Glacier mass balance and its impacts on streamflow in a typical inland river basin in the Tianshan Mountains, northwestern China (postprint)

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Abstract

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m3, accounting for 18.56% of the total streamflow. We found that the annual streamflow in different catchments in the Urumqi River Basin had a strong response to the changes in glacier mass balance, especially from July to August, and the glacier meltwater runoff increased significantly. In summary, it is quite possible that the results of this research can provide a reference for the study of glacier water resources in glacier-recharged basins in arid and semi-arid areas.

Full Text

Glacier Mass Balance and Its Impacts on Streamflow in a Typical Inland River Basin in the Tianshan Mountains, Northwestern China

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Abstract

Glaciers are known as natural "solid reservoirs" and play a dual role in water resource composition and river runoff regulation in arid and semi-arid regions of China. In this study, we used in situ observation data from Urumqi Glacier No. 1 in Xinjiang Uygur Autonomous Region, combined with meteorological station data and a digital elevation model, to develop a distributed degree-day model for glaciers in the Urumqi River Basin. This model simulated glacier mass balance processes and quantified their effects on streamflow during 1980–2020. The results indicate that mass loss and the equilibrium line altitude (ELA) of glaciers showed increasing trends over the past 41 years, with average mass balance and ELA being −0.85 ($\pm$0.32) *m w.e./a (meter water − equivalent per year) and* 4188 *m a.s.l., respectively. Glacier mass loss increased significantly during* 1999–2020, *pr* m^3, accounting for 18.56% of total streamflow. We found that annual streamflow in different catchments of the Urumqi River Basin responded strongly to changes in glacier mass balance, particularly from July to August, with glacier meltwater runoff increasing significantly. In summary, these research results can provide a valuable reference for studying glacier water resources in glacier-recharged basins in arid and semi-arid regions.

Keywords: glacier mass balance; glacier meltwater runoff; glacier modelling; Urumqi River Basin; Tianshan Mountains

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1 Introduction

Mountain glaciers, often called the "world' s water tower," are vital water resources for maintaining ecological environments and ensuring residential water availability \cite{Li_{2018}, Deng_{2019}, Immerzeel_{2019}}. The total glacier area in China is approximately 5.18$×10^{4}$ km^2, accounting for 7.10% of the world' s mountain glacier area \cite{Xing_{2018}}. With climate warming, these glaciers are retreating at an accelerated rate \cite{Huai_{2014}, Huai_{2018}, Xu_{2020}, Bhattacharya_{2021}}. Glaciers are mainly distributed in arid and semi-arid areas of northwestern China, where their meltwater accounts for 25%–29% of surface runoff. They play a pivotal role in water resource composition and are decisively significant to ecosystems in these arid regions. If warming continues, glacier meltwater will further increase surface runoff in mountains \cite{Li_{2018}, Cai_{2021}}. Most studies have shown that compared with changes in glacier area and length, glacier surface mass balance serves as a more crucial bridge linking climate change with glacier dynamics and hydrology, becoming a significant "indicator" of climate change \cite{Bolch_{2012}}. Therefore, under the background of climate change, researching inter-annual and annual variations in glacier mass balance is of great significance for understanding changing water resource patterns, maintaining sustainable agricultural development and ecosystem stability, and informing water resource management and disaster prevention in arid and semi-arid northwestern China \cite{Li_{2018}}.

Among several methods for quantifying glacier mass balance, traditional glaciological methods (stakes or snow pit measurements) can achieve higher accuracy \cite{Bentley_{2012}}. However, such fieldwork is extremely difficult due to high altitudes and harsh weather conditions in mountainous regions. Recently, geodetic technology using remote sensing datasets has largely replaced glaciological methods \cite{Brun_{2017}, Xu_{2017}, Bhattacharya_{2021}, Li_{2021}, Wang_{2021}}. Nevertheless, geodetic technology cannot estimate annual or inter-annual changes in glacier mass balance because it is constrained by uncertainties in sensor and satellite data \cite{Anant_{2018}}. Modelling, as another technical approach for evaluating glacier mass balance, has evolved from degree-day models to complex energy balance models. While energy balance models can describe physical processes on glacier surfaces in detail, they are limited by observations and have difficulty calculating related energy fluxes because vertical profile data for cloud cover, wind speed, humidity, and temperature are not readily available. In contrast, the degree-day model is based on the empirical relationship between snow or ice melting and positive accumulated temperature near the surface \cite{Hock_{2003}}, with temperature data being widely available and easy to interpolate. Therefore, degree-day models have been widely used to reconstruct glacier mass balance \cite{Braithwaite_{2000}, Slangen_{2016}, Johannesson_{2017}, Zhu_{2020}, Geck_{2021}, Zhang_{2021}}, and their simulation accuracy is usually better than that of energy balance models at the basin scale \cite{Hock_{2003}}.

The Urumqi River Basin is located in arid and semi-arid areas of northwestern China and serves as the major water source for Urumqi City, the capital of Xinjiang Uygur Autonomous Region. The basin is a typical glacier-replenishment-type basin \cite{Liu_{2019}}. Glacier meltwater is important for agricultural construction and economic development in Urumqi City and is crucial for maintaining the fragile ecological balance and socioeconomic sustainable development of the region. Due to global warming, glaciers in the Urumqi River Basin are generally in a state of retreat \cite{Huai_{2018}}. However, previous glacier research in the basin mainly focused on glacier area changes or mass balance variations of Urumqi Glacier No. 1 (UG1) in the headwaters \cite{Xu_{2017}, Huai_{2018}, Li_{2021}}. Therefore, studying glacier mass balance at the whole basin scale is urgently needed. For these reasons, this study, based on mass balance data from UG1 and meteorological and hydrological data, established a distributed degree-day model with 1-day temporal resolution and 30-m spatial resolution to reconstruct glacier mass balance and ELA in the Urumqi River Basin during 1980-2020. Additionally, we evaluated the contributions of glacier meltwater runoff to streamflow in typical glacier-recharged basins and discussed the relationships among glaciers, climate, and streamflow. Our study can provide scientific guidance and decision-making support for government responses to glacier change and its impacts.

2 Study Area

The Urumqi River Basin (43°00 -44°07 N, 86°45 -87°56 E) is situated on the northern slope of the Tianshan Mountains in China, covering an area of 4684 km^2. The basin originates from the Tanger II peak and extends northward through Urumqi City, with a total length of 214 km before disappearing in the northwestern Gurbantunggut Desert \cite{Saydi_{2019}}. The area above the Yingxiongqiao hydrological station in the upper reaches, which provides vital water resources for Urumqi City, was selected as the research area with a drainage area of 1088 km^2 (Fig. 1). The glacier area in the river basin is 33.29 km^2, accounting for approximately 3.06% of the total drainage area. Glaciers are distributed between 3400 and 4500 m a.s.l., with more than 80% concentrated between 3700 and 4200 m a.s.l. (Fig. 1c). Under the influence of climate warming, glaciers are melting rapidly, resulting in increased glacier meltwater runoff in the upper reaches of the Urumqi River Basin \cite{Huai_{2018}}.

UG1 (43°06 N, 86°49 E) is located in the source region of the Urumqi River Basin (Fig. 1b) and is a north-facing valley glacier. Due to glacier melting, UG1 separated into eastern and western branches in 1993, with an area of 1.558 km^2 in 2015. UG1 has been monitored since 1959 and serves as one of the reference glaciers of the World Glacier Monitoring Service (WGMS) and a reference glacier in Central Asia.

The Urumqi River Basin is situated in the hinterland of the Eurasian continent and has a typical temperate continental climate influenced by the westerlies. As shown in Figure 2, temperature and precipitation at the Daxigou weather station showed increasing trends. The average annual temperature and precipitation during 1980-2020 were -4.7°C and 493 mm, respectively. Generally, 77% of precipitation occurred from May to August. In winter, temperature is controlled by the Siberian anticyclonic circulation, resulting in low temperatures and less precipitation \cite{Li_{2007}}.

3 Data and Methods

3.1 Meteorological and Area Data

To run the model, we obtained daily temperature and precipitation data from the Daxigou weather station in the Urumqi River Basin from 1979 to 2020 (Fig. 1; Table 1). The weather station is situated in the river source region and belongs to the China Meteorological Administration (http://data.cma.cn). Additionally, we used data from an automatic weather station (AWS) located at 3835 m a.s.l. in the basin source, which has 30-minute scale observation records of temperature and precipitation.

Considering that variations in glacier area affect mass balance calculations on long time scales during 1980–2020, we divided the glacier boundary used in the degree-day model into two periods: the glacier boundary during 1980–2000 was extracted from a Landsat TM image from 1991, and the boundary during 2001–2020 was taken from a Landsat TM image from 2010 (http://www.usgs.gov/). To reduce the influence of clouds and snow on glacier boundary extraction, we selected satellite images under cloud-free conditions. The digital elevation model (DEM) used ASTER GDEM2.0 data with 30-m spatial resolution from the Geospatial Data Cloud (http://www.gscloud.cn/), primarily used to obtain altitude information of the glaciers.

3.2 Mass Balance Data

In the study region, only one glacier has surface mass balance obtained through field observations, located at the source of the Urumqi River (Fig. 1). UG1 is the longest-observed glacier in China and is crucial for understanding glacier melting mechanisms, hydrological cycles, and climate change in the Urumqi River Basin. Mass balance data were obtained from WGMS and annual reports of the Tianshan Glaciological Station, Chinese Academy of Sciences. To ensure data continuity, we used monthly mass balance data of UG1 from 2001 to 2014 and annual mass balance data from 1980 to 2018 to calibrate and validate the model, as mass balance data from 1966 to 1979 were reconstructed by previous models.

3.3 Runoff Data

The catchment areas controlled by the Yingxiongqiao, Houxia, Zongkong, and UG1 hydrological stations are 1088.00, 400.00, 28.66, and 3.46 km^2, respectively (Fig. 1; Table 1). To investigate the basic relationship between glaciers and runoff, we selected annual and monthly runoff data from these four hydrological stations. The dataset was obtained from the China Hydrological Yearbook and the Tianshan Glaciological Station, Chinese Academy of Sciences.

Table 1 Meteorological and hydrological stations in this study

Station	Latitude	Longitude	Elevation (m)	Observed period (yy-mm-dd–yy-mm-dd)
Meteorological station				
Daxigou	43°06 N	86°50 E	3539	1979-01-01–2020-12-31
AWS	43°07 N	86°48 E	3835	2018-06-01–2019-09-30
Hydrological station				
Yingxiongqiao	43°22 N	87°12 E	1920	1980-01-01–2011-12-31
Houxia	43°12 N	87°07 E	2160	1980-01-01–2011-12-31
Zongkong	43°07 N	86°52 E	3400	1980-01-01–2011-12-31
UG1	43°06 N	86°49 E	3693	1980-01-01–2011-12-31

Note: AWS, automatic weather station; UG1, Urumqi Glacier No. 1.

4 Model Description and Validation

4.1 Model Description

A spatially distributed degree-day model \cite{Hock_{2003}} and accumulation model were used to calculate glacier mass balance in the Urumqi River Basin. The main components include glacier melting, snow melting, snow accumulation, and refreezing. We used daily air temperature and precipitation from the Daxigou weather station, combined with temperature lapse rates and precipitation gradients, to drive the model. We defined a mass balance year from 1 September in one calendar year to 31 August in the following year \cite{Wu_{2011}}. The formula is as follows:

$$B = \int_{t_1}^{t_2} (f \cdot M_{snow/ice} + A_s) dt$$

where B (m w.e.) is glacier mass balance; f is the refreezing ratio; $M_{snow/ice}$ (m w.e.) is the ablation amount of snow or ice; A_s (m w.e.) is snow accumulation; and dt is the simulation period.

$M_{snow/ice}$ is calculated by a degree-day model based on the empirical relationship between ice or snow melting amount and air temperature \cite{Braithwaite_{2000}, Hock_{2003}}:

$$M_{snow/ice} = \begin{cases} DDF_{snow/ice} \cdot (T - T_t) & \text{if } T > T_t \\ 0 & \text{if } T \leq T_t \end{cases}$$

where DDF (mm/(d · °C)) is the degree-day factor. Because ice and snow surfaces have different albedos regarding solar radiation, this factor differs for ice and snow \cite{Zhang_{2017}, Tsai_{2018}}. T (°C) is the extrapolated daily average temperature at each elevation on the glacier surface, and T_t (°C) is the threshold temperature for ice and snow melting. If $T > T_t$ and snow on the glacier surface is completely melted, the remaining temperature is used to melt ice.

A_s is modeled from precipitation data using a dual-threshold temperature model to distinguish between rain and snow. Based on temperature during precipitation, the process can be divided into three possibilities: rainfall, snowfall, and sleet \cite{Berghuijs_{2014}, Hantel_{2015}}. When T is higher than T_r (critical temperature of rain), it is rainfall; when T is between T_s (critical temperature of snow) and T_r, it is sleet, and within this range, the percentage of snow and rain of total precipitation is obtained by linear interpolation; and when T is lower than T_s, it is snowfall. This study did not consider snow redistribution caused by wind or avalanches. A_s is calculated by:

snow/icest[(1)],tBfMAd   snow/icettsnow/icet(DDF„0,)TTTTMTT

where P (mm) is precipitation; and T_r and T_s (°C) are the critical temperatures for rain and snow conversion, respectively.

Glacier meltwater runoff (R, m^3) is described as \cite{Yang_{1981}}:

$$R = \int_{t_1}^{t_2} (B + P) \cdot A dt$$

where A (km^2) is glacier area.

4.2 Model Parameters and Calibration

Our modeling method requires air temperature lapse rates (TLR), altitude precipitation gradients (APG), DDF values for snow and ice, T_r, and T_s. However, since glaciers in the Urumqi River Basin are mainly located at high elevations with limited measured meteorological and glacier data, determining these parameters is challenging and may substantially affect model performance.

In glacier mass balance simulation, temperature and precipitation are the principal input parameters controlling snow/rainfall distribution, which affect snow cover and glacier melting \cite{Shea_{2015}}. Studies have shown that temperature and precipitation in the Urumqi River Basin vary greatly with elevation across different months \cite{Li_{2019}}. Therefore, temporal variability of TLR and APG should be considered in glacier mass balance estimation. We calculated monthly average TLR and APG based on data from meteorological stations at different elevations in the basin (Fig. 1) and used these values to extrapolate temperature and precipitation from the Daxigou weather station to all glaciers. Details of TLR and APG were provided by Li et al. (2019).

We used a degree-day model to calculate snow and ice melting on glacier surfaces based on the empirical relationship between melting amount and temperature \cite{Braithwaite_{2000}, Hock_{2003}}. In the calculation process, if snow exists on the glacier surface, melting is calculated as a function of DDF_{snow}. When snow is depleted, ice melting is calculated as a function of DDF_{ice}. Some studies deduced DDF values for ice and snow based on field mass balance data from UG1. Generally, DDF_{ice} varies from 5.6 to 8.9 mm/(d·°C), and DDF_{snow} varies from 2.7 to 3.1 mm/(d·°C) \cite{Liu_{1998}, Huintjes_{2010}, Wu_{2011}}. On this basis, since glacier mass loss is mainly concentrated in summer (May–August), we calibrated parameters using measured summer mass balance data of UG1 from 2001 to 2014, finding that DDF_{ice} and DDF_{snow} values were 7.3 and 2.9 mm/(d·°C), respectively.

In glacier accumulation areas, the melting process is complex. Because the accumulation area surface comprises grainy snow and new snow, grainy snow changes and merges during ablation, and meltwater penetrates the grainy snow layer. Part of the grainy snow refreezes to form "internal recharge," while the remainder is lost as ice runoff. Previous studies found that meltwater refreezing of UG1 accounts for only 1.0% \cite{Wang_{2020}}. UG1 is located in the source area of the Urumqi River Basin, and its local climate and surrounding topography are well represented in the basin. Moreover, glaciers in the Urumqi River Basin are "summer accumulation" continental glaciers \cite{Shi_{2000}} with high ice temperatures in summer, and less meltwater forms "internal supply" through refreezing. Therefore, meltwater refreezing in the whole basin could be ignored. Research on threshold temperatures for ice and snow melting and rain/snow division is extremely limited in the Tianshan Mountains of China. Consequently, we adopted the most commonly used values: $T_t = 0°C$, $T_r = 2°C$, and $T_s = 0°C$ \cite{Hock_{2003}, Huintjes_{2010}, Zhang_{2017}, Azam_{2020}}. All parameter values are shown in Table 2.

Table 2 Selected values of parameters used in the glacier mass balance model and the range of parameters used to estimate errors

Model parameter	Value used in model	Range used for error estimation	Error value (m w.e./a)
Air temperature lapse rate (TLR) (°C/m)	Mean monthly TLR	-	-
Altitude precipitation gradient (APG) (mm/m)	Mean monthly APG	-	-

Model parameter	Value used in model	Range used for error estimation	Error value (m w.e./a)
DDF for ice (mm/(d · °C))	7.3	6.3–8.3	±0.21
DDF for snow (mm/(d · °C))	2.9	2.4–3.4	±0.08‖Thresholdtemperatureforsnow/icemelt (°C)

Note: - means no value. DDF, degree-day factor.

4.3 Model Validation

Due to scarce meteorological and glacier mass balance observation data in the Urumqi River Basin, verifying our model' s accuracy is challenging. The validation process is crucial for model performance in truly simulating glacier mass balance. Therefore, we validated our modeling method based on available measured datasets. First, to ensure accuracy of TLR and APG inputs, we used data generated from the Daxigou weather station combined with monthly TLR and APG to compare and verify observations from the AWS in the glacier area (Fig. 1). Then, we simulated the annual mass balance of UG1 using our model and compared it with measured values (1980–2018) to evaluate the model' s ability to reproduce annual mass balance changes.

Additionally, the determination coefficient (R^2) and root mean square error (RMSE) were used to calibrate and verify model performance. R^2 values indicate the model' s ability to simulate glacier mass balance changes, while RMSE manifests the model' s ability to calculate glacier mass balance magnitude.

4.4 Model Performance

We first evaluated forcing data generated using monthly TLR and APG from the Daxigou weather station against AWS observations. The AWS measurements of air temperature during 2018–2019 were reproduced well (Fig. 3). Daily average temperature changes simulated by the model closely matched observed data from the AWS ($R^2 = 0.98$; RMSE = 2.43°C) (Fig. 3a). Precipitation was also well simulated, with good agreement between simulated monthly precipitation and observed data during 2018-2019 ($R^2 = 0.99$; RMSE = 5.10 mm) (Fig. 3b). Therefore, temperature and precipitation generated by this method are in good accordance with observations and can be used as model parameters.

As shown in Figures 4–5, our method performs well during calibration and validation. Simulated and observed mass balance values of UG1 during the calibration period from 2001 to 2014 are shown in Figure 4a, indicating that selected parameters provide good simulation results for monthly mass balance changes. Overall, simulated monthly mass balance values correlated significantly with measured values ($R^2 = 0.78$; $n = 52$; $P < 0.01$; RMSE = 0.10 m w.e.). From the perspective of different months (Fig. 5), simulated mass balance values from May to August agreed well with measured values, with R^2 values exceeding 0.50. The June mass balance simulation showed the highest correlation with measured values ($R^2 = 0.75$; $n = 13$; $P < 0.01$), while remaining months showed relatively lower correlations, possibly resulting from differences in ice and snow DDF values across months. Figure 4b shows simulated and observed annual mass balance values of UG1 during the validation period. Analyses reveal that simulated annual mass balance values agree well with observed values and show significant positive correlation ($R^2 = 0.64$; $n = 39$; $P < 0.01$; RMSE = 0.22 m w.e.). The simulated annual average mass balance is -0.46 m w.e./a, slightly higher than the observed value (-0.49 m w.e./a). Based on these results, our model can reproduce observations well and explain mass balance changes, giving us confidence in using it to estimate mass balance of other glaciers in the Urumqi River Basin.

4.5 Error Evaluation

To enhance understanding of long-term regional glacier changes, we used the modeling method to calculate glacier mass balance in the Urumqi River Basin. Most modeling involves calibration procedures where parameters are adjusted to maximize agreement between simulated and observed values, representing a compromise between methodological requirements and database availability. With only one glacier in the basin having field-observed data, the model uses data from a single glacier for parameter correction, which may limit reliability and representativeness of glacier mass balance for the entire basin, introducing some uncertainty.

Model error sources mainly depend on selected parameters. To quantify uncertainty in annual mass balance caused by parameters, we reran the model by changing parameters one at a time while keeping others unchanged. Since seasonal changes in TLR and APG were considered and their accuracy verified, their uncertainty was not included. Because a double-threshold temperature model was adopted for rain/snow separation, uncertainty in separation thresholds (T_r and T_s) was ignored. When the reasonable parameter range is unknown, the variation range for the ice and snow melting threshold (T_t) should be set to $±$1°C, a common method for estimating parameter uncertainty \cite{Tong_{2016}, Azam_{2019}}. The parameter range used is shown in Table 2. Results show that DDF_{ice} has the most significant effect on glacier mass balance in the Urumqi River Basin (Table 2), playing a vital role in simulation. In this study, error transitivity was used to sum all parameter uncertainties, estimating glacier mass balance uncertainty. Through comprehensive evaluation, uncertainty in annual glacier mass balance for the whole region is $±$0.32 m w.e./a.

5 Results

5.1 Glacier Mass Balance Since 1980

Glacier mass balance is a direct and reliable index reflecting glacier state. Using a distributed degree-day model, we simulated glacier mass balance in the Urumqi River Basin during 1980-2020. Figure 6 describes simulated glacier mass balance values. Results showed that multi-year cumulative mass balance during the study period was -34.68 ($±13.12)*mw.e., withanannualaveragemassbalanceof*−0.85(±0.32)*mw.e./a.Comparedwithglaciermassbalanc*
< 0.01), *characterizedbyobviousinter−annualvariation*, *withamaximumof*−0.16(±0.32)*mw.e.*(1993)*andamin*
m w.e. (2015). According to the nonparametric Mann-Kendall test, the melting process showed an accelerated trend and shifted to more negative equilibrium since 1998.

Therefore, we divided glacier mass balance changes into two stages according to the abrupt change point (Fig. 6). In the first stage (1980-1998), annual mass balance ranged from -1.18 to -0.16 m w.e., with an average annual value of -0.62 ($±0.32)*mw.e./a*, *showingnoteworthyfluctuationcharacteristics.Inthesecondstage*(1999–2020), *annualmass*
m w.e./a. Compared with the first stage, glacier mass loss in the second stage was more intense, with volume loss about 1.7 times that of the first stage. This accelerated mass loss was also confirmed by observable glacier UG1 in the study area \cite{Huai_{2020}}.

To further analyze intra-annual variation, we reconstructed seasonal glacier mass balance variations (Fig. 6). Inter-annual variation in summer mass balance decreased, showing a prominent downward trend ($P < 0.01$) during 1980-2020. Over 41 years, summer mass balance was negative (-0.96 m w.e./a), with inter-annual fluctuation highly consistent with annual mass balance ($R^2 = 0.98$, $P < 0.01$). The average summer mass balance in the second stage (-1.15 m w.e./a) was nearly 1.6 times that of the first stage (-0.74 m w.e./a), indicating significantly increased mass balance loss rates after 1998. This phenomenon was mainly due to climate warming and precipitation occurring mainly from May to August, accounting for about 77% of annual precipitation in the Urumqi River Basin (Fig. 7). Therefore, as temperature increases, the proportion of precipitation also increases, and decreased new snow reduces glacier surface albedo, leading to greater melting \cite{Fujita_{2008}, Jia_{2020}}. By comparison, over 41 years, inter-annual variation in winter mass balance was small (0.11 m w.e./a), with a slightly downward overall trend. The average winter mass balance in the first stage (0.12 m w.e./a) was slightly higher than in the second stage (0.10 m w.e./a), showing no significant periodic change.

From monthly glacier mass balance changes (Figs. 7-8), the accumulation period (September-May of the following year) was long in the study area but not remarkable (0.14 m w.e.). Compared with other months, the most obvious accumulation occurred in May due to increased precipitation. However, the ablation period (June-August) was short but serious (-0.96 m w.e.). Glaciers began entering the loss state in early June, showing a gradually increasing ablation trend.

Ablation was most intense in July, influenced by temperature. During this period, overall temperature rise on glaciers changed greatly, leading to striking differences in monthly mass balance. Generally, annual mass balance changes showed "weak accumulation and strong ablation" characteristics.

Glacier mass balance changes have notable vertical zonal characteristics due to significant differences in hydrothermal combinations across elevation zones \cite{Wang_{2016}}. To explore elevation profile characteristics, we determined the spatial average of mass balance at 100-m height intervals (Fig. 9a). Over 41 years, the maximum negative balance (-2.85 m w.e.) of annual average mass balance appeared at the glacier terminus (3400-3500 m a.s.l.). When elevation increased to 4100-4200 m a.s.l., it turned positive, with maximum positive balance (0.47 m w.e.) at 4400-4500 m a.s.l. Glacier advance or retreat is directly determined by ELA changes. Compared with other parameters (such as area or length), ELA change most directly reflects climate change. Therefore, based on annual mass balance of each elevation zone, we calculated ELA of glaciers in the Urumqi River Basin. During 1980-2020, ELA showed an upward fluctuating trend (Fig. 9b), with an average value of 4188 m a.s.l. The highest elevation (4378 m a.s.l.) appeared in 2015, and the lowest (3969 m a.s.l.) in 1993, indicating 2015 and 1993 were the most intense and weakest melting years, respectively, consistent with annual mass balance estimates. Similar to height changes in simulated mass balance, ELA of UG1 also showed a fluctuating upward trend overall \cite{Huai_{2020}}.

5.2 Climate Change, Mass Balance and ELA

Over the past 41 years (1980-2020), glaciers in the Urumqi River Basin experienced serious mass loss (Fig. 6), especially in the last 20 years. These findings align with Huai et al. (2018), who analyzed accelerated glacier retreat over the past 50 years using topographic maps, Landsat series images, SPOT5 images, Google Earth, and meteorological data. As shown in Figure 2, basin air temperature had a significant upward trend during 1980-2020, with a rate of 0.43°C/10a. In particular, annual mean temperature during 1999-2020 increased by 1.00°C compared with 1980-1998. Meanwhile, annual precipitation showed a slight increasing trend, with precipitation during 1999-2020 increasing by nearly 75.48 mm compared with 1980-1998 (Fig. 2). Temperature variation was significant, but precipitation change was less obvious, which may have greatly impacted glacier accumulation.

For glacier mass balance, snow/ice melting is highly correlated with surface air temperature, commonly exhibited as cumulative positive temperature, while accumulation is mainly based on solid precipitation \cite{Braithwaite_{1995}, Hock_{2003}}. Compared with annual average temperature and total precipitation, cumulative positive temperature and solid precipitation in the mass balance can more clearly reveal the reciprocity between glacier mass balance and local climate change. Therefore, we analyzed changing trends of cumulative positive temperature and solid precipitation during 1980-2020. Cumulative positive temperature shows a significant upward trend ($P < 0.01$), especially from 1999 to 2020 (Fig. 10a). Solid precipitation had a slight increasing trend without obvious periodic fluctuation (Fig. 10b).

We further analyzed impacts of positive accumulated temperature changes on glacier mass balance and ELA. The number of cumulative positive temperature days (CPTD) in the second stage (1999-2020) increased more prominently than in the first stage (1980-1998), and multi-year daily average temperature in the second stage was notably higher (Fig. 11). Under climate warming, CPTD in the second stage increased at 0.32 d/a, directly prolonging the ablation period and increasing glacier mass loss. Cumulative positive temperature in the Urumqi River Basin was highly synchronous with inter-annual changes in glacier annual mass balance and ELA, with R^2 values of 0.83 ($P < 0.01$) and 0.65 ($P < 0.01$), respectively. This shows that glacier changes in the Urumqi River Basin have been mainly controlled by temperature in recent years.

5.3 Influence of Glacier Meltwater Runoff Change on Streamflow

In arid and semi-arid western China, mountain glaciers are a vital component of surface water resources. Glacier meltwater runoff provides valuable freshwater resources and river runoff \cite{Jansson_{2003}}. In recent decades, almost all glaciers in the Urumqi River Basin have experienced considerable retreat \cite{Huai_{2018}}, with accelerated mass loss in recent years (Fig. 5). With regional population growth and rapid economic development, local water resource demand will continue increasing \cite{Org_{2015}, Pritchard_{2017}}. Therefore, accelerated glacier melting will definitively impact regional water resource utilization. To explore glacier ablation impacts on streamflow, this study used the method proposed by Yang (1981) to estimate glacier meltwater contributions to streamflow in different catchments.

Regarding seasonal distribution (Fig. 12), glacier meltwater runoff and streamflow in different catchments were both concentrated in summer, especially July and August, significantly synchronized with glacier mass balance changes ($R^2 = 0.98$, $P < 0.01$). Seasonal variation showed a single-peak distribution, with high summer temperatures dominating glacier melting and summer rainfall accounting for about 77% of annual precipitation. In contrast, winter (September–April of the following year) had low temperatures and less glacier melting. Figure 13a illustrates annual streamflow, glacier meltwater runoff, and their contributions in the Urumqi River Basin during 1980-2011. The average annual streamflow was 2.59$×10^{8}$ m^3, with glacier meltwater runoff of 0.48$×10^{8}$ m^3, accounting for approximately 18.56% of streamflow (Table 3). Notably, in years with relatively lower streamflow (e.g., 1986 and 2001), glacier meltwater runoff accounted for a higher percentage. Therefore, although glacier coverage in the Urumqi River Basin is relatively small, glacier meltwater runoff still constitutes a considerable proportion of streamflow, indicating it is a crucial water resource in this arid and semi-arid region with extremely limited water supplies.

To further explore contributions of different glacier cover areas to runoff, we constructed a linear regression model between glacier area proportion and glacier meltwater runoff proportion in different basin sections (Fig. 13b). Qualitatively, there is a clearly positive correlation between glacier meltwater runoff proportion and glacier area proportion ($R^2 = 0.98$; $P < 0.01$), indicating that larger glacier area proportions correspond to larger meltwater runoff proportions. However, the actual proportion of glacier meltwater in basin streamflow is not simply affected by glacier area proportion but also by many factors such as temperature, precipitation, evaporation, and base flow. Therefore, in arid and semi-arid areas, specific proportions of glacier meltwater runoff in different regions or basins require further calculation.

Table 3 Areas of glacier and catchment, average annual streamflow, and glacier meltwater runoff in the Urumqi River Basin

Catchment	Glacier area (km^2)	Catchment area (km^2)	Streamflow ($\times 10^{4}$ m^3)	Glacier meltwater runoff ($\times 10^{4}$ m^3)
Yingxiongqiao	33.29	1088.00	25,868.75	4,800.00
Houxia	16.54	400.00	13,992.27	2,384.00
Zongkong	2.89	28.66	1,002.34	416.00
UG1	1.56	3.46	121.03	225.00

Note: UG1, Urumqi Glacier No. 1.

6 Conclusions

In this study, a distributed degree-day model with 1-day temporal resolution and 30-m spatial resolution was established by combining meteorological and remote sensing data. Based on this model, we reconstructed and analyzed glacier mass balance changes in the Urumqi River Basin during 1980–2020, discussing factors affecting glacier mass balance and the glacier-runoff relationship. Model results were well verified against UG1, confirming the model's ability to estimate glacier mass balance in the basin.

Results show that glacier mass loss and ELA in the Urumqi River Basin increased during 1980–2020. During the simulation period, average annual mass balance was -0.85 ($\pm$0.32) m w.e./a, slightly higher than average glacier mass loss in the Tianshan Mountains, with average ELA at 4188 m a.s.l. Especially in recent decades, glacier mass loss increased significantly, with average annual mass balance during 1999–2020 being almost 1.7 times that during 1980–1998 due to increased accumulated positive temperature and extended ablation seasons. Annual glacier mass balance changes showed most obvious accumulation in May due to increased precipitation and most intense ablation in July due to temperature influence, presenting overall "weak accumulation and strong ablation" characteristics. Throughout the study period, streamflow changes were heavily synchronized with glacier mass balance changes.

This study analyzed glacier mass balance changes in a typical glacier-recharged basin in arid and semi-arid areas and estimated glacier meltwater runoff contributions to streamflow. The results provide a basis for better understanding glacier-climate relationships and their impacts on streamflow.

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References

Anant K, Negi H S, Kumar K, et al. 2018. Estimation of recent changes in thickness and mass balance of the Patsio glacier in the Great Himalayan region using geodetic technique and ancillary data. *Geocarto International*, 35(1): 47-63.

Azam M F, Wagnon P, Vincent C, et al. 2019. Snow and ice melt contributions in a highly glacierized catchment of Chhota Shigri Glacier (India) over the last five decades. *Journal of Hydrology*, 574: 760-773.

Azam M F, Srivastava S. 2020. Mass balance and runoff modelling of partially debris-covered Dokriani Glacier in monsoon-dominated Himalaya using ERA5 data since 1979. *Journal of Hydrology*, 590: 125432, doi:10.1016/j.jhydrol.2020.125432.

Bentley C R. 2012. Glossary of glacier mass balance and related terms. *Arctic, Antarctic and Alpine Research*, 44(2): 256-258.

Berghuijs W R, Woods R A, Hrachowitz M. 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change*, 4(7): 583-586.

Bhattacharya A, Bolch T, Mukherjee K, et al. 2021. High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. *Nature Communications*, 12(1): 4133-4133.

Bolch T, Kulkarni A V, Kb A, et al. 2012. The state and fate of Himalayan glaciers. *Science*, 336(6079): 310-314.

Braithwaite R J. 1995. Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling. *Journal of Glaciology*, 41(137): 153-160.

Braithwaite R J, Zhang Y. 2000. Sensitivity of mass balance of five Swiss glaciers to temperature changes assessed by tuning a degree-day model. *Journal of Glaciology*, 46(152): 7-14.

Brun F, Berthier E, Wagnon P, et al. 2017. A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nature Geoscience*, 10(9): 668-673.

Cai X R, Li Z Q, Zhang H, et al. 2021. Vulnerability of glacier change in the Tianshan Mountains region of China. *Journal of Geographical Sciences*, 31(10): 1469-1489.

Deng H J, Chen Y N, Li Y. 2019. Glacier and snow variations and their impacts on regional water resources in mountains. *Journal of Geographical Sciences*, 29(1): 84-100.

Fujita K. 2008. Effect of precipitation seasonality on climatic sensitivity of glacier mass balance. *Earth and Planetary Science Letters*, 276(1-2): 14-19.

Geck J, Hock R, Loso M G, et al. 2021. Modeling the impacts of climate change on mass balance and discharge of Eklutna Glacier, Alaska, 1985-2019. *Journal of Glaciology*, 67(265): 909-920.

Hantel M, Ehrendorfer M, Haslinger A. 2015. Climate sensitivity of snow cover duration in Austria. *International Journal of Climatology*, 20(6): 615-640.

Hock R. 2003. Temperature index melt modelling in mountain areas. *Journal of Hydrology*, 282(1): 104-115.

Huai B J, Li Z Q, Wang S J, et al. 2014. RS analysis of glaciers change in the Heihe River Basin, Northwest China, during the recent decades. *Journal of Geographical Sciences*, 24(6): 993-1008.

Huai B J, Wang Y T, Li Z Q, et al. 2018. Glacier changes and its effect on water resources in Urumqi River Basin, Tianshan Mountains, China, from 1964 to 2014. *Arabian Journal of Geosciences*, 11(22): 716.

Huai B J, Sun W J, Wang J Y, et al. 2020. A long glacier mass balance record analysis in Chinese Urumqi Glacier No. 1 and the relationships with changes in large-scale circulations. *Arabian Journal of Geosciences*, 13(22): 1202.

Huintjes E, Li H L, Sauter T, et al. 2010. Degree-day modelling of the surface mass balance of Urumqi Glacier No. 1, Tian Shan, China. *The Cryosphere Discussions*, 4(1): 207.

Immerzeel W W, Lutz A F, Andrade M, et al. 2019. Importance and vulnerability of the world' s water towers. *Nature*, 577: 364-369.

Jóhannesson T, Sigurdsson O, Laumann T, et al. 2017. Degree-day glacier mass-balance modelling with applications to glaciers in Iceland, Norway and Greenland. *Journal of Glaciology*, 41(138): 345-358.

Jansson P, Hock R, Schneider T. 2003. The concept of glacier storage: a review. *Journal of Hydrology*, 282(1-4): 116-129.

Li H L, Wang P Y, Li Z Q, et al. 2021. An application of three different field methods to monitor changes in Urumqi Glacier No. 1, Chinese Tien Shan, during 2012-2018. *Journal of Glaciology*, 68(627): 41-53.

Li K M, Zhong X F, Jiang Y, et al. 2018. Study on vertical gradient change of air temperature and precipitation in Urumqi River basin during 1961-2016. *Journal of Glaciology and Geocryology*, 40(3): 607-615. (in Chinese)

Li Y, Li Z Q. 2020. Temporal and spatial characteristics of climate changes in the Urumqi River Basin of Tianshan Mountain over 50 years. *Meteorological and Environmental Research*, 1(12): 42-45.

Li Z Q, Li C J, Li Y F, et al. 2007. Preliminary results from measurements of selected trace metals in the snow-firn pack on Urumqi Glacier No. 1, eastern Tien Shan, China. *Journal of Glaciology*, 53(182): 368-373.

Li Z Q, Wang F T, Li H L, et al. 2018. Science and long-term monitoring of continental-type glaciers in arid region in China. *Bulletin of the Chinese Academy of Sciences*, 33(12): 1381-1390. (in Chinese)

Liu Y, Liu Y C, Jiao K Q, et al. 2019. Advances on water resources research in upper reaches of the Urumqi River since 1990. *Journal of Glaciology and Geocryology*, 41(4): 958-967. (in Chinese)

Liu S Y, Ding Y J, Wang N L, et al. 1998. Mass balance sensitivity to climate change of the glacier NO.1 at the Urumqi River head, Tianshan Mts. *Journal of Glaciology and Geocryology*, 20(1): 10-14. (in Chinese)

Org Z. 2015. World population and human capital in the twenty-first century. *Canadian Studies in Population*, 42(3-4): 91.

Pritchard H D. 2017. Asia' s glaciers are a regionally important buffer against drought. *Nature*, 545(7653): 169-174.

Saydi M, Ding J L, Sagan V, et al. 2019. Snowmelt modeling using two melt-rate models in the Urumqi River watershed, Xinjiang Uygur Autonomous Region, China. *Journal of Mountain Science*, 16(10): 2271-2284.

Shea J M, Immerzeel W W, Wagnon P, et al. 2015. Modelling glacier change in the Everest region, Nepal Himalaya. *The Cryosphere*, 9(3): 1105-1128.

Shi Y F, Liu S Y. 2000. Estimation on the response of glaciers in China to the global warming in the 21st century. *Chinese Science Bulletin*, 45(7): 668-672.

Slangen A, Church J A, Agosta C, et al. 2016. Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change*, 6(7): 701-705.

Tong K, Su F, Xu B. 2016. Quantifying the contribution of glacier meltwater in the expansion of the largest lake in Tibet. *Journal of Geophysical Research: Atmospheres*, 121(19): 11158-11173.

Tsai V C, Ruan X Z. 2018. A simple physics-based improvement to the positive degree day model. *Journal of Glaciology*, 64(246): 661-668.

Wang P P, Li Z Q, Xu C H, et al. 2021. Region-wide glacier area and mass budgets for the Shaksgam River Basin, Karakoram Mountains, during 2000-2016. *Journal of Arid Land*, 13(2): 175-188.

Wang P Y, Li Z Q, Schneider C, et al. 2020. A test study of an energy and mass balance model application to a site on Urumqi Glacier No. 1, Chinese Tian Shan. *Water*, 12(10): 2865, doi:10.3390/w12102865.

Wang S, Wang J, Pu J C. 2016. Application of a distributed degree-day model of glaciers in the upper reaches of the Beida River Basin. *Environmental Earth Sciences*, 75(6): 493.

Wu L H, Li H L, Wang L. 2011. Application of a degree-day model for determination of mass balance of Urumqi Glacier No. 1, eastern Tianshan, China. *Journal of Earth Science*, 22(4): 470-481.

Xing W C, Li Z Q, Zhang H, et al. 2018. Spatial-temporal variation of glacier resources in Chinese Tianshan Mountains since 1959. *Acta Geographica Sinica*, 72(9): 1594-1605. (in Chinese)

Xu C H, Li Z Q, Wang F T, et al. 2017. Using an ultra-long-range terrestrial laser scanner to monitor the net mass balance of Urumqi Glacier No. 1, eastern Tien Shan, China, at the monthly scale. *Journal of Glaciology*, 63(241): 1-11.

Xu L P, Li P H, Li Z Q, et al. 2020. Advances in research on changes and effects of glaciers in Xinjiang Mountains. *Advances in Water Science*, 31(06): 946-959. (in Chinese)

Yang Z N. 1981. The basic characteristics of runoff in the modern glaciation areas of China. *Scientia Sinica*, 4: 468-476. (in Chinese)

Zhang H, Li Z Q, Zhou P. 2021. Mass balance reconstruction for Shiyi Glacier in the Qilian Mountains, northeastern Tibetan Plateau, and its climatic drivers. *Climate Dynamics*, 56(3): 969-984.

Zhang Y, Enomoto H, Ohata T, et al. 2017. Glacier mass balance and its potential impacts in the Altai Mountains over the period 1990-2011. *Journal of Hydrology*, 553: 662-677.

Zhu M L, Yao T D, Xie Y, et al. 2020. Mass balance of Muji Glacier, northeastern Pamir, and its controlling climate factors. *Journal of Hydrology*, 590(195): 125447, doi:10.1016/j.jhydrol.2020.125447.

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