J Arid Land (2022) 14(4): 455–472
https://doi.org/10.1007/s40333-022-0012-1

Science Press   Springer-Verlag

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

PENG Jiajia[1,2], LI Zhongqin[1,3,4*], XU Liping[1,2*], MA Yuqing[1,2], LI Hongliang[3], ZHAO Weibo[3], FAN Shuang[4]

[1] College of Sciences, Shihezi University, Shihezi 832003, China;
[2] Xinjiang Production and Construction Corps Key Laboratory of Oasis Town and Mountain-basin System Ecology, Shihezi 832003, China;
[3] State Key Laboratory of Cryospheric Sciences/Tianshan Glaciological Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China;
[4] College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China

Abstract: Glaciers are known as natural "solid reservoirs", and they play a dual role between the composition of water resources and the river runoff regulation in arid and semi-arid areas of China. In this study, we used *in situ* observation data from Urumqi Glacier No. 1, Xinjiang Uygur Autonomous Region, in combination with meteorological data from stations and a digital elevation model, to develop a distributed degree-day model for glaciers in the Urumqi River Basin to simulate glacier mass balance processes and quantify their effect on streamflow during 1980–2020. The results indicate that the mass loss and the equilibrium line altitude (ELA) of glaciers in the last 41 years had an increasing trend, with the average mass balance and ELA being −0.85 (±0.32) m w.e./a (meter water-equivalent per year) and 4188 m a.s.l., respectively. The glacier mass loss has increased significantly during 1999–2020, mostly due to the increase in temperature and the extension of ablation season. During 1980–2011, the average annual glacier meltwater runoff in the Urumqi River Basin was 0.48×10^8 m^3, 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.

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

Citation: PENG Jiajia, LI Zhongqin, XU Liping, MA Yuqing, LI Hongliang, ZHAO Weibo, FAN Shuang. 2022. Glacier mass balance and its impacts on streamflow in a typical inland river basin in the Tianshan Mountains, northwestern China. Journal of Arid Land, 14(4): 455–472. https://doi.org/10.1007/s40333-022-0012-1

1 Introduction

As the "world's water tower", mountain glaciers are vital water resources in maintaining the ecological environment and ensuring residential water availability (Li et al., 2018; Deng et al., 2019; Immerzeel et al., 2019). The total area of glaciers in China is approximately 5.18×10^4 km^2, accounting for 7.10% of the world's mountain glacier area (Xing et al., 2018). With climate

*Corresponding author: LI Zhongqin (E-mail: lizq@lzb.ac.cn); XU Liping (E-mail: xlpalw@163.com)
Received 2022-01-06; revised 2022-03-20; accepted 2022-04-08

warming, these glaciers are retreating at an accelerated rate (Huai et al., 2014, 2018; Xu et al., 2020; Bhattacharya et al., 2021). Glaciers are mainly distributed in arid and semi-arid areas of northwestern China, and their melting water accounts for 25%–29% of the surface runoff. They play a pivotal role in the composition of water resources and are of decisive significance to the ecosystems in arid areas. If the climate continues to warm, glacier meltwater will further increase surface runoff in mountains (Li et al., 2018; Cai et al., 2021). Most studies have shown that compared with the changes in glacier area and length, glacier surface mass balance is a more crucial bridge of climate change with glacier dynamics and hydrology, and has become a considerable "indicator" of climate change (Bolch et al., 2012). Therefore, under the background of climate change, it is of great significance to research the inter-annual and annual changes of glacier mass balance to understand the changing pattern of water resources, maintaining sustainable agricultural development and ecosystem stability, as well as water resource management and disaster prevention in arid and semi-arid areas of northwestern China (Li et al., 2018).

Among several methods for quantifying glacier mass balance, the traditional glaciological methods (stakes or snow pits measurement method) can obtain a higher accuracy (Bentley, 2012). However, it is very difficult to carry out such fieldwork because of the high altitude and harsh weather conditions in the mountains. Recently, geodetic technology using remote sensing datasets has largely replaced glaciological methods (Brun et al., 2017; Xu et al., 2017; Bhattacharya et al., 2021; Li et al., 2021; Wang et al., 2021). Nevertheless, geodetic technology can't estimate the annual or inter-annual changes of the glacier mass balance, because it is confined by the uncertainty of sensor and satellite data (Anant et al., 2018). Modelling, as another technical approach to evaluate glacier mass balance, has evolved from a degree-day model to a complex energy balance model. The energy balance model can describe the physical processes on the glacier surface in detail. However, limited by observations, the energy balance model has difficulty calculating the related energy flux because the data of vertical profile of cloud cover, wind speed, humidity, and temperature are not easy to obtain. In contrast, the degree-day model is based on the empirical relationship between the melting of snow or ice and positive accumulated temperature near the surface (Hock, 2003), and its temperature data are widely available and easy to interpolate. Therefore, the degree-day model has been widely used to reconstruct the glacier mass balance (Braithwaite and Zhang, 2000; Slangen et al., 2016; Jóhannesson et al., 2017; Zhu et al., 2020; Geck et al., 2021; Zhang et al., 2021), and its simulation accuracy is usually better than that of the energy balance model at the basin scale (Hock, 2003).

The Urumqi River Basin is located in arid and semi-arid areas of northwestern China. It is the major water source for Urumqi City (the capital of Xinjiang Uygur Autonomous Region, China). The Urumqi River Basin is a typical glacier-replenishment-type basin (Liu et al., 2019). Glacier meltwater is important to the agricultural construction and economic development of Urumqi City and is of great significance to maintaining the fragile ecological balance and socioeconomic sustainable development of the region. Owing to global warming, glaciers in the Urumqi River Basin are generally in a state of melting (Huai et al., 2018). However, previous glacier research of the Urumqi River mainly focused on the glacier area or the changes in the mass balance of Urumqi Glacier No. 1 (UG1) in the headwaters of the Urumqi River (Xu et al., 2017; Huai et al., 2018; Li et al., 2021). Therefore, it is urgent to carry out a study of the glacier mass balance at the whole basin scale. For all the reasons mentioned above, this study based on the mass balance data of UG1, and meteorological and hydrological data, established a distributed degree-day model with a 1-d time resolution and 30 m spatial resolution to reconstruct the glacier mass balance and ELA in the Urumqi River Basin during 1980–2020. In addition, the contributions of glacier meltwater runoff to streamflow in the typical glacier recharge basins were evaluated, and the relationships among glaciers, climate, and streamflow were discussed. Our study can provide scientific guidance and decision-making support for the government to cope with glacier change and its impact.

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, China, with an area of 4684 km^2. The basin originates from the Tanger II peak, and extends northward through the Urumqi City. It has a total length of 214 km before disappearing in the northwestern Gurbantunggut Desert (Saydi et al., 2019). The area above the exit of the Yingxiongqiao hydrological station in the upper reaches of the Urumqi River Basin is selected as the research area, which provides vital water resources with a drainage area of 1088 km^2 for the Urumqi City (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., and more than 80% of the glaciers are concentrated between 3700 and 4200 m a.s.l. (Fig. 1c). Under the influence of climate warming, glaciers are melting rapidly, resulting in an increase in glacier meltwater runoff in the upper reaches of the Urumqi River Basin (Huai et al., 2018). UG1 (43°06′N, 86°49′E) is located in the source region of the Urumqi River Basin (Fig. 1b), and it is a valley glacier facing north. 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. It is one of the reference glaciers of the World Glacier Monitoring Service (WGMS) and a reference glacier in Central Asia.

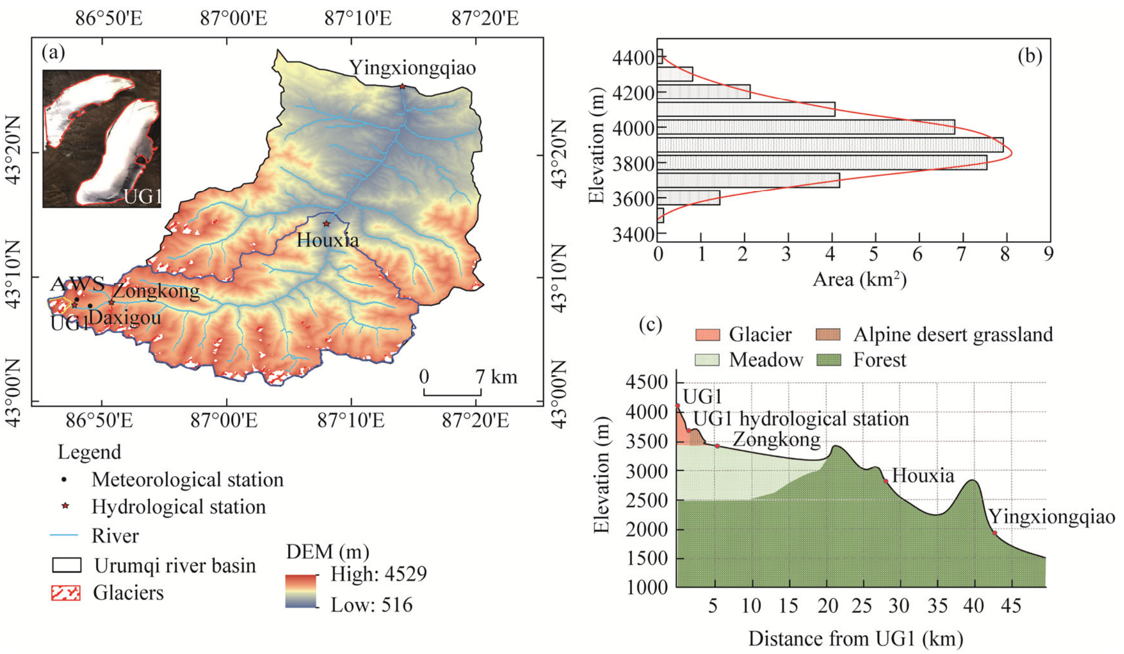

Fig. 1 (a), distribution of glaciers, and their meteorological and hydrological stations in the Urumqi River Basin; (b), area-elevation distribution of the glaciers. (c), profile map of the Urumqi River Basin and the distribution of the outlet location of each catchment. AWS, automatic weather station; UG1, Urumqi Glacier No. 1; DEM, digital elevation model.

The Urumqi River Basin is situated in the hinterland of the Eurasian continent and has a typical temperate continental climate due to the influence of the westerlies. As shown in Figure 2, the results indicate that temperature and precipitation at the Daxigou weather station showed an increasing trend. The average annual temperature and precipitation during 1980–2020 were –4.7°C and 493 mm, respectively. In general, 77% of the precipitation occurred from May to August. In winter, the temperature is controlled by the Siberian anticyclonic circulation, which results in low temperature and less precipitation (Li et al., 2007).

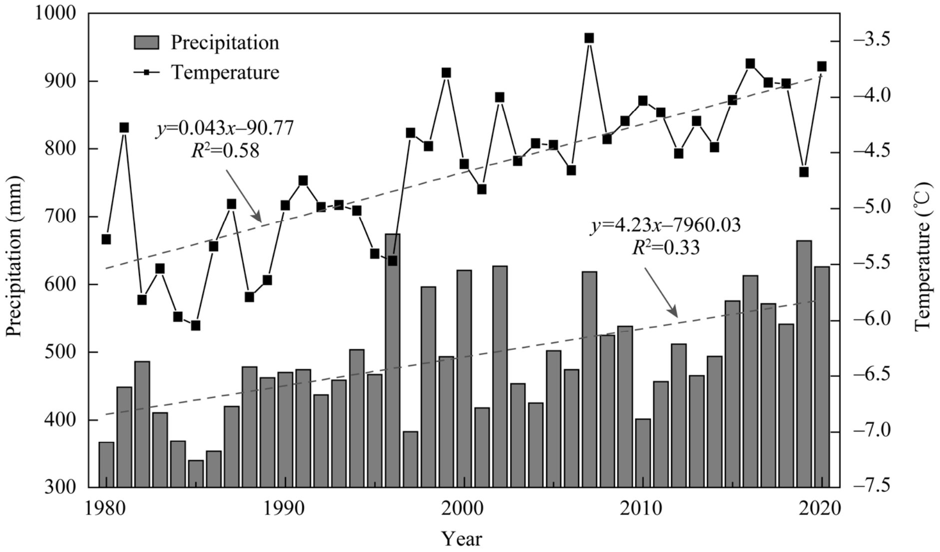

Fig. 2 Annual average temperature and average annual precipitation in the Urumqi River Basin

3 Data

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 of the Urumqi River Basin, and belongs to the China Meteorological Administration (http://data.cma.cn). In addition, we also used the data from an automatic weather station (AWS) located at an altitude of 3835 m a.s.l. in the source of the basin, which has a 30-min scale observation record of temperature and precipitation.

Considering that the variations in glacier area will affect the calculation of mass balance values on a long time scale 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 Landsat TM image in 1991, and the glacier boundary during 2001–2020 was taken from Landsat TM image in 2010 (http://www.usgs.gov/). To reduce the influence of clouds and snow on the extraction of glacier boundary, we chose satellite images under cloud-free conditions. The digital elevation model (DEM) used ASTER GDEM2.0 data with a spatial resolution of 30 m. These data came from the Geospatial Data Cloud (http://www.gscloud.cn/), and were mainly used to obtain the altitude information of the glacier.

3.2 Mass balance data

In the study region, there is only one glacier with a surface mass balance obtained through field observations, which is located at the source of Urumqi River (Fig. 1). UG1 is the longest glacier observed in China, and is very important for understanding the mechanisms of glacier melting, hydrological cycle, glaciers, and climate change in the Urumqi River Basin. The mass balance data could be obtained from WGMS and annual reports of the Tianshan Glaciological Station, Chinese Academy of Sciences. To ensure the continuity of measured data, we used the monthly mass balance data of UG1 from 2001 to 2014 and annual mass balance data of UG1 from 1980 to 2018 to calibrate and validate the model because the mass balance data of UG1 from 1966 to 1979 were reconstructed by previous models.

3.3 Runoff data

The catchment areas controlled by the Yingxiongqiao hydrological station, Houxia hydrological station, Zongkong hydrological station and UG1 hydrological station 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	1979-09-01–2020-08-31
	AWS	43°07′N	86°48′E	3835	2018-08-01–2019-04-30
Hydrologicl station	Yingxiongqiao	43°22′N	87°12′E	1920	1980-01-01–2011-12-31
	Houxia	43°12′N	87°07′E	2148	2014-01-01–2016-12-31
	Zongkong	43°07′N	86°52′E	3408	1983-01-01–2018-12-31
	UG1	43°06′N	86°49′E	3706	1980-01-01–2018-12-31

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

4 Methods

4.1 Model description

A spatial distributed degree-day model (Hock, 2003) and accumulative model were used to calculate the glacier mass balance of the Urumqi River Basin. The main components of this model include glacier melting, snow melting, snow accumulation, and refreezing. We used air temperature and precipitation from the Daxigou weather station at a day scale combined with the temperature lapse rates and the precipitation gradient to drive the model. We defined a mass balance year that was from 1 September in one calendar year to 31 August in the following year (Wu et al., 2011). The formula is as follows:

$$B = \int_t [(1-f)M_{\text{snow/ice}} + A_s] d_t, \quad (1)$$

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

$M_{\text{snow/ice}}$ is calculated by a degree-day model, which is based on the empirical relationship between the amount of ice or snow melting and air temperature (Braithwaite and Zhang, 2000; Hock, 2003).

$$M_{\text{snow/ice}} = \begin{cases} \text{DDF}_{\text{snow/ice}}(T - T_t), & T > T_t \\ 0, & T \le T_t \end{cases}, \quad (2)$$

where DDF (mm/(d·°C)) is the degree-day factor. Because the surface of ice and snow has different albedos in regard to solar radiation, this factor is different for ice and snow (Zhang et al., 2017; Tsai et al., 2018). T (°C) is the extrapolated daily average temperatureat each elevation on the glacier surface; and T_t (°C) is the threshold temperature for ice and snow melting. If $T>T_t$ and the snow on the glacier surface is completely melted, the remaining temperature is used to melt the ice.

A_s is modelled from the precipitation data using a dual-threshold temperature model to distinguish between rain and snow. According to the temperature at the time of snowfall, the precipitation process can be divided into three possibilities: rainfall, snowfall, and sleet (Berghuijs et al., 2014; Hantel et al., 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 temperature 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 the redistribution of snow caused by wind or avalanches. A_s is calculated by the following equation:

$$A_s = \begin{cases} 0, \ T > T_{\mathrm{r}} \\ P \times \dfrac{T_{\mathrm{r}} - T}{T_{\mathrm{r}} - T_{\mathrm{s}}}, \ T_{\mathrm{s}} \le T \le T_{\mathrm{r}}, \\ P, \ T < T_{\mathrm{s}} \end{cases} \quad (3)$$

where P (mm) is the precipitation; and T_{r} and T_{s} (°C) are the critical temperatures of rain and snow conversion, respectively.

The glacier meltwater runoff (R, m^3) is described as Yang (1981):

$$R = \int_t [(B + P) \times A] d_{\mathrm{t}}, \quad (4)$$

where A (km^2) is the glacier area.

4.2 Model parameters and calibration

In our modelling method, air temperature lapse rates (TLR), altitude precipitation gradients (APG), DDF of snow and ice, T_{r}, and T_{s} are needed to operate the model. However, since glaciers in the Urumqi River Basin are mainly located at high elevation, there are few measured meteorological and glacier data. Therefore, it is challenging to consider these parameters in this region, which may affect the performance of the model to a large extent.

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

We used a degree-day model to calculate the amount of snow and ice melting on the glacier surface, which is based on the empirical relationship between the amount of melting and temperature (Braithwaite and Zhang, 2000; Hock, 2003). In the calculation process, if there is snow on the glacier surface, the melting amount should be calculated as a function of DDF_{snow}. When snow is melted out, ice is melted as a function of DDF_{ice}. Some studies deduced the DDF of ice and snow, which were based on the field mass balance data of UG1. In general, the DDF of ice varies from 5.6 to 8.9 mm/(d·°C), and the DDF of snow varies from 2.7 to 3.1 mm/(d·°C) (Liu et al., 1998; Huintjes et al., 2010; Wu et al., 2011). On this basis, since the glacier mass loss is mainly concentrated in summer (May–August), we calibrated the parameters based on the measured data of summer mass balance of UG1 from 2001 to 2014, and found that the DDF values of ice and snow were 7.3 and 2.9 mm/(d·°C), respectively. In areas of glacier accumulation, the melting process is very complex. Because the surface of the accumulation area is composed of grainy snow and new snow, grainy snow will change and merge during the ablation process, and the meltwater will penetrate the grainy snow layer. Part of grainy snow will refreeze to form "internal recharge", and the other part will be lost as ice runoff. Previous studies have found that the refreezing amount of meltwater of UG1 accounts for only 1.0% (Wang et al., 2020). The 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, the glaciers in the Urumqi River Basin are "summer accumulation" continental glaciers (Shi et al., 2000), which have high glacier ice temperature in summer, and less meltwater forms an "internal supply" through refreezing. Therefore, the refreezing amount of meltwater in the whole basin could be ignored. In the Tianshan Mountains of China, researches on the threshold temperatures of ice and snow melting, and the division of snow and rain are extremely limited. Therefore, in this study, we adopted the most commonly used values T_t=0°C, T_r=2°C, and T_s=0°C (Hock et al., 2003; Huintjes et al., 2010; Zhang et al., 2017; Azam and Srivastava, 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 the errors

Model parameter	Value used in model	Range used for error estimation	Error value
Air temperature lapse rate (TLR) (°C/m)	Mean monthly TLR	-	-
Altitude precipitation gradient (APG) (mm/m)	Mean monthly APG	-	-
DDF for ice (mm/(d•°C))	7.3	5.6–8.9	0.281
DDF for snow (mm/(d•°C))	2.9	2.7–3.1	0.009
Threshold temperature for snow/ice melting (T_t) (°C)	0.0	T_t–1–T_t+1	0.027
Threshold temperature for snow (T_s) (°C)	0.0	-	-
Threshold temperature for rain (T_r) (°C)	2.0	-	-
Toal (m w.e./a)	-	-	0.317

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

4.3 Model validation

Due to the scarcity of meteorological and glacier mass balance observation data in the Urumqi River Basin, it is very challenging to verify the accuracy of our model method. The model validation process is very important to the model performance to truly simulate the glacier mass balance in the Urumqi River Basin. Therefore, we validated our modelling method based on the measured datasets available in the study area. First, to ensure the accuracy of the input of TLR and APG, we used the data generated from temperature and precipitation from the Daxigou weather station, and combined them with the monthly TLR and APG to compare and verify the observation data 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 the measured value of the glacier (1980–2018). This process can evaluate the ability of the model, and reproduce the annual mass balance change.

In addition, the determination coefficient (R^2) and root mean square error (RMSE) were used to calibrate and verify the performance of the model. R^2 values can indicate the model's ability to simulate changes in glacier mass balance, and RMSE can manifest the model's ability to calculate the size of glacier mass balance.

4.4 Model performance

We first evaluated the forcing data generated using the monthly TLR and APG from the Daxigou weather station against observations from the AWS. The AWS measurements of the air temperature during 2018–2019 are reproduced well (Fig. 3). From Figure 3a, we can see that the daily average temperature change simulated by the model is closely related to the observed data from the AWS (R^2=0.98; RMSE=2.43°C). Compared with temperature, precipitation is 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, the temperature and precipitation generated by this method are in good accordance with the observed data, and can be used as the parameters of model.

As shown in Figures 4–5, our method performs well during calibration and validation. The simulated and observed values of the mass balance of UG1 during the calibration period from 2001 to 2014 are shown in Figure 4a, indicating that the selected parameters provide good simulation results for the monthly mass balance changes of UG1. Overall, the simulated value of the monthly mass balance is significantly correlated with the measured value (R^2=0.78; n=52; P<0.01; RMSE=0.10 m w.e.). From the perspective of different months (Fig. 5), the simulated

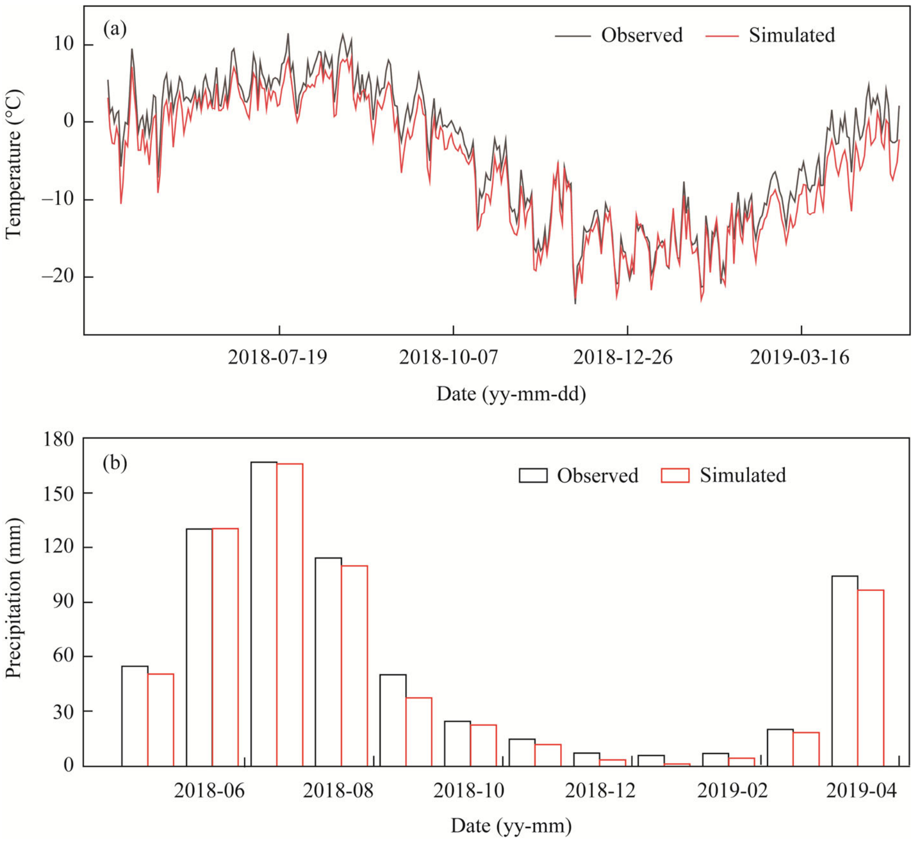

Fig. 3 Observed and simulated daily average temperature (a) and monthly precipitation (b) at the automatic weather station during 2018–2019

mass balance values of each month from May to August are in good agreement with the measured values, and R^2 values are larger than 0.50. Among them, the mass balance simulation value of UG1 in June has the highest correlation with the measured value (R^2=0.75; n=13; P<0.01), and that of the remaining months is relatively low, which might result from the difference in ice and snow DDF in different months. Figure 4b shows the simulated and observed annual mass balance values of UG1 during the validation period. The analyses reveal that the annual mass balance simulated value of UG1 is in good agreement with the observed value and is a significant positive correlation (R^2=0.64; n=39; P<0.01; RMSE=0.22 m w.e.). Among them, the simulated value of annual average mass balance is –0.46 m w.e./a, which is slightly higher than the observed value (–0.49 m w.e./a). Based on the above results, our model can reproduce well observation results, and explain the changes in mass balance. These results make us confident in using this model to estimate the mass balance of other glaciers in the Urumqi River Basin.

4.5 Error evaluation

In this study, to enhance our understanding of the long-term change in glaciers on a regional scale, we used the modelling method to calculate the glacier mass balance in the Urumqi River Basin. Most modelling involves a calibration procedure in which model parameters are adjusted to achieve the maximum agreement between simulated and observed values. This process is a compromise between clarifying the methodological requirements for model calibration and the database availability. There is only one glacier in the Urumqi River Basin in which the measured data were obtained through field observation. Therefore, the model only uses the data of one glacier for parameter correction, which may limit the reliability and representativeness of glacier mass balance in the whole Urumqi River Basin. There may be a certain degree of uncertainty.

The error source of the model mainly depends on the selected model parameters. To quantify

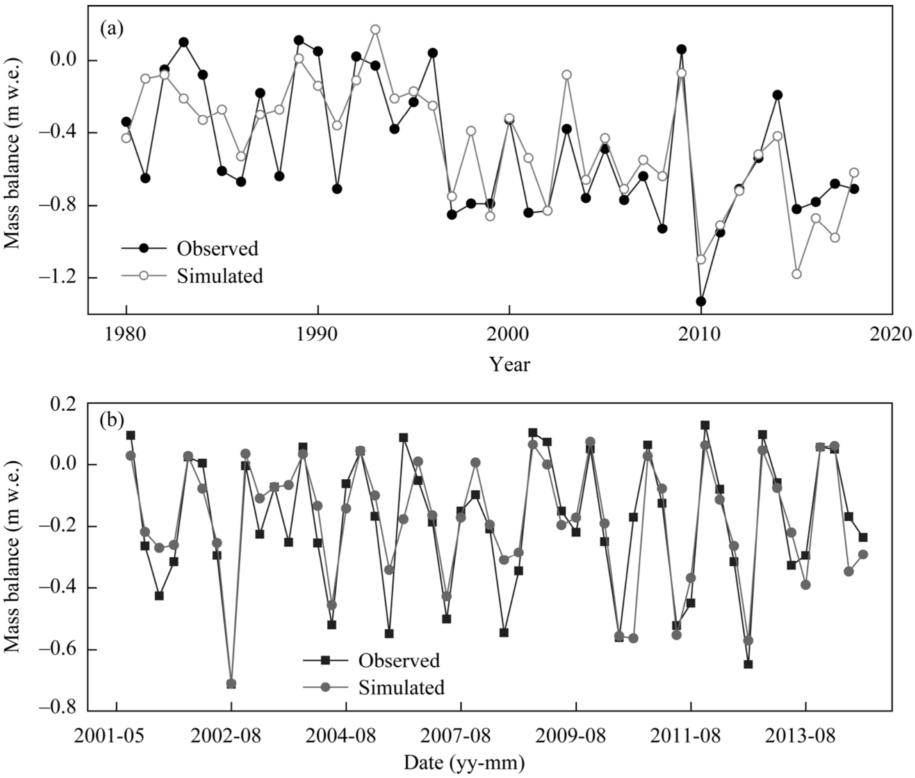

Fig. 4 (a), observed and simulated annual mass balance of Urumqi Glacier No. 1 (UG1); (b), monthly mass balance of UG1.

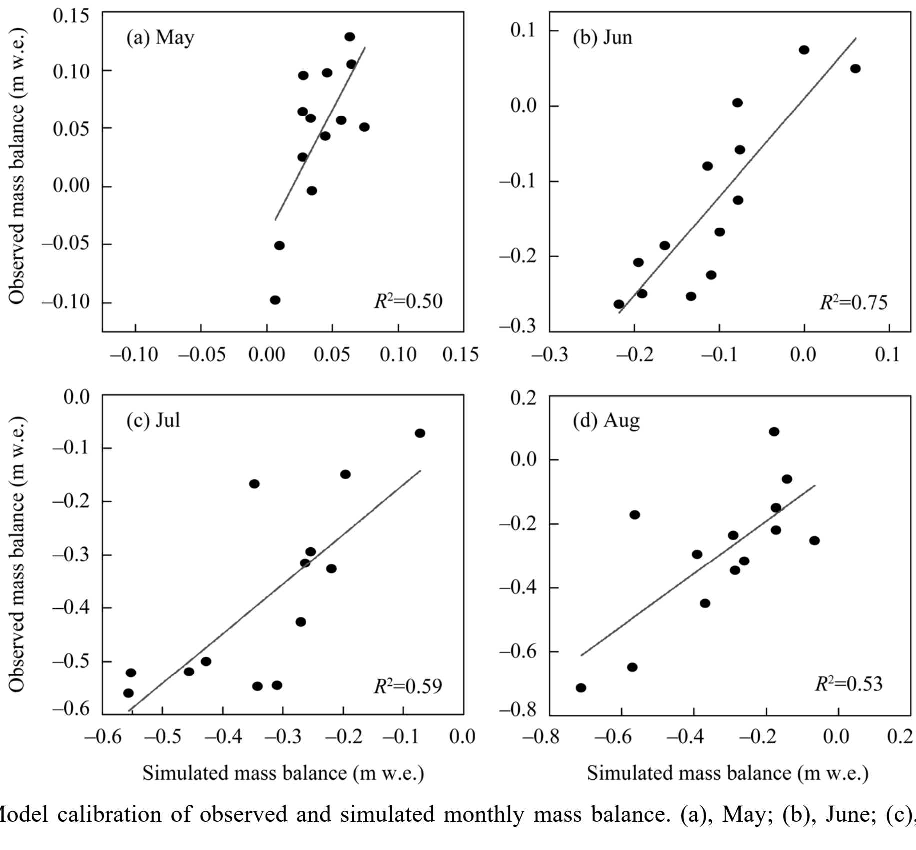

Fig. 5 Model calibration of observed and simulated monthly mass balance. (a), May; (b), June; (c), July; (d), August.

the uncertainty of the annual mass balance caused by the parameters in the Urumqi River Basin, we reran the model by changing the parameters one by one at a time while keeping all other parameters unchanged. Since the seasonal changes in the TLR and APG were considered in this study and their accuracy was verified, their uncertainty was not considered in this test. Because the double threshold temperature model was adopted for rain and snow separation in this study, the uncertainty of the rain and snow separation threshold (T_r and T_s) was ignored. In addition, when the reasonable range of model parameters is unknown to ensure the authenticity of the ice and snow melting threshold (T_t), the variation range should be set to ±1°C, which is a common method to estimate parameter uncertainty (Tong et al., 2016; Azam et al., 2019). The parameter range used in the model is shown in Table 1. The results show that compared with the reference operation, the DDF_{ice} has the most significant effect on the glacier mass balance of the Urumqi River Basin (Table 1), which plays a vital role in the simulation of glacier mass balance. In this study, the transitivity of errors is used to sum all parameter uncertainties, by which the uncertainty of glacier mass balance is estimated. Through comprehensive evaluation, the uncertainty in the annual glacier mass balance in the whole region is ±0.32 m w.e./a.

5 Results and discussion

5.1 Glacier mass balance since 1980

Glacier mass balance is a direct and reliable index to reflect glacier state. In this paper, we used a distributed degree-day model to simulate the glacier mass balance in the Urumqi River Basin during 1980–2020. Figure 6 describes the simulated value of the glacier mass balance in the basin. The results showed that the multi-year cumulative mass balance during the study period was −34.68 (±13.12) m w.e., and the annual average mass balance was −0.85 (±0.32) m w.e./a. Compared with the glacier mass balance in the Tianshan Mountains, the glacier mass loss in the Urumqi River Basin was about twice as much as that in the Tianshan Mountains (–0.40 (±0.09) m w.e.) (Bhattacharya et al., 2021), which indicates that glacier mass loss in the Urumqi River Basin is more remarkable than that in the Tianshan Mountains. These results may be caused by the fact that the elevation distribution of glaciers in the Urumqi River Basin is lower than that in the Tianshan Mountains, and the glacier melting rate (0.79%/a) in the Urumqi River Basin is slightly higher than that in the Tianshan Mountains (0.35%/a) (Huai et al., 2018; Xing et al., 2018). The glacier mass balance of the Urumqi River Basin has generally shown a downward trend since 1980 (P<0.01). The annual glacier mass balance was characterized by obvious inter-annual variation, with a maximum value of –0.16 (±0.32) m w.e. (1993), and a minimum value of −1.56 (±0.32) m w.e. (2015). According to the nonparametric Mann–Kendall test, the melting process showed an accelerated trend, and has changed to a more negative equilibrium since 1998. Therefore, we divided the change in glacier mass balance in the Urumqi River Basin into two stages according to the abrupt change point (Fig. 6). In the first stage (1980–1998), the annual mass balance ranged from –1.18 to –0.16 m w.e., and the average annual value was –0.62 (±0.32) m w.e./a, with noteworthy fluctuation characteristics. In the second stage (1999–2020), the annual mass balance ranged from −1.56 to −0.42 m w.e., with the average annual value of −1.04 (±0.32) m w.e./a. Compared with the first stage, the glacier mass loss in the second stage was more intense, and the volume of glacier mass loss in the second stage was about 1.7 times that in the first stage. This accelerated glacier mass loss was also confirmed by the observable glacier UG1 in the study area (Huai et al., 2020).

To further analyze the intra-annual variation in glacier mass balance in the Urumqi River Basin, we reconstructed the seasonal variation in glacier mass balance and displayed in Figure 6. The inter-annual variation in glacier mass balance in summer decreased, and had a prominent downward trend (P<0.01) during 1980–2020. Over the 41 years, the summer mass balance wasnegative (−0.96 m w.e./a), and its inter-annual fluctuation was highly consistent with the 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), which indicates that

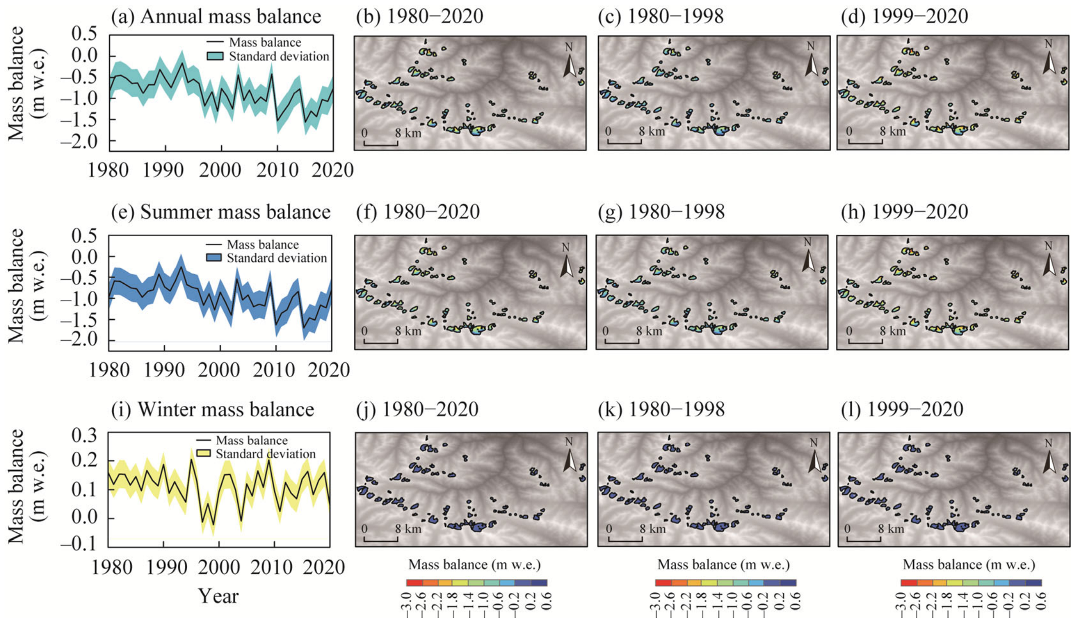

Fig. 6 (a)–(d), annual mass balance of the Urumqi River Basin during 1980–2020; (e)–(h), summer mass balance of the Urumqi River Basin during 1980–2020; (i)–(l), winter mass balance of the Urumqi River Basin during 1980–2020.

the loss rate of mass balance in summer increased significantly after 1998. This phenomenon was mainly due to climate warming and precipitation mainly occurred from May to August, accounting for about 77% of the whole year in the Urumqi River Basin (Fig. 7). Therefore, when the temperature increase, the proportion of precipitation will also increase, and the decrease of new snow will reduce the albedo of glacier surface, which leads to a greater melting (Fujita et al., 2008; Jia et al., 2020). By comparison, over the 41 years, the inter-annual variation in winter mass balance was small (0.11 m w.e./a), and the overall trend was slightly downward. The average winter mass balance in the first stage (0.12 m w.e./a) was slightly higher than that of the second stage (0.10 m w.e./a). Therefore, there was no significant periodic change. From the monthly change in glacier mass balance in the year (Figs. 7–8), the accumulation period (September–May in the following year) of glaciers was long in the study area, but the accumulation was 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 the loss was serious (−0.96 m w.e.). At the beginning of June, the glaciers began to enter the loss state, and showed a gradual increasing trend of ablation. The ablation was the most intense in July, which is influenced by temperature. During this period, the overall temperature rising of the glacier changed greatly, which also led to the striking differences in the mass balance of each month. Generally, the change in mass balance in the year showed the change characteristics of "weak accumulation and strong ablation".

The change of glacier mass balance has notable vertical zonal characteristics because of the significant difference in the key factors, such as hydrothermal combinations in different elevation zones (Wang et al., 2016). To explore the characteristics of the elevation profile of the glacier mass balance in the Urumqi River Basin, we determined the spatial average of the mass balance at a height of 100 m, and determined the elevation distribution of the glacier mass balance (Fig. 9a). Over the past 41 years, the maximum negative balance (−2.85 m w.e.) of the annual average mass balance in the Urumqi River Basin appeared at the glacier terminus (3400–3500 m a.s.l.). When the elevation increased to 4100–4200 m a.s.l., it turned into a positive balance, and the maximum positive balance (0.47 m w.e.) appeared at 4400–4500 m a.s.l. The advance or retreat of glacier was directly determined by the change of ELA. Comparing with other characteristic parameters

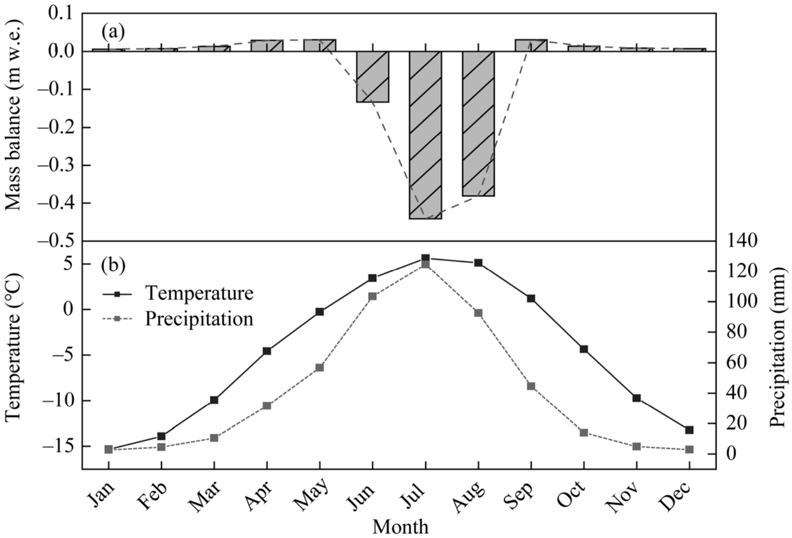

Fig. 7 (a), monthly glacier mass balance in the Urumqi River Basin; (b), monthly mean air temperature and precipitation at the Daxigou weather station.

(such as area or length), the change of ELA is the most direct reflection of climate change. Therefore, on the ground of the annual mass balance of each elevation zone, ELA of the glaciers in the Urumqi River Basin was calculated. During 1980–2020, ELA in the Urumqi River Basin had an upwards trend of fluctuation (Fig. 9b). The average value of ELA was as high as 4188 m a.s.l., and the highest elevation (4378 m a.s.l.) appeared in 2015, and the lowest elevation (3969 m a.s.l.) appeared in 1993, which indicates that 2015 and 1993 were the most intense and weakest years of glacier melting, respectively, which is consistent with the estimated results of the mass balance of the glacier year. Similar to the height change of the mass balance simulated by glaciers in the Urumqi River Basin during the same period, the ELA of UG1 also had a fluctuating upward trend overall (Huai et al., 2020).

5.2 Climate change, mass balance and ELA

Over the past 41 years (1980–2020), glaciers in the Urumqi River Basin have experienced the serious mass loss (Fig. 6), especially in the last 20 years. These findings are consistent with the research results of Huai et al. (2018), who analyzed the accelerated retreat of glaciers in the past 50 years in combination with a topographic map, Landsat series images, SPOT5 images, Google Earth and meteorological data. As shown in Figure 2, air temperature of the basin had a significant upwards trend during 1980–2020, with an upwards rate of 0.43°C/10a. In particular, the annual mean temperature during1999–2020 increased by 1.00°C compared with the period of 1980–1998. On the other hand, during 1980–2020, annual precipitation revealed a slight increasing trend and precipitation during 1999–2020 increased by nearly 75.48 mm compared with that during 1980–1998 (Fig. 2). The variation of temperature in the basin was significant, but the change of precipitation is less obvious than that of temperature, which may have had a great impact on glacier accumulation in the basin.

For glacier mass balance, the melting of snow/ice is highly correlated with surface air temperature, which is commonly exhibited in the shape of cumulative positive temperature, and the accumulation is mainly based on solid precipitation (Braithwaite, 1995; Hock, 2003). Compared with the annual average temperature and total precipitation, the 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 the changing trends of cumulative positive temperature and solid precipitation during 1980–2020. The cumulative positive temperature shows a significant upwards trend (P<0.01), especially from 1999 to 2020 (Fig. 10a). Solid precipitation had a slight increasing trend and without an obviously

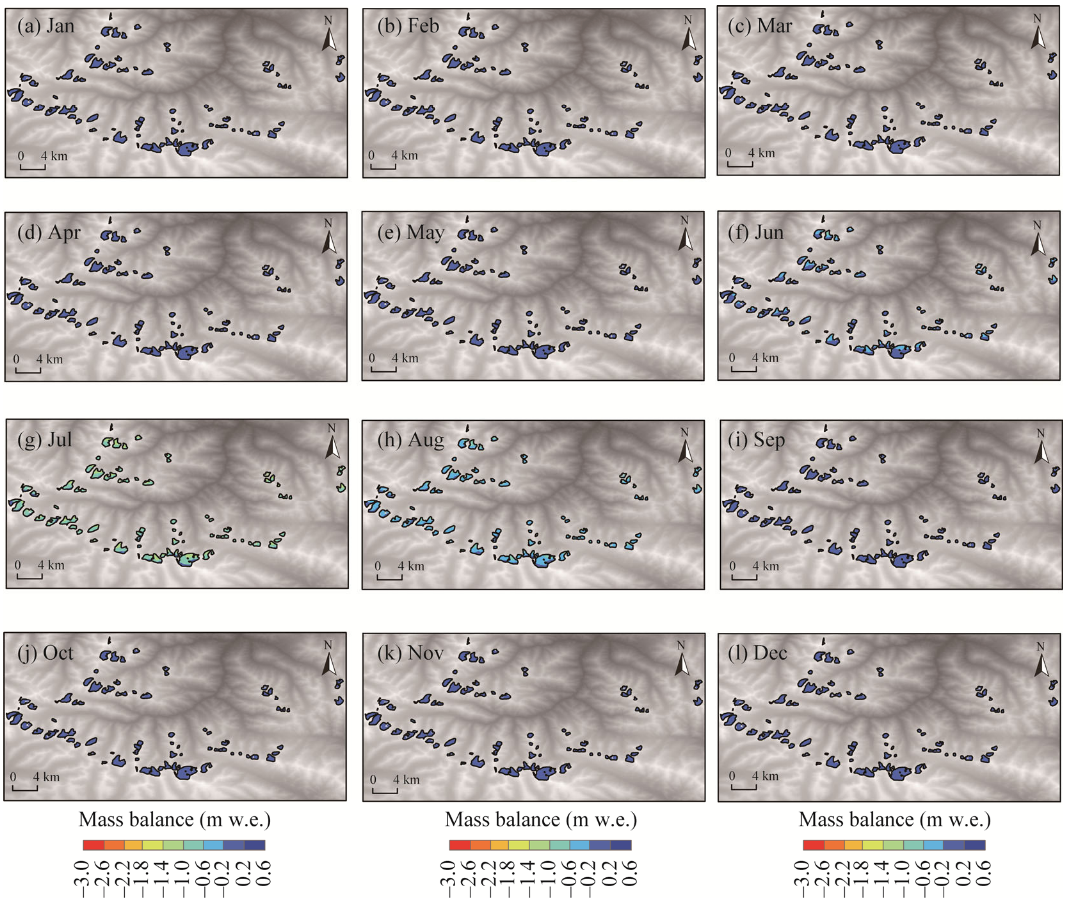

Fig. 8 Monthly changes in glacier mass balance in the Urumqi River Basin during 1980–2020. (a), January; (b), February; (c), March; (d), April; (e), May; (f), June; (g), July; (h), August; (i), September; (j), October; (k), November; (j), December.

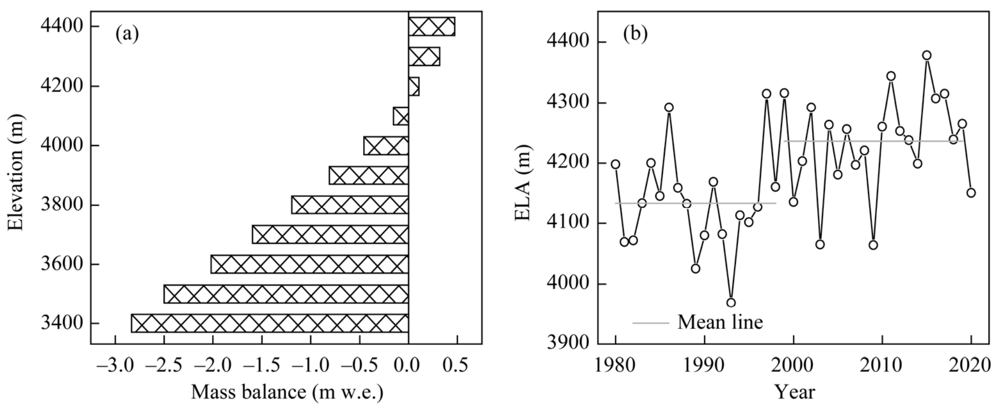

Fig. 9 (a), glacier mass balance changes with elevations in the Urumqi River Basin; (b), simulated equilibrium line altitude (ELA) of glaciers in the Urumqi River Basin during 1980–2020.

periodic fluctuation (Fig. 10b). We further analyzed the impact 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 that in the first stage (1980–1998), and the multi-year daily average temperature in the second stage was notably higher than that in the first stage (Fig. 11). We can see that under the background of climate warming, the number of CPTD in the second stage increased at a rate of 0.32 d/a, which directly prolongs the length of ablation period, and increases glacier mass loss. The cumulative positive temperature in the Urumqi River Basin was highly synchronous with the inter-annual changes of glacier annual mass balance and ELA, with R^2 values of 0.83 (P<0.01) and 0.65 (P<0.01), respectively. This result shows that the change of glaciers in the Urumqi River Basin has been mainly controlled by temperature in recent years.

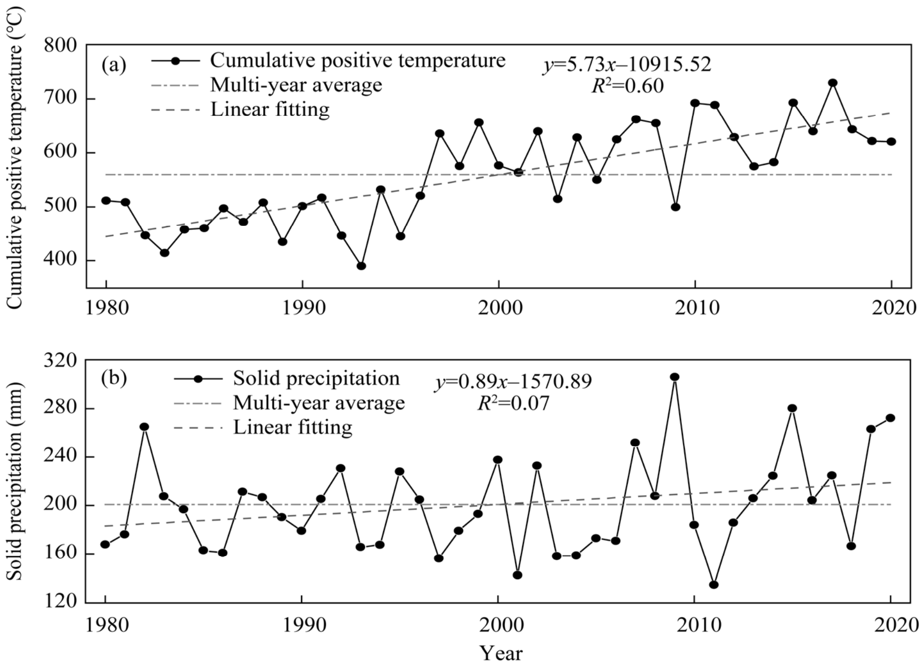

Fig. 10 (a), variation in cumulative positive temperature; (b), variation in solid precipitation.

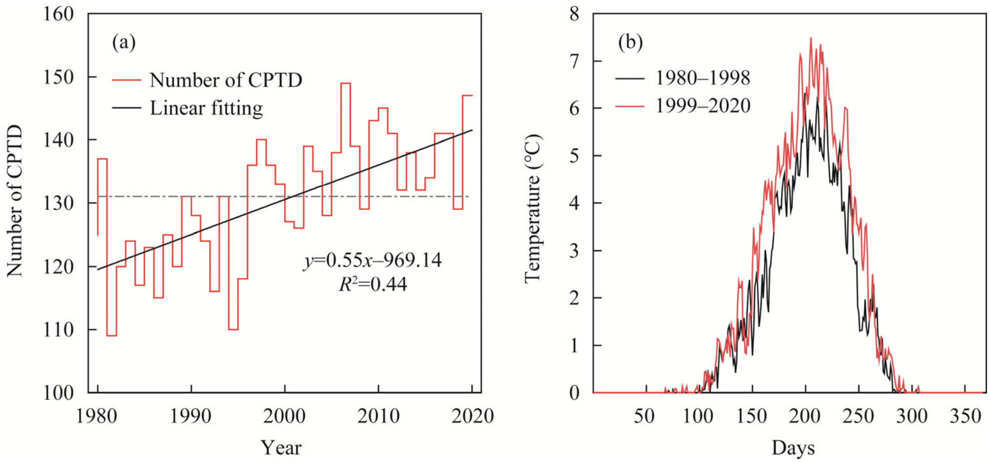

Fig. 11 (a), number of cumulative positive temperature days (CPTD) during 1980–2020; (b), mean daily temperatures (>0°C) for two periods (1980–1998 and 1999–2020).

5.3 Influence of glacier meltwater runoff change on streamflow

In arid and semi-arid areas of western China, mountain glaciers are a vital part of surface water resources. Glacier meltwater runoff provides valuable freshwater resources and river runoff (Jansson et al., 2003). In recent decades, almost all glaciers in the Urumqi River Basin have experienced considerable retreat (Huai et al., 2018), and it is found that the glacier mass loss has accelerated in recent years (Fig. 5). With the growth of regional population and rapid economic development, the local demand for water resources will continue to increase (Org, 2015; Pritchard, 2017). Therefore, the accelerated melting of glaciers in the basin will have a definite impact on the utilization of water resources in the region. To explore the impact of glacier ablation on streamflow, this study used the method proposed by Yang (1981) to estimate the contribution of glacier meltwater to streamflow in different catchments in the Urumqi River Basin.

Regarding the seasonal distribution (Fig. 12), glacier meltwater runoff and streamflow in different catchments of the Urumqi River Basin were both concentrated in summer, especially in July and August, which was significantly synchronized with the change of glacier mass balance (R^2=0.98, P<0.01). The seasonal variation had a single peak distribution, for which the high temperature in summer dominated glacier melting, and the summer rainfall accounted for about 77% of the annual precipitation. In contrast, in winter (September–April of the following year), the temperature was low, and there was less glacier melting. Figure 13a illustrates the annual streamflow, glacier meltwater runoff, and their contribution to the annual streamflow in the Urumqi River Basin during 1980–2011. The average annual streamflow of the Urumqi River Basin is 2.59×10^8 m^3 during 1980–2011, and that of the glacier meltwater runoff was 0.48×10^8 m^3, which accounted for approximately 18.56% of the streamflow (Table 3). It is worth noting that in years when streamflow was relatively lower, such as in 1986 and 2001, glacier meltwater runoff

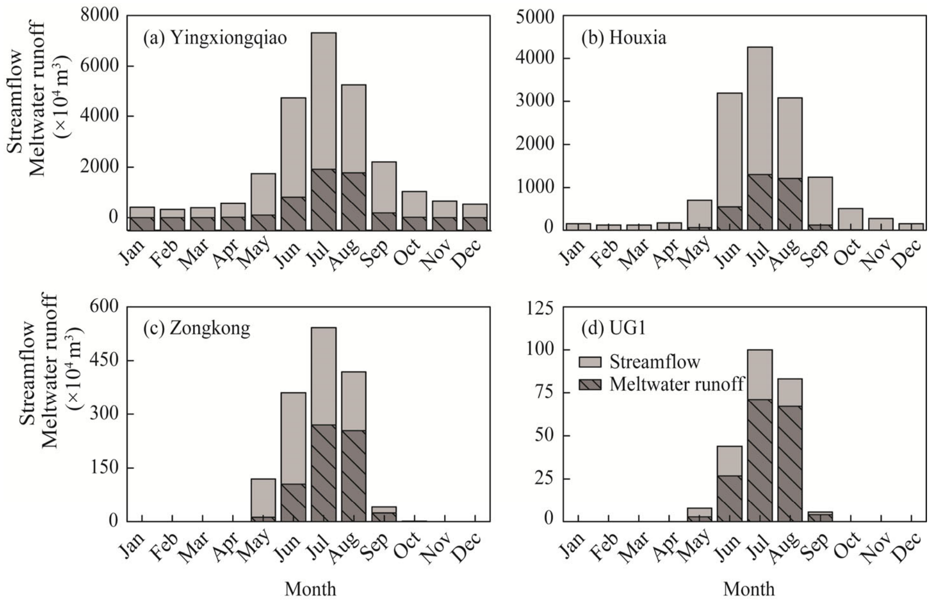

Fig. 12 Mean monthly streamflow and glacier meltwater runoff in the Urumqi River Basin. (a), Yingxiongqiao; (b), Houxia; (c), Zhongkong; (d), Urumqi Glacier No. 1 (UG1).

accounted for a higher percentage of streamflow. Therefore, we believe that although the glacier coverage area of the Urumqi River Basin is relatively insignificant, glacier meltwater runoff still accounts for a considerable proportion of streamflow in this area. In other words, glacier meltwater runoff is one of the crucial sources of water resources in the Urumqi River Basin, which also shows that glacier meltwater runoff is of great importance in arid and semi-arid areas with extremely limited water supplies. To further explore the contribution of different glacier cover areas to runoff in arid and semi-arid areas, we constructed a linear regression model between the proportion of glacier area and the proportion of glacier meltwater runoff in different sections in the Urumqi River Basin (Fig. 13b). From a qualitative point of view, it can be concluded that there is an obviously positive correlation between the proportion of glacier meltwater runoff and the proportion of glacier area (R^2=0.98; P<0.01), which indicates that the larger the proportion of glacier area is, the larger the proportion of glacier meltwater runoff is. However, the actual proportion of glacier meltwater in the streamflow of the basin is not simply affected by the proportion of glacier area, but is also affected by many factors, such as temperature, precipitation, evaporation, and base flow of the basin. Therefore, in arid and semi-arid areas, the specific proportions of glacier meltwater runoff in different regions or basins need to be further calculated.

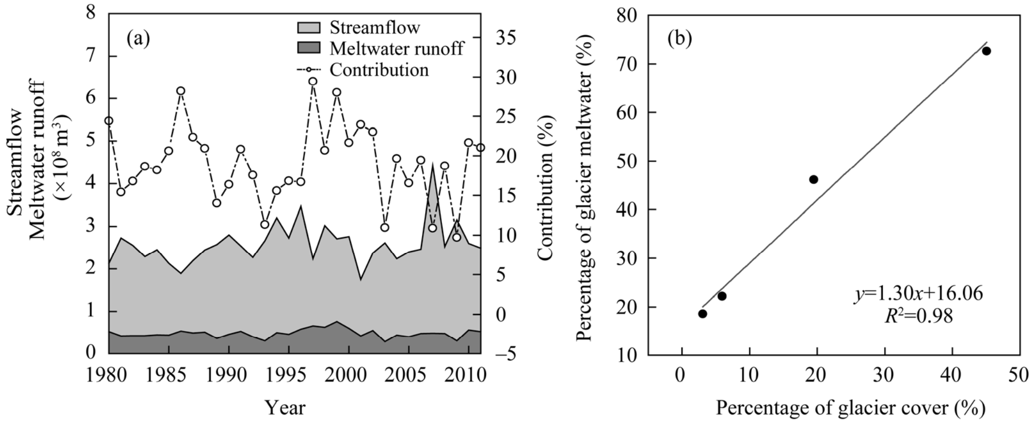

Fig. 13 (a), annual streamflow, glacier meltwater runoff and its contribution in the Urumqi River Basin during 1980–2011; (b), regression relationship between percentage of glacier cover and percentage of glacier meltwater.

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

Catchment	Glacier area (km^3)	Catchment area (km^3)	Streamflow (×10^4 m^3)	Glacier meltwater runoff (×10^4 m^3)
Yingxiongqiao	33.29	1088.00	25,868.75	4800.51
Houxia	23.72	400.00	13,992.27	3241.39
Zongkong	5.58	28.66	1484.04	669.47
UG1	1.56	3.45	243.43	173.71

Note: UG1, Urumqi Glacier No. 1.

6 Conclusions

In this study, a distributed degree-day model with the 1-d temporal resolution and 30-m spatial resolution was established by combining meteorological and remote sensing data. Based on this model, we reconstructed and analyzed the changes in glacier mass balance in the Urumqi River Basin during 1980–2020. At the same time, the factors affecting glacier mass balance and the relationship between glaciers and runoff were discussed. The results of model were well verified in UG1, which can be monitored in the region, confirming the model's ability to estimate glacier mass balance in the Urumqi River Basin.

The results show that the mass loss and ELA of glaciers in the Urumqi River Basin had an increasing trend during 1980–2020. During the simulation period, the average annual mass balance was −0.85 (±0.32) m w.e./a, which was slightly higher than the average glacier mass loss in the Tianshan Mountains, and the average ELA is 4188 m a.s.l. Especially in recent 20 years, the glacier mass loss has increased significantly in the Urumqi River Basin. The average annual glacier mass balance during 1999–2020 was almost 1.7 times that during 1980–1998 due to the increase in accumulated positive temperature and the extension of ablation season. At the same time, the annual change in glacier mass balance had the most obvious accumulation due to increased precipitation in May, and the most intense ablation due to the influence of temperature in July, presenting the overall change characteristics of "weak accumulation and strong ablation". During the whole study period, the change of streamflow was heavily synchronized with the change of glacier mass balance.

This study analyzed the changes of glacier mass balance in typical glacier recharge basin in arid and semi-arid areas, and estimated the contribution of glacier meltwater runoff to streamflow. The results provide a basis for a better understanding of the glacier-climate relationship and its impacts on streamflow.

Acknowledgements

This work was funded by the Third Xinjiang Scientific Expedition Program (2021xjkk0801), the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0201), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20060201, XDA20020102), and the National Natural Science Foundation of China (41761134093, 31760151).

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