Figure 4 [Figure 4: see original paper], glacier areas in all five regions retreated rapidly, with the most noticeable percentage of annual area variation occurring particularly in TGMG and AMG areas.

Figure 5 [Figure 5: see original paper] displays variations in GMB and ELA. GMB decreased substantially at a rate of -14 mm/a, whereas ELA exhibited an increasing trend at a rate of 0.5 mm/a. Especially after 1984, mass balance remained essentially negative; notably, it fell below -500.0 mm after 1997, indicating massive loss. Figure 6 [Figure 6: see original paper] shows that annual GMB at various altitudes decreased sharply during 1960–2009, with greater reductions at higher altitudes, peaking at elevations >4200 m. Figure 7 [Figure 7: see original paper] reveals that glacial accumulation decreased while melt volume increased at a rate of 2.7×10^{4} m^3/a, with the melt area being 1.3 times that of the accumulation area.

Figure 8 [Figure 8: see original paper] displays correlation coefficients between climatic factors and GMB and ELA. Climatic factors contributed differently to glacier area variation: temperature and precipitation demonstrated significantly negative correlations with GMB, whereas snowy days and wind speed showed significantly positive correlations (correlation coefficient above 0.3387). Snowy days and ELA exhibited significantly negative correlations with a coefficient of -0.3763 (at 99% confidence level). Relationships between other climatic factors and either ELA or GMB were relatively weak.

Figure 9 [Figure 9: see original paper] illustrates relationships between GMB, ELA, and climatic factors. GMB exhibited polynomial relations with wind speed, temperature, precipitation, and snowy days, whereas ELA showed a linear relation with snowy days. To analyze sensitivity of GMB and ELA to climate change, we established linear relationships as follows:

$$GMB = -316.34T_{min} - 651.84$$
$$GMB = -313.10T_{max} - 843.27$$
$$GMB = -3.68P + 430.87$$
$$GMB = 810.40v - 2144.00$$
$$GMB = 21.52SD - 1592.10$$
$$ELA = -3.37SD + 4272.00$$

where GMB is glacier mass balance (mm); ELA is equilibrium line altitude (m); and Tmin, Tmax, P, v, and SD are minimum temperature (°C), maximum temperature (°C), precipitation (mm), wind speed (m/s), and snowy days (d), respectively.

When minimum and maximum temperatures increased by 1.0°C, GMB decreased by approximately 316.0 and 313.0 mm, respectively—about 40.0 mm smaller than reference results [?]. When precipitation increased by 100.0 mm, GMB decreased by approximately 368.0 mm, about 1.7 mm higher than reference results [?]. When wind speed decreased by 1.0 m/s, GMB decreased by about 810.0 mm. When snowy days decreased by 10.0 d, GMB decreased by around 215.0 mm, while ELA increased by about 33.7 m. These results indicate that GMB was more sensitive to temperature and wind speed than to other climatic factors.

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4 Discussion

In all study regions, maximum temperature, minimum temperature, and average temperature during 1960-2017 showed increasing trends of 0.12°C/10a-0.59°C/10a, 0.23°C/10a-0.65°C/10a, and 0.26°C/10a-0.63°C/10a, respectively. Precipitation increased at rates of 8.09-21.70 mm/10a in all areas except TGMG. These findings are mostly consistent with existing literature on climate trends and glacial change [?, ?, ?]. However, the estimated percentage of annual area variation in this study is 4% higher than previous results, and climate trend rates are lower than those in existing literature [?, ?, ?, ?]. These differences may be due to varying time scales and methods. Overall, these results further reveal the wide range of climate and glacial trends across western China. Regional wind speed and snowy days decreased at rates of 0.06-0.29 m/(s • 10a) and 0.66-6.32 d/10a, respectively. Sunshine hours also decreased at rates of 0.87-26.51 h/10a in all areas except WKMG and EKMG. These climate factors influenced glaciers to varying degrees.

Climate regions of western China—especially temperature, precipitation, and wind speed—are significantly related to GMB in the TMG area. This study estimates that every 1.0°C increase in minimum and maximum temperature caused GMB to decrease by approximately 316.0 and 313.0 mm, respectively. Every 100.0 mm increase in precipitation led to a 368.0 mm decrease in GMB, while every 1.0 m/s decrease in wind speed induced an 810.0 mm decrease in GMB. Increasing snowy days caused GMB to increase by 215.0 mm per 10.0 d. Pu et al. [?] found that every 1.0°C and 100.0 mm increase in temperature and precipitation created corresponding GMB changes of approximately 356.0 mm/°C and 366.3 mm/100.0 mm, respectively. Although present estimates differ from that study, both confirm that climate change affects glaciers; the discrepancy may be due to differences in climate change and statistical spatial and temporal scales.

Physical explanations support these trends. Previous research suggests that temperature increases can cause substantial GMB losses in different regions [?, ?]. Chen et al. [?] proposed that the retreat rate of glaciers in the central Qilian Mountains increased during 1956-2011 while ice surface elevation decreased. Zhu et al. [?] examined climate experiment and gravity recovery data in Central Asia and found periodic GMB fluctuations, indicating significant correlation with precipitation. Wei et al. [?] also suggested that glaciers experienced rapid mass loss in China' s Altay Mountains. Similarly, Kononova et al. [?] pointed out that atmospheric circulation and summer precipitation influenced GMB in TMG. Others reported significant correlations between glaciers, precipitation, and temperature [?, ?]. In summary, climatic factor variations affect glaciers via two main mechanisms: (1) temperature significantly influences glacial melting, precipitation greatly influences glacial accumulation, and both determine the nature, development, and evolution of glaciers [?, ?, ?]; and (2) glacier area sensitivity to climate change is closely related to glacier size, with smaller glaciers being more sensitive to climate warming than larger ones [?, ?, ?]. The present research confirms and extends these findings but with some differences. In this study, when temperature increased by 1.0°C, GMB loss could be offset by a 20.0% precipitation increase–approximately 12.0% higher than reported in literature [?, ?, ?]. This result could be attributed to the relatively longer time series of meteorological parameters and glacier data, plus the abundance of data sites. Moreover, this study revealed that snowy days, sunshine hours, and wind speed showed decreasing trends during the study period, which caused GMB increases. Specifically, the maximum shrinkage of glacier area in AMG and TGMG areas corresponded to the greatest temperature rise and wind speed increase, along with fewer snowy days and less precipitation. These results further demonstrate that glacial melting is driven by multiple climatic factors.

The above analysis indicates that GMB is most sensitive to temperature changes among all climatic factors. When temperature increases, glaciers become thinner and their area gradually shrinks, leading to a rise in the snow line and an increase in ELA. However, precipitation plays a different role in GMB. Furthermore, reduced sunshine hours and slower wind speed may inhibit glacial ablation. Smaller glaciers are more sensitive to climate warming than larger ones. Consequently, glacier area shrinkage is actually affected by the combination of many meteorological parameters and physical features of glaciers.

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5 Conclusions

Maximum temperature, minimum temperature, and average temperature in all regions presented significantly increasing trends, with the maximum rate of increase (0.61°C/10a) in the TGMG area. Precipitation also increased in most areas except for a reduction of -5.33 mm/10a in TGMG, with the greatest increase (21.70 mm/10a) in the HMG area. Snowfall, wind speed, sunshine hours, and snowy days exhibited decreasing trends. Wind speed decreased by up to 0.19 and 0.28 m/(s • 10a) in AMG and TGMG areas, respectively. The variation ranges of temperature, precipitation, and wind speed were greatest in AMG, TMG, and HMG areas compared with other regions.

Glaciers have retreated rapidly during the past 57 years in western China. The average area variation was largest in TMG and HMG areas, and the annual percentage of glacier area retreated most intensively in AMG and TGMG areas. Annual GMB decreased sharply, with glacier melt volume being 1.3 times that of accumulation, whereas ELA showed an increasing trend. After 1997, glacier mass balance fell below -500.0 mm, reflecting massive loss.

Temperature and precipitation demonstrated significantly negative correlations, whereas wind speed and snowy days showed significantly positive correlations with GMB over the past 57 years. Glacier mass balance was more sensitive to temperature and wind speed than to other climatic factors. The pronounced warming trend and fewer snowy days may be the driving factors behind glacial retreat. Although precipitation increased, declines in sunshine hours and wind speed may have slowed glacial melting.

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