Journal of Glaciology

Letter

Cite this article: Xu C, Li H, Wang F, Li Z, Zhou P, Liu S (2024). Heatwaves in summer 2022 forces substantial mass loss for Urumqi Glacier No. 1, China. *Journal of Glaciology* 1–5. https://doi.org/10.1017/jog.2024.4

Received: 11 May 2023
Revised: 3 December 2023
Accepted: 5 January 2024

Keywords:
climate change; glacier mass balance; glacier monitoring; heatwaves; Urumqi Glacier No.1

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Heatwaves in summer 2022 forces substantial mass loss for Urumqi Glacier No. 1, China

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Abstract

Extreme heat events in the summer of 2022 were observed in Eurasia, North America and China. Glaciers are a unique indicator of climate change, and the European Alps experienced substantial glacier mass loss as a result of the conditions in 2022, which prompted a wide range of community concerns. However, relevant findings for glaciers in China have not been currently reported. Here, we document the response of Urumqi Glacier No. 1 in the eastern Tien Shan to the extreme heat observed in 2022 based on in situ measurements that span more than 60 years. In 2022, Urumqi Glacier No. 1 exhibited the second largest annual mass loss on record, and the summer mass balance was the most negative on record. The hottest summer on record and relatively lower solid precipitation ratio contributed to the exceptional mass losses at Urumqi Glacier No. 1 in 2022, demonstrating the significant influence of heatwaves on extreme glacier melt in China.

1. Introduction

The unprecedented warmth of the summer of 2022 generated worldwide publicity. The World Meteorological Organization reported that global average air temperature in 2022 was 1.15 ± 0.13°C higher than the 1850–1900 mean, and 2022 was on track to be the fifth or sixth warmest year on record (WMO, 2022). Extremely high air temperatures covered Eurasia and North America, and China was also affected by the long-lasting extreme heat events (Lu and others, 2022). According to the Chinese National Climate Center, the average air temperature for the year 2022 in China was 0.62°C higher than the 1991–2020 average, presenting a warm-dry climate with the second-highest value in history (Fig. 1). Mean summer air temperatures in China were 1.10°C higher than the 1991–2002 average, and the highest value observed since 1961. There were 23 provinces in China with high air temperatures above 40°C and 366 national weather stations with daily maximum temperatures equal to or exceeding historical extremes (Chao and others, 2023).

Glaciers are unique indicators of climate variations (Zemp and others, 2015; Vargo and others, 2020). In the European Alps, glaciers experienced substantial mass loss in 2022 and the Swiss Academy of Sciences reported that 2022 was a 'disastrous' year and Swiss glaciers had lost more than 6% of their volume, which far outstripped the historic record since 2002 (WMO, 2022). Chinese mountain glaciers also undergo rapid changes against the backdrop of heatwaves, but relevant quantitative findings have not been currently reported.

Urumqi Glacier No. 1 is a northeast-facing mountain glacier at the source of the Urumqi River in eastern Tien Shan with an area of 1.52 km^2 in 2018 (Fig. S1; Li and others, 2022). The glacier is the only one in China that has more than 30 years of ongoing glaciological mass-balance measurements (WGMS, 2022). Previous studies show the variations of annual glaciological mass balance for Urumqi Glacier No. 1 agreed well with the mean value of global reference glaciers (Li and others, 2011). Thus, this glacier can probably reflect glacier status at large scales.

Summer air temperature records (1959–2022) at the nearby Daxigou Meteorological Station (~3 km southeast of Urumqi Glacier No. 1 at an altitude of 3539 m a.s.l.) show a significant increasing trend (Fig. 1). In the summer of 2022, the average air temperature at the Daxigou Meteorological Station was the highest on record, and consistent with the national annual mean air temperature across China. Based on the historical record of temperatures at Daxigou Meteorological Station, the summer temperatures observed in 2022 exceeded the 97.5% quantile (Fig. S2a) and are classified as an extreme event (Yan and others, 2002).

Changes in glacier mass balance are the undelayed response to climatic change (Huss and others, 2021). Here, we document the mass-balance response to extreme heat based on the extensive in situ measurements of mass balance at Urumqi Glacier No. 1.

2. Results and discussion

Glaciological mass-balance measurements for Urumqi Glacier No. 1 have been well documented by previous studies (e.g. Liu and others, 1997). Combining the uncertainty in glaciological measurement evaluated by Xu and others (2019), a total mass change of −0.042 ± 0.002 Gt was observed at Urumqi Glacier No. 1 from 1959 to 2022 and this corresponded to a cumulative

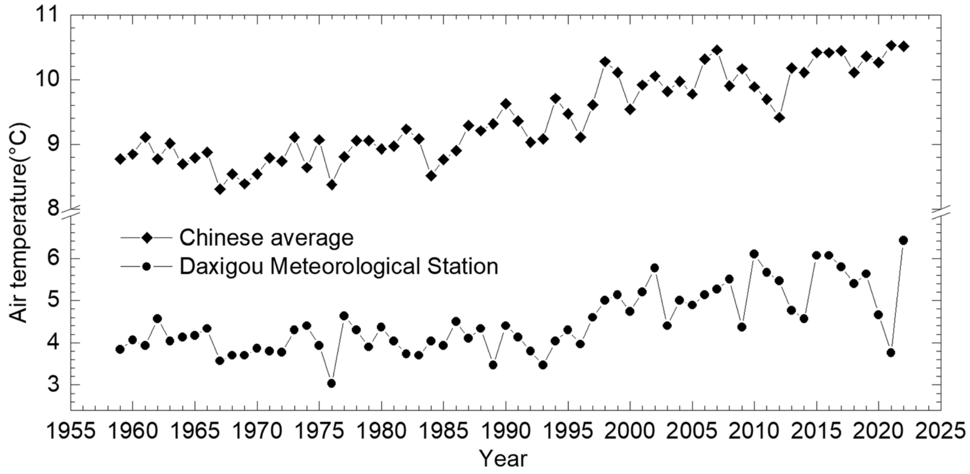

Figure 1. Average annual air temperature in China and summer air temperature (June–August) at the Daxigou Meteorological Station (nearby Urumqi Glacier No. 1) from 1959 to 2022. The climatic data are derived from the China Meteorological Data Service Centre.

mass balance of −21.98 ± 1.2 m w.e. Between 1959 and 2022, the glacier experienced two periods of accelerated ablation (Li and others, 2020). The net mass balance of Urumqi Glacier No. 1 in 2022 (−1251 ± 100 mm w.e.) was the second most negative value on record (Fig. 2). The lowest observed net mass balance was recorded in 2010 (−1327 ± 100 mm w.e.). Applying the same quantile thresholds as for air temperature, the net mass balance observed in 2022 exceeds the 97.5% quantile (Fig. S2b), and the summer balance observed in 2022 is the most negative on record (Fig. 2).

Decadal changes in glacier mass balance versus altitude help put the extreme conditions of 2022 in context. There was no accumulation area in 2022 and the mass balance at each altitude band was more negative than the annual average value of the 1990s, 2000s and 2010s, especially at higher altitudes (Fig. 3a). Compared with the previous 5 years (Fig. 3b), the mass balance of each altitude band in 2022 was especially negative at higher altitudes. As winter balances were not extremely low in 2022 (Fig. 2), we confirm that strong ablation at high altitudes drove substantial glacier mass loss in 2022.

Summer air temperature and annual precipitation are the main drivers controlling mass balance of Urumqi Glacier No. 1 (Liu and others, 1997; Li and others, 2020). The extreme summer air temperatures of 2022 (Fig. 1) are one of the major contributing factors to the extreme glacier mass loss. Precipitation phase is another important factor that affects glacier mass balance (Jouberton and others, 2022). At the headwaters of the Urumqi River, 99.5% of total precipitation falls as snow when the air temperature is below −2.0°C and <40% of total precipitation falls as snow when the air temperature is above 2.0°C (Chen and others, 2023). Daily mean temperatures observed at the Daxigou Meteorological Station were above −2°C for the whole summer of 2022. An automatic weather station (AWS) located at an elevation of 3835 m a.s.l. on a moraine ridge beside Urumqi Glacier No. 1 (Fig. S1) recorded air temperatures between −1.7 and 10.0°C throughout the summer of 2022 (Fig. S3), with average daily temperatures above 2°C. If we adopt the previously used threshold temperature of 0°C for solid/liquid precipitation separation at Urumqi Glacier No. 1 (Zhang and others, 2022), the solid precipitation at the AWS only accounted for 13% of the summer

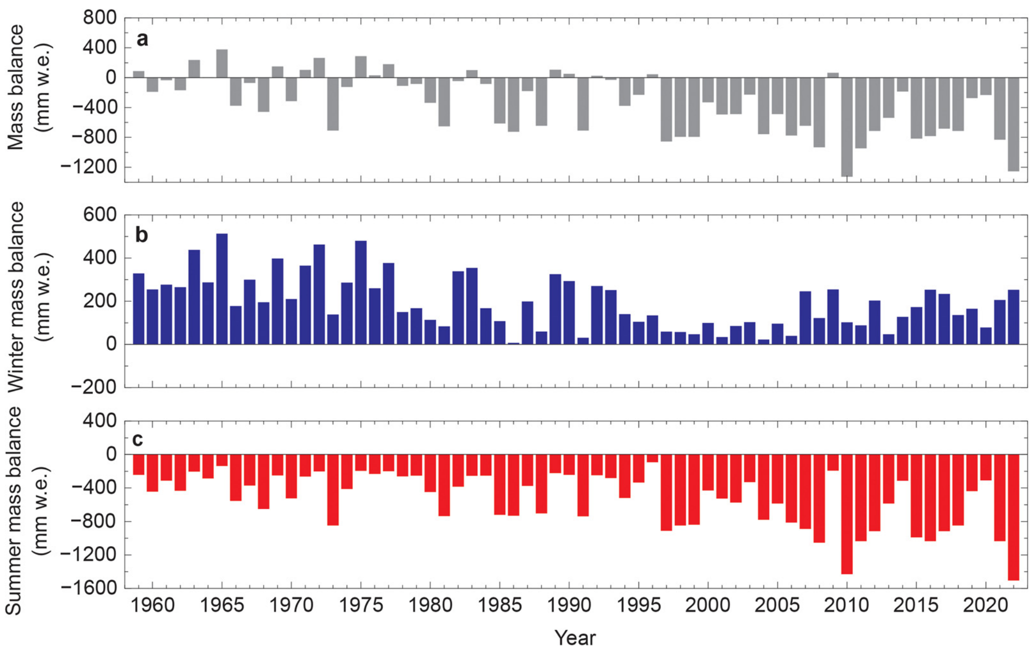

Figure 2. Annual (a), winter (b) and summer (c) mass balances for Urumqi Glacier No. 1 for the period 1959–2021.

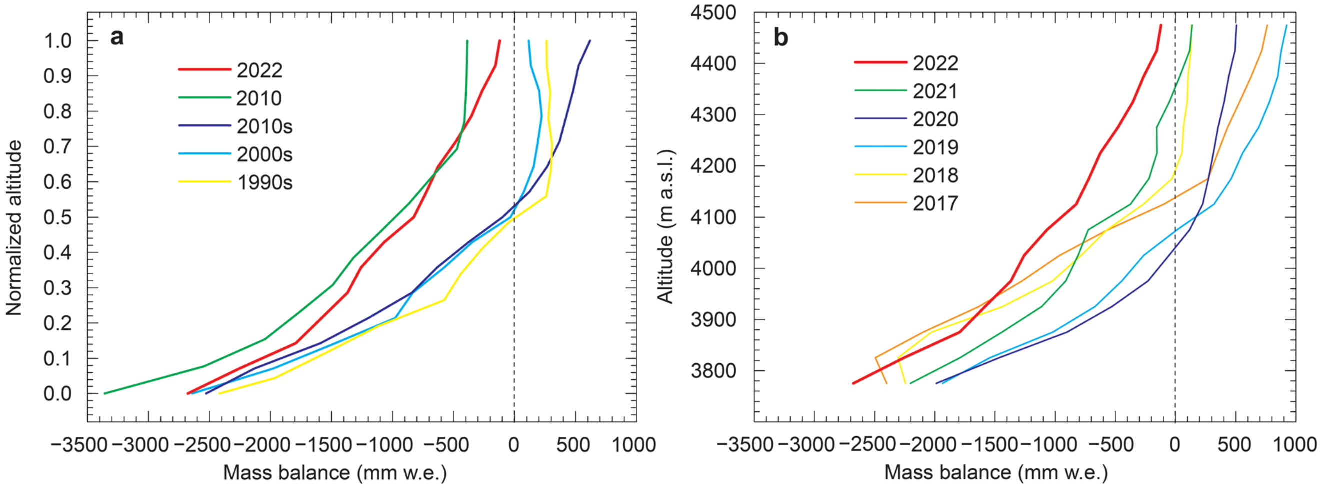

Figure 3. Comparison of the altitudinal distribution of glaciological mass balance on interdecadal (a) and annual (b) scales. Departures are derived from the 1959–2022 average. Normalized elevation is calculated as $(h-h_{min})/(h_{max}-h_{min})$, where h is the mid-value of each elevation band (50 m interval), h_{min} and h_{max} are the maximum and minimum mid-value of the elevation bands, respectively, for different periods. Note that the normalized elevation is used to have a better comparison of the observed results due to the retreat and the subsequent altitude increase of the glacier terminus.

total. The extreme summer temperatures observed in the region resulted in zero summer accumulation at Urumqi Glacier No. 1, and the total precipitation observed at Daxigou Meteorological Station over the 2022 mass-balance year was the lowest since 2010 (Fig. S4). The lower solid precipitation ratio, decreasing total precipitation and continuous high air temperature may jointly reduce glacier accumulation during the summer of 2022 (Jouberton and others, 2022).

The meteorological records at the Urumqi Glacier No. 1 AWS can theoretically result in a slight summer accumulation of 48 mm w.e. in 2022. However, this cannot compensate for the strong ablation caused by extreme summer air temperatures. A temperature-index model (Zhang and others, 2022) driven by

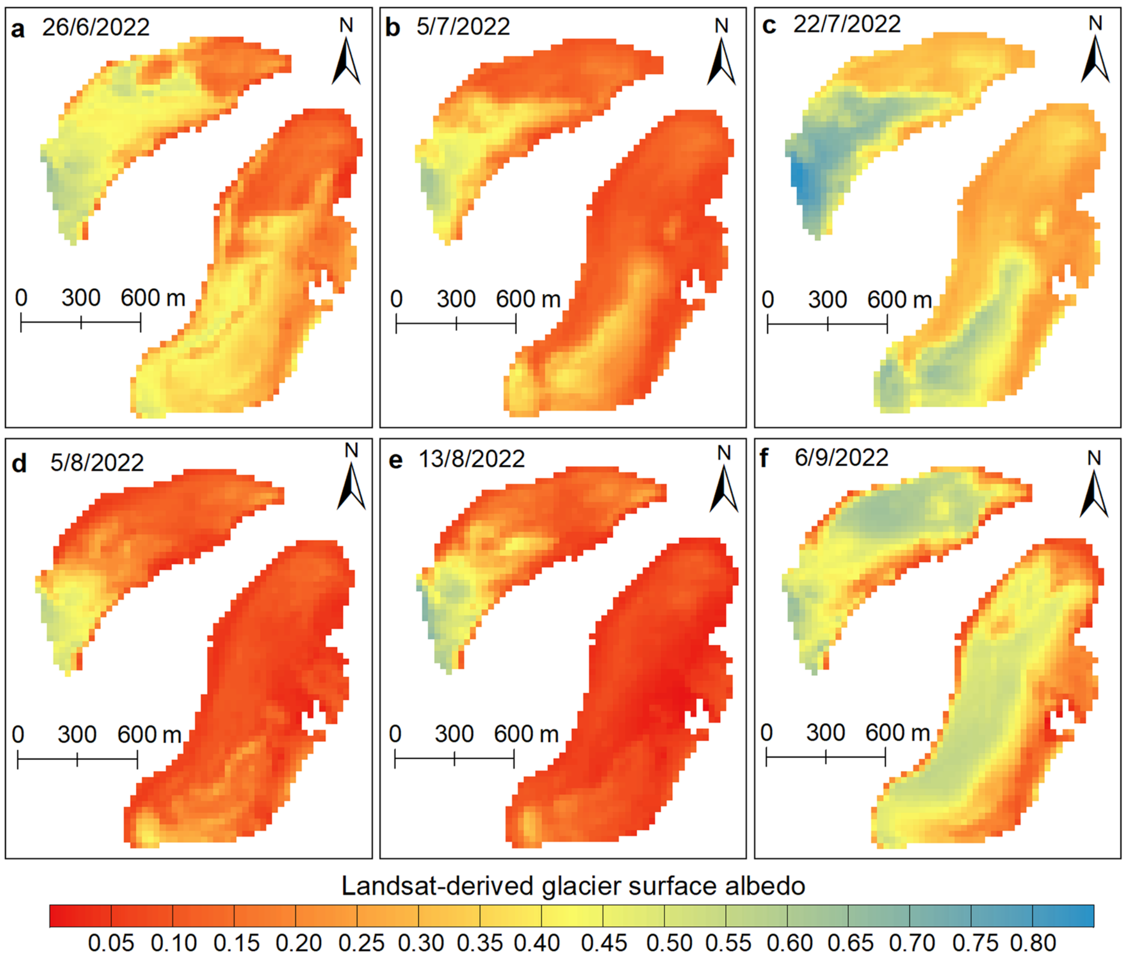

Figure 4. Spatial distribution of Landsat-derived surface albedo for Urumqi Glacier No. 1 on selected dates of the ablation period in 2022 (date: day/month/year).

https://doi.org/10.1017/jog.2024.4 Published online by Cambridge University Press

summer air temperatures observed at the AWS produces −2146 mm w.e. of summer ablation at the glacier terminus (3700–3750 m a.s.l.). This contributes to ~83.3% of the annual mass loss and to ~75.6% of the summer mass loss at the terminus. This model uses snow and ice melt degree-day factors of 7.4 and 2.6 mm $°C^{-1}$ d^{-1}, respectively, based on in situ measurements of summer mass balance at Urumqi Glacier No. 1 between 2001 and 2020 (Zhang and others, 2022). Previous studies have indicated that the temperature-index models have a good performance in simulating the mass balance of Urumqi Glacier No. 1 (Wu and others, 2011).

Glacier surface albedo is another key factor to influence mass balance by governing the quantity of net shortwave radiation. Here we selected six Landsat images on cloudless days to find the spatial distribution of surface albedo during the 2022 ablation season (see Supplementary Table S1; Liu and others, 1997). The process for deriving glacier surface albedo from Landsat images includes geolocation, radiometric calibration, atmospheric correction, topographic correction, anisotropic correction and narrow-to-broadband conversion, which have been described in detail by Yue and others (2017). The spatially distributed surface albedo presented relatively high values at the early (26 June 2022) and end (6 September 2022) of the ablation season. In the middle of the ablation season, the spatial pattern of surface albedo was characterized by lower values except for 22 July 2022; the proportion of surface albedo less than 0.30 (bare ice albedo value) was 79% on 5 July 2022, 0.91% on 5 August 2022 and 88% on 13 August 2022, respectively (Fig. 4). High albedos observed on 22 July 2022 are related to fresh snow cover, as air temperatures on the eve of the satellite transit were low enough to result in solid precipitation (Fig. S3). Overall, the mean surface albedos in the middle ablation season of 2022 ranged from 0.14 to 0.40, which were lower than the corresponding value for the normal mass-balance year of 2014 (Yue and others, 2017). The lower surface albedos, especially at higher elevations, may result in more negative mass balances for Urumqi Glacier No. 1 in 2022.

The response of glaciers to heat waves is a growing concern. For example, European heat waves contributed to 35% of the overall glacier mass loss in 2022, and 56% of the average summer mass loss between 2010 and 2020 (Cremona and others, 2022). In the Nooksack River basin, USA, heatwaves enhanced glacier ablation and increased discharge in the North Fork Nooksack River by 24% (Pelto and others, 2022). Our results indicate that Urumqi Glacier No. 1, and other glaciers in the region, are potentially more sensitive to heatwaves than glaciers in other mountain regions. The increasing intensity, frequency and duration of regional heatwaves around the world (Perkins-Kirkpatrick and others, 2020) will pose a substantial threat to mountain glaciers.

3. Conclusions

The annual glacier mass balance observed at Urumqi Glacier No. 1 in 2022 was the second most negative over a 60-year record, and the summer mass loss was the most negative on record. Meteorological records in the region indicate that the summer of 2022 was the hottest on record, and the extreme heat contributed to ~83.3 and ~75.6% of the annual and summer mass loss at the glacier terminus, respectively. The high summer temperatures resulted in a lower solid precipitation ratio, reduced summer snow accumulations and led to lower surface albedos especially at higher elevations. These factors contributed to the exceptional glacier mass losses observed at Urumqi Glacier No. 1 in 2022, and increasing trends in the frequency and severity of regional heatwaves will likely produce more extremes in glacier melt.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2024.4

Data. Glaciological mass-balance data for this paper are available at https://doi.org/10.5904/wgms-fog-2022-09. Meteorological data are available from the China Meteorological Data Service Centre (http://data.cma.cn/en) upon request.

Acknowledgements. This work was funded by the National Natural Science Foundation of China (42001067), the Third Xinjiang Scientific Expedition (TXSE) program (2021xjkk1401), Gansu Provincial Science and Technology Program (22ZD6FA005), State Key Laboratory of Cryospheric Science (SKLCS-ZZ-2022) and the National Cryosphere Desert Data Center (20D03). We are grateful to Joseph Shea (Scientific Editor), Hester Jiskoot (Associate Chief Editor) and two anonymous referees for their very constructive comments in improving the manuscript.

Author contributions. C. X. and Z. L. developed the concept of this study. H. L. and P. Z. collected and prepared the data. C. X. wrote the first draft of the manuscript. F. W. edited and reviewed the manuscript. S. L. contributed to the revision of the manuscript.

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