

Article

Study on Change of the Glacier Mass Balance and Its Response to Extreme Climate of Urumqi Glacier No.1 in Tianshan Mountains in Recent 41 Years

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Abstract: Glaciers are susceptible indicators of climate change and crucial parts of the world's water cycle. In the context of global warming, we took the Urumqi Glacier No.1 (UG1) as an example, which is situated at the source of the Urumqi River on the northern slope of the Tianshan Mountains, Xinjiang, combined with the climate data of Daxigou Meteorological Station from 1980 to 2020, and the change of glacier mass balance and its response to extreme climate are discussed. The results suggest that the glacier mass balance of UG1 showed a downward trend over the studied 41-year period, and the mass loss increased. The cumulative glacier mass balance value was $-19,776$ mm w.e., and the average annual value was -482 mm w.e.a⁻¹. The Mann-Kendall trend test showed that the change point occurred around 1994, and the mass balance of UG1 became more negative after 1994. In the same period, the changing mass balance trend of UG1 was not the same in different seasons. The inter-annual variation of summer mass balance was drastic, showing a marked downward trend; the inter-annual change of winter mass balance was small, showing a slight uptrend. The changing of extreme climate indices where UG1 is located showed that only TX90p and TX10p changed observably from 1980 to 2020, and the extreme precipitation indices changed evidently and had been on the rise. The changing trend of extreme climate indices indicated that the temperature was rising, the warming was significant, and the precipitation was increasing. During 1980–2020, the glacier mass balance was substantially correlated with the extreme temperature indices (TX90p, TXx) but not with the extreme precipitation indices. Analyzing on a seasonal scale, the summer mass balance was memorably correlated with the extreme temperature indices (TX90p, TX10p, TXx), and the correlation coefficient between winter mass balance and the extreme precipitation index R95p and winter precipitation was in the range 0.36–0.40 ($p < 0.05$). According to the correlation between glacier mass balance and extreme climate indices, the summer mass balance was mainly affected by temperature, and the winter mass balance was affected primarily by precipitation.

Keywords: glacier mass balance; extreme climate indices; climate change; correlation; Urumqi Glacier No.1



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1. Introduction

Mountain glaciers, a component of the “global water tower”, are significant sources of water to maintain the safety of the ecological environment, ensure agricultural production, and maintain sustainable socio-economic development [1,2]. Under the trend of climate warming, many glaciers around the world are showing a trend of thinning and accelerated melting, which has a considerable impact on the ecological environment, water cycle, and water resources [3,4], leading to an increase in the risk of glacier disasters [5,6]. Over the

past few decades, the temperature has continued to rise, and the glacier area and ice volume have shown a shrinking trend in the Tianshan Mountains, China [7,8]. Glacier meltwater in semi-arid and arid regions contributes significantly to the composition of water resources and is essential for maintaining the ecosystem [9]. On the other hand, as a “solid reservoir”, glaciers influence river discharge on both an annual and an inter-annual scale via “peak cutting and valley filling” [10]. Glacier mass balance is a crucial link connecting climatic change with glacier dynamics and hydrology when compared to variations in glacier length and area. It is now a significant “indicator” of climate change [11]. Therefore, in the context of climate warming, the inter-annual and seasonal variations in glacier mass balance as well as the reaction of glacier mass balance to climatic change must therefore be studied, which is essential for comprehending how water resources are changing throughout time, maintaining stable agricultural development and ecosystems, and preventing disasters in arid and semi-arid regions of northwest China [12].

As global warming intensifies, extreme climate events have increased significantly, which has substantially impacted ecological security and human society and has become an essential part of ecological environment research [13,14]. As one of the critical parameters to reveal the value of glacier ablation and accumulation, glacier mass balance is susceptible to climate change [15]. The dynamic shift in glacier mass balance is an essential primary condition to reflect the evolution of glacier scale and runoff. It is the key link between glacier, climate, and water resources. In recent years, many scientific fields have made extensive use of the extreme climate index, especially when it comes to the effects of extreme climate change on vegetation ecology [16–19]. As a significant solid water resource, extreme climate events have a significant impact on glaciers, which cannot be underestimated, and researchers have begun to pay attention to it [20,21]. Hock (2003) found that temperature and precipitation had the greatest impact on glacier mass balance in mountainous areas by establishing the relationship model between glacier mass balance and climate elements [22]. Azam et al. (2014) studied the sensitivity of the Chhota Shigri Glacier’s glacier mass balance to climate change in the Indian Himalayas through a degree-day model and discovered that the glacier mass balance is more susceptible to temperature changes than the change in precipitation [23]. Grunewald et al. (2010) investigated how glaciers responded to extreme climates in the southernmost region of Europe and discovered that tiny glaciers reacted more quickly to extreme climates. By predicting the future development trend of glaciers, they found that glaciers in this region will gradually disappear in the next few decades [20]. To sum up, under the background of climate warming, there is still a lack of research to investigate the relationship between glacier mass balance and extreme climate and the extent to which glacier mass balance responds to extreme climate. Therefore, based on the observed mass balance data of Urumqi Glacier No.1 (UG1), which has the longest monitoring record in China, this paper used the Mann-Kendall trend and catastrophe test to analyze the inter-annual and seasonal variation trend of glacier mass balance. In addition, based on the temperature and precipitation data of the Daxigou Meteorological Station, the RCLimDex model was used to display the extreme climate index of the region where the glacier is located and to reveal the extreme climate change trend. Furthermore, the correlation analysis method was used to investigate the connection between glacier mass balance and extreme climate index, and the response degree of glacier mass balance to extreme climate was analyzed. The research results are expected to provide scientific guidance and decision-making support for colleagues at home and abroad who study the evolution characteristics of extreme climate events and for coping with glacier changes and their impacts.

2. Materials and Methods

2.1. Study Area

UG1 (43°06′ N, 86°49′ E) is a typical inland glacier, a cirque-valley type glacier [24,25], located in the headwater region of the Urumqi River on the northern slope of the Tianshan Mountains, China (Figure 1). The region where the UG1 is located is primarily controlled

by the westerly circulation, the Siberian anticyclone, and the westerly jet in the upper troposphere [12]. Based on the measured data from the Daxigou Meteorological Station (3593 m a.s.l.) at the terminus of UG1, from 1959 to 2017, the annual average temperature in this region reached $-4.6\text{ }^{\circ}\text{C}$. About 460 mm of precipitation fell per year, with 78% of that falling between May and August, and the precipitation type was mainly solid precipitation [26]. Due to climate warming, UG1 continued to shrink and split into east and west branches in 1993. UG1 had an area of 1.558 km^2 in 2015, with an altitude between 3743~4267 m a.s.l. [27]. In addition, the World Glacier Monitoring Service only lists UG1 as the reference glacier in China. As one of the key observation and research glaciers in the world, it has been surveyed for a long time with continuous observation data.

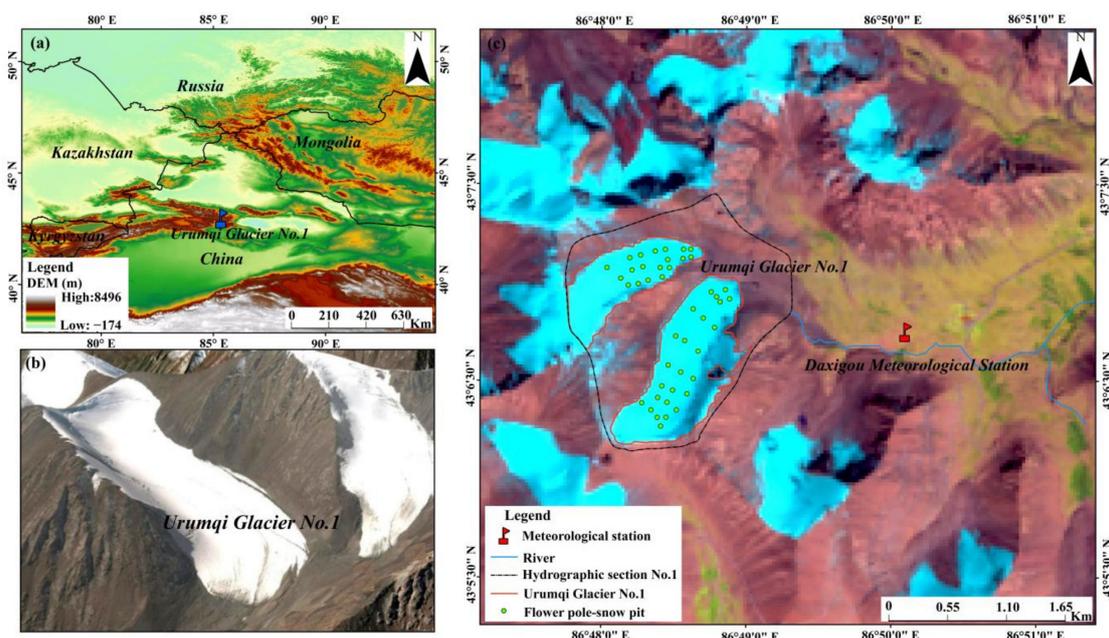


Figure 1. (a) Location map of Urumqi Glacier No.1 (UG1). (b) Image of UG1. (c) Location of Daxigou Meteorological Station.

2.2. Data

2.2.1. Glacier Mass Balance Data

Tianshan Glaciological Station, Chinese Academy of Sciences, adopted the traditional “flower pole-snow pit method” to observe the mass balance of UG1 according to the requirements of the relevant glacier mass balance observation specifications issued by the World Glacier Monitoring Service (WGMS), and the flower poles are evenly distributed on the glacier surface. The mass balance observation flower rod network array of UG1 is shown in Figure 1. The data of flower rod points are from the Tianshan Glaciological Station, Chinese Academy of Sciences. The mass balance value of the whole glacier in the observation period was calculated by calculating the mass balance value of a single point, and then the entire glacier was calculated by using the contour method based on the mass balance maps [28]. The specific calculation method is as follows:

$$b_n = \sum_{i=1}^n S_i b_i / S \quad (1)$$

where b_n represents the glacier’s overall mass balance value; S_i and b_i respectively represent the region between two adjacent contour lines and the accompanying elevation zone’s mass balance value; n represents the number of elevation zones; S represents the total area of the glacier.

2.2.2. Meteorological Data

To accurately reflect the climate change in the region where UG1 is located, the meteorological data selected in this study are the temperature and precipitation data of the Daxigou Meteorological Station from 1980 to 2020. The distance between the meteorological station and the UG1 terminus is only about 2 km, and the station's altitude is about 3539 m a.s.l. The earliest observation at Daxigou Meteorological Station mainly used louvers and Chinese standard rain gauges. In recent years, the instruments were replaced with temperature and humidity sensors and Norwegian weighing rain and snow gauge TB200 [29]. The data of this meteorological station is provided by The China Meteorological Data Service Center (<http://data.cma.cn>, accessed on 25 May 2022).

2.3. Methods

2.3.1. Extreme Climate Index

In this study, 8 extreme climate indices that are frequently used to investigate extreme climate occurrences were chosen [30,31], including 5 extreme temperature indices and 3 extreme precipitation indices (Table 1). Based on the daily maximum (low) temperature, daily average temperature, and daily precipitation data of the Daxigou Meteorological Station from 1980 to 2020, the extreme climate indices were calculated and obtained using the RCLimDex model, which was developed and maintained by the Climate Research Branch of the Meteorological Service of Canada [32].

Table 1. Selection and definition of extreme climate indices.

Classification	Index	Indicator Name	Definitions
Extreme temperature index	TX90p (d)	Warm days	Percentage of days when TX > 90th percentile
	TX10p (d)	Cool days	Percentage of days when TX < 10th percentile
	TXx (°C)	Max temperature	Monthly maximum value of daily maximum temperature
	TNn (°C)	Min temperature	Monthly minimum value of daily minimum temperature
	DTR (°C)	Diurnal temperature range	Monthly mean difference between TX and TN
Extreme precipitation index	R95p (mm)	Very wet days	Annual total precipitation when RR > 95th percentile
	R99p (mm)	Extremely wet days	Annual total precipitation when RR > 99th percentile
	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as precipitation ≥ 1.0 mm) in the year
Others	TM (°C)	Average annual temperature	Annual average temperature
	PRE (mm)	Annual precipitation	Total rainfall in a precipitation

2.3.2. Mann-Kendall Trend Test

Mann-Kendall (MK) trend test is a nonparametric test method used to test the location of abrupt changes in the annual mass balance sequence of glaciers. The formula is as follows:

$$UF = \begin{cases} \frac{S+1}{\sqrt{VAR(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S-1}{\sqrt{VAR(S)}}, & S < 0 \end{cases} \quad (2)$$

where UF represents the standardized test statistic; building inverse sequence $UB = -UF$; S represents the test statistic. Within a 95% confidence interval, calculate the threshold level

± 1.96 . If either UF or UB is greater than 0, the glacier mass balance is trending downhill; when it is less than 0, it means that it is in an upward trend. If UF and UB curves connect at a position inside the confidence interval, this point denotes a mutation point. When the UF or UB curve exceeds the confidence interval, it indicates that the glacier mass balance changes significantly.

2.3.3. Correlation Analysis

By calculating the correlation coefficient between the two groups of elements, we can quantitatively analyze the correlation between meteorological factors and glacier mass balance. The calculation formula of the correlation coefficient value of r is:

$$r_{WB} = \frac{\sum_{i=1}^N (W_i - \bar{W})(B_i - \bar{B})}{\sqrt{\sum_{i=1}^N (W_i - \bar{W})^2} \sqrt{\sum_{i=1}^N (B_i - \bar{B})^2}} \quad (3)$$

where W_i is the meteorological element value; B_i is the glacier mass balance; \bar{W} and \bar{B} are the corresponding mean. The value range of the correlation coefficient value of r is $-1.0 \sim 1.0$. If the value of r is closer to 1.0, the more significant the positive correlation is; if the value of r is closer to -1.0 , the more significant the negative correlation is; if $r = 0$, it indicates that the two are independent of each other.

3. Results

3.1. Glacier Mass Balance

3.1.1. Annual Glacier Mass Balance

Glacier mass balance is the sum of the accumulation and ablation of glaciers in a certain period [33] and is a key “indicator” of climate change [34]. Figure 2a reveals that from 1980 to 2020, the annual glacier mass balance of UG1 displayed a downward trend, and the negative change was significant ($p < 0.01$). The inter-annual variation of the mass balance of UG1 was drastic, with a maximum value of 106 mm w.e. (1989) and a minimum value of -1327 mm w.e. (2010). The cumulative mass balance value in 41 years was $-19,776$ mm w.e., and the average annual value was -482 mm w.e.a $^{-1}$. The shifting trend of UG1’s mass balance was tested using the nonparametric Mann-Kendall test in the long-term series from 1980 to 2020, and the results revealed that the melting of UG1 had an increased tendency and had started to show a more negative balance from about 1994. Therefore, according to the change-point (Figure 2b), the mass balance change of UG1 was essentially split into two stages. In the first stage (1980–1993), the annual glacier mass balance showed a positive and negative alternating state, showing a slight upward trend, with a varied range of $-706 \sim 106$ mm w.e., and an annual average value of -262 mm w.e.a $^{-1}$, with obvious volatility features. In the second stage (1994–2020), the annual glacier balance was significantly negative ($p < 0.01$), with a range of $-1327 \sim 63$ mm w.e., and an average annual value of -597 mm w.e.a $^{-1}$. The annual average mass loss of the second stage was more intense than that of the first stage, and it was roughly twice as much as that of the first stage.

3.1.2. Seasonal Glacier Mass Balance

Glacier mass balance exhibits seasonal variations in western China due to the influence of the Indian monsoon and westerlies [35]. To further explore the seasonal changes in the mass balance of UG1, this study selected the summer mass balance (May–August) and winter mass balance (September–April of the next year) for exploration and analysis (Figure 3). From 1980 to 2020, the inter-annual change of the summer mass balance of UG1 was varied and showed a notable downward trend ($p < 0.01$). In the 41 mass balance years, the inter-annual variability of the summer mass balance was remarkably coincident with the annual mass balance ($R^2 = 0.92$, $p < 0.01$), which was negative (-696 mm w.e.a $^{-1}$). Among them, the average summer mass loss in the second stage (-774 mm w.e.a $^{-1}$) was nearly twice as high as the average summer mass loss in the first stage (-372 mm w.e.a $^{-1}$),

showing that the summer mass loss rate dramatically increased after 1994. The primary cause of this phenomena was global warming. This region has precipitation primarily in the summer, with May to August making up around 77% of the year’s total [36]. Therefore, as the temperature rises, the amount of rainfall will also climb. Additionally, as new snow falls, the albedo of the glacier’s surface will decrease, causing more melting. In the 41 winter mass balance years ($154 \text{ mm w.e.a}^{-1}$), the inter-annual change was negligible, and the overall trend was somewhat upward. The annual average mass balance ($170 \text{ mm w.e.a}^{-1}$) in winter in the first stage was marginally greater than the second stage’s ($150 \text{ mm w.e.a}^{-1}$), with no discernible difference.

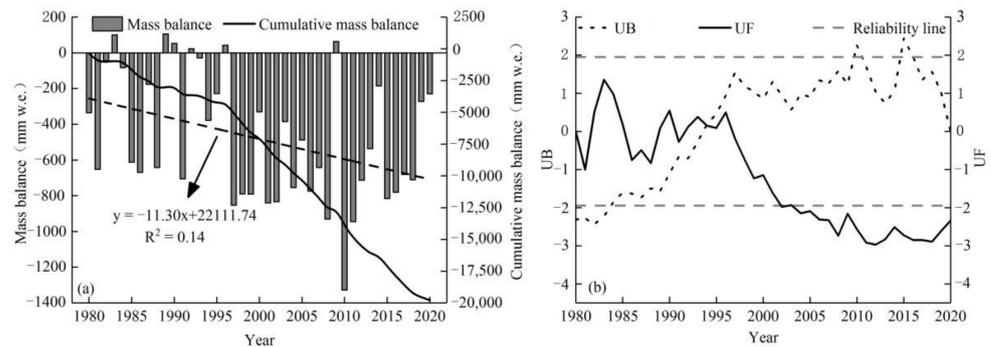


Figure 2. (a) Changes of mass balance of Urumqi Glacier No.1 from 1980 to 2020; (b) Mann-Kendall mutation test of mass balance.

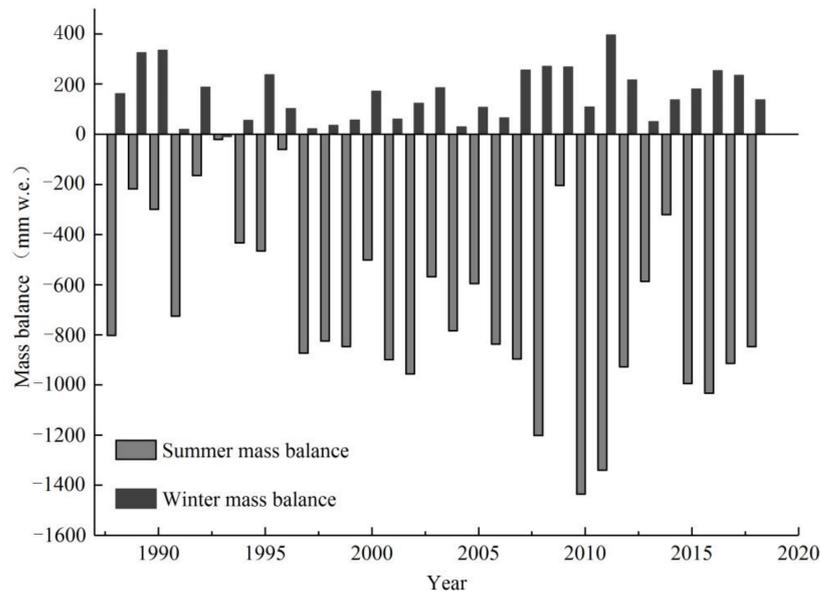


Figure 3. Seasonal variation of mass balance of Urumqi Glacier No.1.

3.2. Change Characteristics of Extreme Climate Events

The mass balance of UG1 changed abruptly in 1994, much like the previous abrupt test on it, and the changes in the mass balance of UG1 in 1980–2020, 1980–1993, and 1994–2020 were different. Therefore, this section will explore whether the changes in extreme climate events were also different from the three time periods of 1980–2020, 1980–1993, and 1994–2020.

Figure 4 and Table 2 show the changing trend of extreme climate indices in the region where UG1 is located. From 1980 to 2020, the maximum temperature (TXx), the minimum temperature (TNn), and the diurnal temperature range (DTR) in the extreme temperature indices did not change significantly. On the contrary, the warm days (TX90p) and the cold days (TX10p) changed markedly. Among them, TX90p showed an evident increase trend,

with a rate of 5.632 d/(10a), and TX10p decreased observably at the rate of -3.150 d/(10a). From 1980 to 2020, the extreme precipitation indices presented a remarkable change trend. Among them, the total amount of very wet days (R95p) and the total amount of extremely wet days (R99p) increased markedly at the rate of 34.119 mm/(10a) and 16.442 mm/(10a), respectively. The simple daily intensity index (SDII) increased significantly at the rate of 0.393 mm/(d·10a). From 1980 to 1993, the annual average temperature (TM), annual precipitation (PRE), and extreme climate indices in the region where UG1 is located did not change significantly. From 1994 to 2020, only TX10p and DTR changed observably, and both showed a prominent decreasing trend, which were -3.639 d/(10a) and -0.042 °C/(10a), respectively. Only the SDII extreme precipitation indices showed a striking increase trend, and the changes of other extreme precipitation indices were not significant, indicating that the daily precipitation in the region where UG1 is located was increasing from 1994 to 2020.

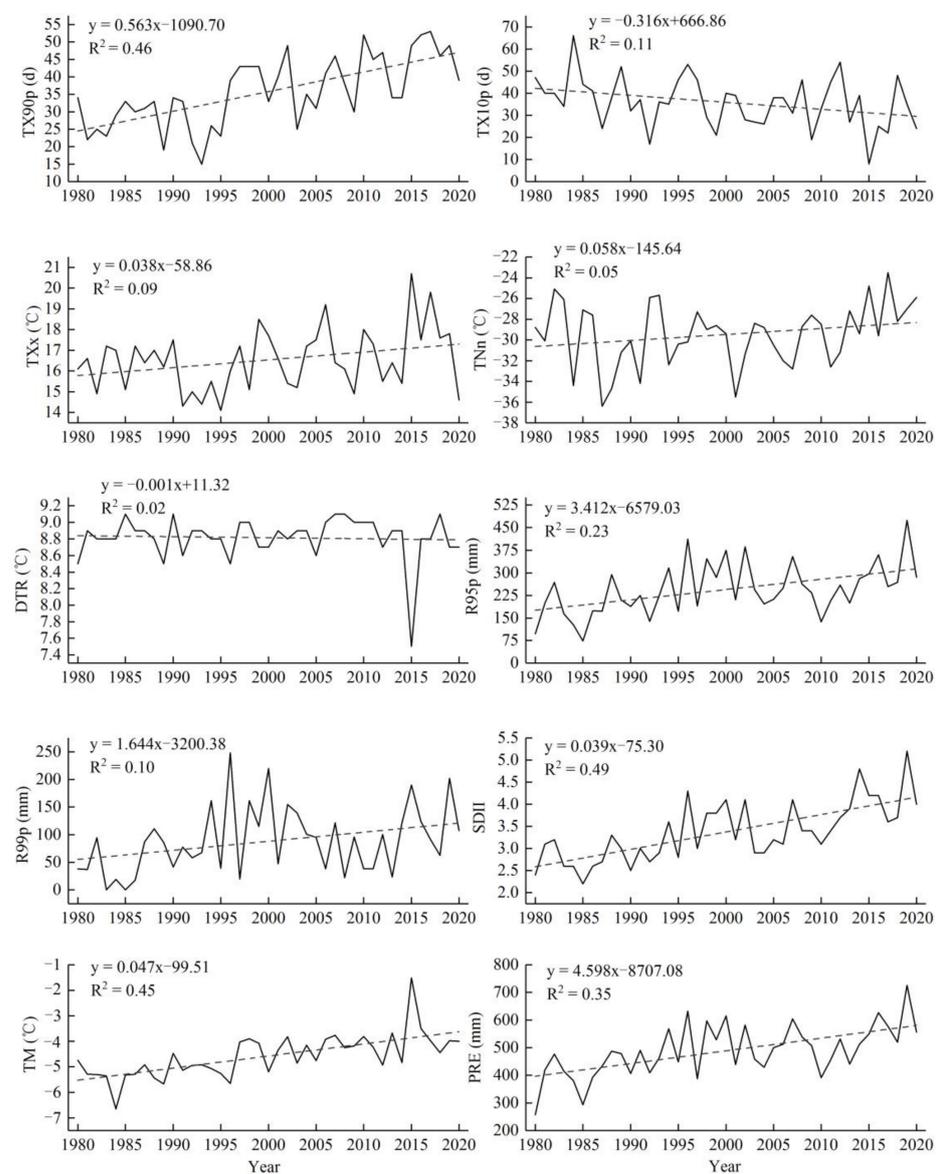


Figure 4. Liner trend in extreme climate indices during 1980–2020. The solid lines denote linear fit.

Table 2. Trends of regional average climate extreme variables in the region of Urumqi Glacier No.1 during periods 1980–2020, 1980–1993, and 1994–2020.

Index	Change Trend of Extreme Climate Index (Every 10 Years)		
	1980–2020	1980–1993	1994–2020
TX90p (d)	5.632 **	−3.473	5.336
TX10p (d)	−3.150 **	−11.912	−3.639 **
TXx (°C)	0.377	−0.925	0.618
TNn (°C)	0.581	−0.857	1.553
DTR (°C)	−0.012	0.068	−0.042 *
R95p (mm)	34.119 **	40.363	5.374
R99p (mm)	16.442 *	32.890	−9.377
SDII	0.393 **	0.110	0.309 *
TM (°C)	0.475 **	0.313	0.442 *
PRE (mm)	45.979 **	82.321	19.522

Note(s): Definitions of climate variables see Table 1. * $p < 0.05$; ** $p < 0.01$.

Compared with 1980–1993, the change rate of extreme temperature index TX90p and TNn during 1994–2020 was more incredible. The TX90p decreased at a rate of 3.473 d/(10a) during 1980–1993 and increased at a rate of 5.336 d/(10a) during 1994–2020; TNn decreased at a rate of 0.857 °C/(10a) during 1980–1993 and increased at a rate of 1.553 °C/(10a) during 1994–2020. On the contrary, the change rate of TX10p, TXx, and DTR in 1994–2020 was smaller than that in 1980–1993. The TX10p of 1980–2020 and 1994–2020 decreased at the rate of 11.912 d/(10a) and 3.639 d/(10a), respectively. From 1980 to 1993, TXx decreased at a rate of 0.925 °C/(10a), while from 1994 to 2020, TXx increased at a rate of 0.618 °C/(10a). From 1980 to 1993, DTR increased at a rate of 0.068 °C/(10a), while from 1994 to 2020, DTR decreased at a rate of 0.042 °C/(10a). In addition, compared with 1980–1993, during 1994–2020, the extreme precipitation index change rate decreased, except for SDII, which increased. Based on the change characteristics of the extreme climate index in the above two periods, it can be found that the number of days of extreme warm events in the region where UG1 is located increased and the degree increased. Although the rainfall showed an increasing trend, the increasing degree of precipitation from 1994 to 2020 was weaker than that from 1980 to 1993.

3.3. Correlation between Glacier Mass Balance and Extreme Climate

3.3.1. Correlation between Annual Glacier Mass Balance and Extreme Climate

To explore how glacier mass balance responds to extreme climate, a Pearson correlation analysis was conducted between glacier mass balance and extreme climate indices. Figure 5 and Table 3 showed the correlation analysis results of extreme climate indices and mass balance of UG1 in 1980–2020, 1980–1993, and 1994–2020. From 1980 to 2020, there was no noteworthy correlation between the extreme precipitation index and the mass balance of UG1. Except for TX10p, TNn, and DTR, other extreme temperature indices and annual average temperature were markedly related to the mass balance of UG1. Among them, the absolute value of the correlation coefficient between TX90p and TM and the mass balance of UG1 was more significant than 0.50 ($p < 0.01$), and the correlation coefficient between TX90p and the mass balance of UG1 was the highest, with a correlation coefficient of -0.67 , which showed that the mass balance of UG1 had a positive response to the number of warm days and the average annual temperature. The relationship between TXx and UG1's mass balance was adverse, with a correlation coefficient of -0.39 ($p < 0.05$). The correlation between extreme precipitation indices and the extreme temperature indices and the glacier mass balance in 1980–1993 was not significant. From 1994 to 2020, only R99p in the extreme precipitation index was slightly correlated with the glacier mass balance, and the correlation coefficient was 0.47 ($p < 0.05$). It was found that after 1994, the influence of precipitation on the mass balance of UG1 was gradually notable. The extreme temperature index in this stage was comparable to that in the before stage, only TM, TX90p, and TXx

were significantly correlated with the mass balance of UG1, and the correlation values were -0.49 , -0.59 , and -0.46 , respectively. It can be seen that after 1994, the correlation coefficient between the maximum daily temperature and the mass balance of UG1 increased, which suggests that the extremely high temperature had a more extraordinary effect on the glacier mass balance.

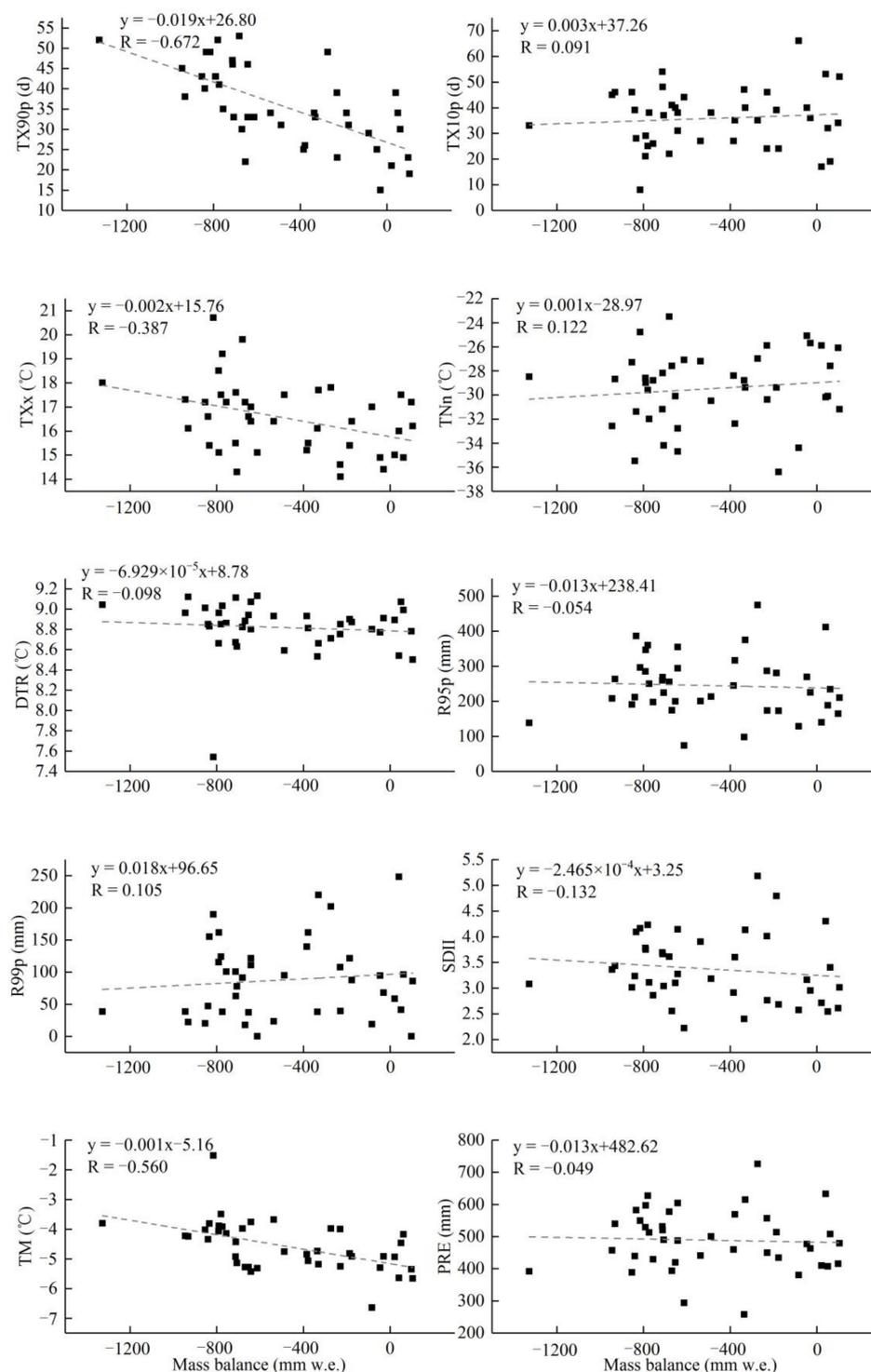


Figure 5. Correlation between annual mass balance and regional mean extreme climate indices of Urumqi Glacier No.1 during periods 1980–2020. The solid lines denote linear fit.

Table 3. Correlation between annual mass balance and regional mean extreme climate indices of Urumqi Glacier No.1 during 1980–2020, 1980–1993, and 1994–2020.

Index	Change Trend of Extreme Climate Index (Every 10 Years)		
	1980–2020	1980–1993	1994–2020
TX90p (d)	−0.672 **	−0.495	−0.594 **
TX10p (d)	0.091	−0.095	0.046
TXx (°C)	−0.387 *	0.054	−0.461 *
TNn (°C)	0.122	0.274	0.112
DTR (°C)	−0.098	−0.113	−0.116
R95p (mm)	−0.054	−0.0330	0.342
R99p (mm)	0.105	0.049	0.467 *
SDII	−0.132	−0.083	0.325
TM (°C)	−0.560 **	0.011	−0.486 *
PRE (mm)	−0.049	0.136	0.357

Note(s): Definitions of climate variables see Table 1. * $p < 0.05$; ** $p < 0.01$.

3.3.2. Correlation between Seasonal Glacier Mass Balance and Extreme Climate

The glacier mass balance changes with the seasons, so it is necessary to explore further the relationship between the glacier mass balance and the extreme climate indices in different seasons. Figure 6 and Table 4 show the correlation analysis results of glacier mass balance and the extreme climate indices in summer and winter from 1980 to 2020. From 1980 to 2020, there was no significant correlation between the summer mass balance of UG1 and the extreme precipitation indices. On the contrary, the summer glacier mass balance was observably correlated with the extreme temperature indices TX90p, TX10p, and TXx. The correlation coefficients were −0.65, 0.49, and −0.47, respectively, and the significance levels were all 0.01, indicating that the summer mass balance was mainly affected by the temperature. From 1980 to 2020, the correlation coefficient between the winter mass balance of UG1 and the extreme precipitation index R95p and the winter precipitation was between 0.36 and 0.40 ($p < 0.05$), respectively. The extreme temperature indices in winter had no significant correlation with the winter mass balance, indicating that the winter mass balance was mainly affected by precipitation.

Table 4. Correlation between mass balance of Urumqi Glacier No.1 in different seasons and extreme climate indices.

Index	Summer	Winter
TX90p (d)	−0.645 **	−0.054
TX10p (d)	0.485 **	0.189
TXx (°C)	−0.466 **	−0.354
TNn (°C)	−0.160	−0.027
DTR (°C)	−0.082	−0.129
R95p (mm)	0.116	0.357 *
R99p (mm)	0.197	0.270
SDII	−0.115	0.189
TM (°C)	−0.802 **	−0.101
PRE (mm)	0.062	0.397 *

Note(s): Definitions of climate variables see Table 1. * $p < 0.05$; ** $p < 0.01$.

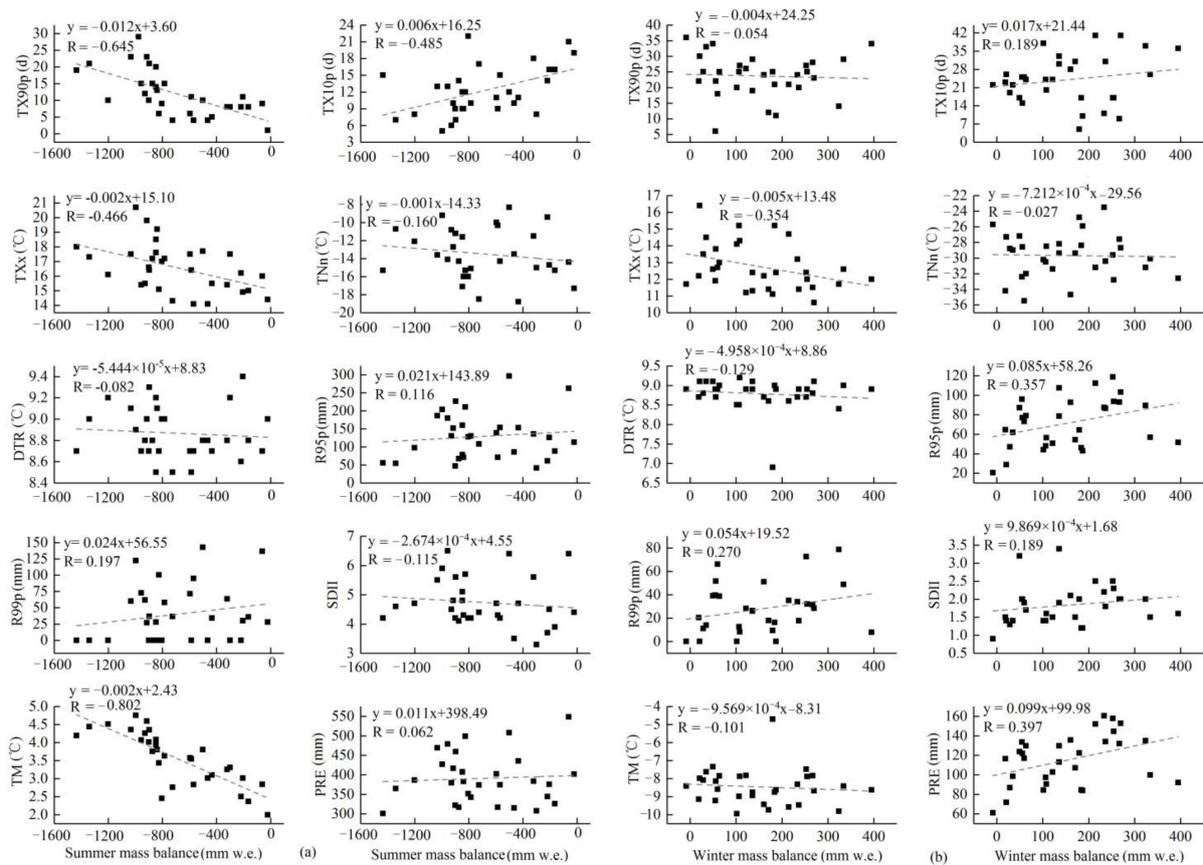


Figure 6. Correlation between mass balance of Urumqi Glacier No.1 in different seasons and extreme climate indices. The solid lines denote linear fit. (a) Summer mass balance. (b) Winter mass balance.

4. Discussion

4.1. Dynamic Change of Glacier Mass Balance

With the warming and humidification intensifying in the arid and semi-arid areas of Northwest China, a large number of glaciers have retreated significantly and become thinner [2,7], resulting in rapid changes in the glacier landscape and an increase in glacier disasters [37,38]. Glacier change is vital in runoff regulation, ecological environment evolution, and social and economic civilization development [9,39]. From 1980 to 2020, the annual mass balance of UG1 generally showed a downward trend. After 1994, the mass loss of UG1 increased significantly, which was in line with the results of Bhattacharya’s study that the glacier mass loss in the Tianshan Mountains increased evidently [34]. According to the summer mass balance of UG1, the seasonal changing characteristics were negative for many years, showing a state of glacier mass loss, and the winter mass balance of UG1 was positive for many years, showing a form of glacier mass accumulation, indicating that the mass loss of UG1 was mainly concentrated in summer. After 1994, the mass loss of the glacier in summer was more serious. Previous studies have shown that slope is an essential topographic factor affecting glacier change [40]. The average slope of UG1 is about 21.4°. Influenced by the slope, the ice body of UG1 will move faster from the accumulation area to the melting area under the negative balance state, accelerating the mass loss of the glacier [41]. In addition, UG1 is located in the arid and semi-arid region of Northwest China, and the climate environment is harsh. Among the climate factors, the glacier mass balance has a close relationship with temperature and precipitation. Temperature is the leading factor in glacier melting, and precipitation is the main cause of glacier accumulation. The combination of the two determines the evolution state of glacier mass.

4.2. Response of Glacier Mass Balance to Extreme Climate

To explore the impact of extreme climate change on the mass balance of glaciers, eight extreme climate indices were selected in this paper. Among them, the indices representing extremely high temperature (TX90p and TXx) revealed an upward trend, and the index TX10p, representing extremely low temperature, displayed a clear decreasing trend, indicating that the number of cold days was decreasing, the temperature was rising, and the warming was marked. In recent years, global climate warming has intensified. The summer temperature in most areas has increased significantly, the winter temperature has gradually warmed up, and the frequency of rainstorm events has increased [42,43]. To explore the connection between glaciers and extreme climate indices, this study attempted to characterize the relationship between glaciers and extreme climate indices through correlation analysis on annual and seasonal scales.

Extreme climate change is more abrupt than regular climate change, and its occurrence will adversely affect human society and the ecological environment [44]. As one of the critical components of the ecosystem, the glacier is extremely sensitive to climate change. UG1 is situated in an area with striking climate change and concentrated rainfall, mainly from May to August [36]. The results of the correlation study revealed that the mass balance of UG1 was significantly correlated with the extreme temperature indices (TX90p, TXx) and the annual average temperature in the annual scale change. In the seasonal scale change, the winter mass balance was only strongly correlated with the extreme precipitation index (R95p) and the annual precipitation. On the contrary, the summer mass balance was the only evident correlation with the extreme temperature indices (TX90p, TX10p, TXx) and the annual average temperature. Similar to the formation mechanism of the glacier, the mass balance of UG1 was in the negative balance as a whole and showed significant correlation with the temperature indices, demonstrating that temperature had a significant impact. From the perspective of seasonal change, the mass accumulation of UG1 was mainly concentrated in winter, which was distinctly related to precipitation and primarily affected by precipitation. The ablation of UG1 was mostly focused on in summer, which was outstandingly related to the temperature and was mainly affected by the temperature. The relationship between glaciers and climate is a relatively complex system. The change of glacier mass balance is a dynamic process, and there are many factors affecting its change. It is still necessary to further evaluate the response mechanism of glacier mass balance change to extreme climate.

5. Conclusions

Based on the observation data of UG1 and the data of daily maximum temperature, daily minimum temperature, daily average temperature, and precipitation from 1980 to 2020, this paper selected 8 extreme climate indices and analyzed the inter-annual and seasonal change characteristics of glacier mass balance using the Mann-Kendall trend test method, and the relationship between glacier mass balance and extreme climate and its response to extreme climate change were explored using the correlation analysis method. The main conclusions are as follows:

- (1) From 1980 to 2020, the mass balance of UG1 showed a downward trend, and the mass loss intensified. The accumulated mass balance value was $-19,776$ mm w.e., and the average annual value was -482 mm w.e.a⁻¹ in the 41 years studied. The mutation analysis showed that the mutation point occurred around 1994, and the mass balance of UG1 was more negative after 1994. The glacier mass balance in the second stage (1994–2020) was about twice that in the first stage (1980–1993). In the same period, the mass balance changes of UG1 were different in different seasons. The summer mass balance had a large inter-annual change and a significant downward trend. The average annual mass balance was -696 mm w.e.a⁻¹. The inter-annual change of the winter mass balance was small and showed a slight upward trend, and the average annual mass balance was 154 mm w.e.a⁻¹.

- (2) From 1980 to 2020, in the extreme climate index changes in the region where UG1 is located, only TX90p and TX10p changed significantly, and the change trends of the two were opposite. TX90p showed a notable increase trend and TX10p showed a marked decrease trend. The extreme precipitation index changed prominently and showed an increase trend. From 1994 to 2020, only TX10p and DTR showed a distinct decrease trend in extreme temperature indices, while only SDII showed a noteworthy increase trend in extreme precipitation.
- (3) From 1980 to 2020, the glacier mass balance was substantially correlated with the extreme temperature indices (TX90p, TXx) but not with the extreme precipitation indices. On the seasonal scale, the summer mass balance was dramatically correlated with the extreme temperature indices (TX90p, TX10p, TXx) but not the extreme precipitation index. The correlation coefficient between glacier mass balance and the extreme precipitation index R95p and winter precipitation was between 0.36 and 0.40 ($p < 0.05$), but there was no marked correlation between winter mass balance and extreme temperature indices.

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