Different characteristics of two surges in Weigeledangxiong Glacier, northeastern Tibetan Plateau

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Keywords: glacier surge, climate change, surge process, Weigeledangxiong Glacier

Supplementary material for this article is available online

Abstract

Glacier surge is a special form of glacier displacement caused by the instability of the glacial dynamic system. It is a quasi-periodic oscillation behavior, which affects the estimation of the overall change of glaciers in the region and potentially threatens the infrastructure and human life in the downstream regions. Most glaciers experience a mass loss with rising air temperatures in recent decades, but little attention has been paid to the influence of climate change on glacial surges. This study identified two surges, triggered in 1992 and 2015 in Weigeledangxiong Glacier, Anyêmaqên Mountains, northeastern Tibetan Plateau, using multi-source remote sensing data (Landsat images, Sentinel-2 images, topographic map, shuttle radar topography mission digital elevation model [SRTM DEM], and the elevation change database). The 1992 surge accelerated abruptly with the maximum velocity of 350 ± 9 m a⁻¹, and a large volume of ice transported downward, causing a sudden advance of 392 ± 42 m from 1992 to 1994, and clear thickening of the ice tongue. The recent surge is still in the active phase, exhibiting a gentler process of slower advance speed and lower peak velocity, as well as a smaller expansion zone than the previous one. These phenomena may be associated with the reduced glacier basal resistance and energy caused by rising temperatures in recent decades. Higher temperatures may cause the discharge of subglacial water through a more developed drainage system, leading to a longer active phase duration. Similar phenomena may exist widely in the Tibetan Plateau and its surrounding areas. Meanwhile, the frontal position of Weigeledangxiong Glacier advancing in the recent surge is not expected to threaten roads near the ice tongue.

1. Introduction

Globally, most glaciers have experienced mass loss and area retreat under the influence of climate warming since the 1950s (IPCC 2019, Hugonnet et al 2021). A rise in the air temperature changes the dynamic equilibrium of glaciers (Ding et al 2019), inducing surges and collapses (Solgaard et al 2020, Shugar et al 2021). Such disasters can threaten infrastructure and human life in the downstream regions (Pritchard 2019, Veh et al 2020).

A surge is a special form of glacier displacement (Meier and Post 1969), representing a quasi-periodic oscillation behavior that includes active and quiescent phases (Sharp 1988). During the active phase, the surface velocity suddenly accelerates and reaches hundreds times of that observed during the quiescent phase (Dolgoushin and Osipova 1975). From this, large amounts of ice in the reservoir zone are transported to the receiving zone; the upper reservoir zone thins, the lower receiving zone thickens, and numerous crevasses are created (Cuffey and Paterson 2010).
This process usually lasts for several years and may be accompanied by advances of several kilometers at the frontal position (Sharp 1988). Although the number of surge-type glaciers is <1% of the total glaciers worldwide (Sevestre and Benn 2015), they widely exist in the Karakoram, Pamir, and Tien Shan regions, where glaciers are more concentrated in the Tibetan Plateau and its surrounding areas (TPs) (Guillet et al 2022). Surge-type glaciers affect the estimation of the overall change of glaciers in the region, thereby limiting the discussion of glacier change drivers, as well as the relationship between changes in glaciers and climate (Guan et al 2022). Moreover, glacier surges are the major inducing factors of glacial lake flooding and glacier debris flow, which may threaten infrastructure and human life (Bazai et al 2021, Hewitt and Liu 2013).

In recent decades, rising air temperatures have caused mass loss of the majority of glaciers in the TPs, thereby decreasing energy and velocity (Dehecq et al 2019). However, the influence of climate change on surges remains poorly understood. The influence of climate is reportedly more direct on glacier surges than on the recurrence interval (Kochtitzky et al 2020). Over the past few decades, englacial and subglacial temperatures have risen markedly under the influence of rising air temperatures (Ding et al 2019). Hydrological and thermal conditions during the surge would be altered under the joint influence of increasing precipitation, particularly for polythermal surge-type glaciers whose ice temperature is below the melting point in the upper region and close to the melting point in the lower region (Gilbert et al 2018). Such phenomenon implies that an increase in air temperature and precipitation may affect the surge process, thereby altering surge characteristics.

Two main theories regarding the surge mechanism have been proposed, namely, hydrological regulation (Kamb et al 1985) and thermal regulation (Murray et al 2003), common in the Alaska and Svalbard regions, respectively. In the TPs, although prior literatures have applied such models to describe surges in the region (Guo et al 2020, Guan et al 2022), recent studies have found that the mechanisms exclusively based on the evolution of hydrological or thermal processes may be unsuitable on polythermal surge-type glaciers in the TPs (Gao et al 2021, 2022, Jiang et al 2021). Moreover, the processes of surges in different periods on the same glacier may be affected by the variations in hydrological and thermal conditions caused by rising air temperature. This phenomenon may increase the confusion of explaining the surge process.

The Anyêmaqên Mountains are located in the northeastern part of the TPs and are the highest mountains of the East Kunlun Mountains (figure 1(a)). Precipitation in this region is abundant, primarily concentrated during May–September, and is influenced by the South Asian monsoon (Yao et al 2012, Li et al 2022), with the annual precipitation

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**Figure 1.** (a)–(c) Location of Weigeledangxiong Glacier on the maps of (a) the TPs and (b) the Æyêmaqên Mountains. (c) Weigeledangxiong Glacier with contour intervals and a centerline starting at the frontal position. Surface characteristics of the ice tongue in the (d) quiescence phase and (e) active phase. (f) Image of crevasses, with the photograph location shown as the red dot in (e). Glacier outlines in (b) use the second Chinese Glacier Inventory (Guo et al 2015). The background of (a) is elevation from SRTM DEM. The background image of (b) and (c) is the Sentinel-2B multi spectral instrument (MSI) image from 19 July 2021.
of ∼500–700 mm (Peng et al 2019). Polythermal glaciers have developed in the region, and the snow line altitude has moved upward from 1990 to 2020, reaching ∼5200 m in 2020 (Li et al 2022). The surge-type glacier in this region was first discovered by Paul (2019) via glacier elevation changes from different digital elevation model (DEM) data and evidence of crevasses and deposits evolution. Weigeledangxiong Glacier is the third largest glacier in the region (area of 12.53 km² in the 2000s) (Guo et al 2015) (figures 1(b) and (c)). Based on field investigations and historical remote sensing images, we found that the frontal region of Weigeledangxiong Glacier has recently bulged and formed a large number of crevasses on the surface. These crevasses started at the location where the direction of glacier displacement changed, parallel to the original displacement direction, and terminated at the lateral moraine (figures 1(d)–(f)). These phenomena have been confirmed by studies on other surge-type glaciers (Trantow and Herzfeld 2018, Muhammad and Tian 2020), suggesting that Weigeledangxiong Glacier is a surge-type glacier that has entered the active phase in recent years, and may threaten roads built on the lateral moraine near the ice tongue which is approximately 252 m from the glacier based on the 19 July 2021 Sentinel-2 remote sensing images. Understanding the active phase may improve the reliability of risks assessment and current management strategies.

To achieve a better understanding of the surge glacier, the objectives of this study were to: (a) identify the surges in Weigeledangxiong Glacier using the changes in the frontal position, surface elevation, and surface velocities obtained from remote sensing data; (b) explain the influence of climate change on the surges; and (c) forecast the changes in the recent surge to avoid potentially catastrophic damage.

2. Data and methods

2.1. Data

In this study, the time series of 33 Landsat images and seven Sentinel-2 images were used to obtain the frontal position and outlines from 1973 to 2021, and the annual surface velocities from 1989 to 2021 (tables 1 and S1). Level-1 precision after radiometric and geometric corrected products from the United States Geological Survey were used. All the images used in this study are multiband and cloud-free in the glacier region.

Two DEMs (Topo-DEM and C-band SRTM DEM) were used to quantify the changes in glacier elevation via the geodetic method (table 1). Topo-DEM was generated using a topographic map based on aerial survey data from July 1985 and drawn by the China Military Geodetic Survey at the 1:50 000 scale. During this process, the contour lines were manually digitized. Subsequently, the Thiessen polygon method was used to convert it to a grid DEM with 30 m grid cells. The vertical accuracy is 3–5 m in flat and hilly areas (slopes <6°), 5–8 m in mountainside areas (slopes 6–25°), and 8–14 m in the high mountainous areas (slopes >25°), according to the national photogrammetrical mapping standards (SAC 2008). The C-band SRTM DEM was acquired using interferometric synthetic aperture radar, and the data were obtained for the period of 11–22 February 2000 (Farr et al 2007). The vertical errors of the C-band SRTM DEM ranged from 7.2 to 12.6 m (Rodríguez et al 2006).

To analyze comprehensive changes in the surface elevation, a 5 year interval (in 2000–2020) glacier surface elevation change database from Hugonnet et al (2021) was applied. In this database, DEMs were generated using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite stereo images and photogrammetry techniques. The co-registration and bias correction methods for different DEMs from Nuth and Kääb (2011) were used. To mitigate the seasonal effects, continuous elevation time series were generated by interpolation from all the available DEMs through the temporal covariance of glacier elevation change. This database provides 5 year interval data in free access.

ERAS reanalysis data (hourly, ∼30 km) were used to analyze the changes in air temperature and precipitation in the Weigeledangxiong Glacier region (table 1). These data contained long-term air temperature and precipitation data to analyze the relationship between changes in glaciers and climate (Hersbach et al 2020).

2.2. Glacier length changes and uncertainty

The band ratio method has been widely used in glacier mapping, which can identify glaciers using the low spectral reflectance in short-wave infrared and the high spectral reflectance in the visible spectrum over ice and snow (Paul et al 2015). Here, the frontal position and outlines of Weigeledangxiong Glacier were derived from Landsat and Sentinel-2 optical images by this method, except Landsat MSS images without short-wave infrared bands. To obtain glacier frontal positions and outlines from the Landsat MSS images, a manually digitized method was used. Finally, all the glacier frontal positions and outlines were modified by manual interpretation using SRTM and Google Earth images.

The positioning accuracy of the images and indistinguishable mixed pixels on the glacier outlines are generally the main sources for uncertainty in extracting the frontal position and outline (Paul et al 2013). The Landsat and Sentinel-2 images used in this study were corrected geometrically. Their positioning accuracy has been previously elucidated, and all of them are much less than half of the pixels (Guan et al 2022, Millan et al 2022). Considering the mixed pixels on the outlines in the images, the uncertainty of the frontal position was <1 pixel of the used image.
We used a method similar to that proposed by Minora et al. (2016) to estimate the uncertainty in glacier area, which takes into account both the uncertainty of the data source and the clarity of glacier outlines in the image (Citterio et al. 2007). The uncertainty of the glacier area \(E_A\) was 0.6%–3.5%, according to formula (1):

\[
E_A = l \times \sqrt{\text{LRE}_{xy}^2 + E_{co}^2}
\]

where \(E_A\) is the uncertainty of area extraction, \(l\) is the length of glacier outlines (excluding ridge lines and common part of adjacent glaciers), \(\text{LRE}_{xy}\) is the resolution error of the optical image in different periods (measured by half-pixel error), and \(E_{co}\) is the image registration error.

### 2.3. Glacier surface elevation changes and uncertainties

Glacier surface elevation change rates from 1985 to 2000 can be calculated by subtracting Topo-DEM from the SRTM DEM, and subsequently dividing by the interval between them (14.5 years). Multitemporal DEMs require co-registration to eliminate both horizontal and vertical offsets (Pieczonka et al. 2013). Hence, we co-registered DEMs via the method described by Nuth and Kääb (2011). All the DEMs were resampled at the same resolution (30 m). The spatial resolution differences between different DEMs can cause altitude-related vertical deviations in the mountains. We corrected this deviation using the relationship between the maximum curvature and elevation difference proposed by Gardelle et al. (2012).

SRTM-C band signals can penetrate a glacier in varying degrees. The transmission depth is generally 0–10 m and is related to the glacier surface characteristic differences, such as the particle size of snow and thickness of the snow layer (Gardelle et al. 2012). The transmission depths of the SRTM-X band in the ice and snow bands are negligible. The difference between the SRTM-C and SRTM-X bands in the glacier region after co-registration likely represents the penetration depth of the SRTM-C band on glaciers (Gardelle et al. 2012), which was estimated as \(\sim 5.2\) m in this region.

Here, the elevation difference between DEMs obtained on ice-free terrain with a slope lower than 10° around Weigeledangxiong Glacier was used to estimate the accuracy of them. The elevation difference between Topo-DEM and SRTM-C was \(-6.72–7.75\) m. The elevation difference between DEMs from Hugonnet et al. (2021) was \(-0.54–0.46\) m (figure S1). The uncertainty in the differences between DEMs was estimated using the normalized median absolute deviation (NMAD) (Shangguan et al. 2015) for ice-free and stable areas. The uncertainty between Topo-DEM and SRTM DEM was 5.88 m. The uncertainty between DEMs from Hugonnet et al. (2021) was \(<0.1\) m:

\[
\text{NMAD} = 1.486 \times \text{MED}(|\tilde{x} - x_i|)
\]

where \(x_i\) is elevational difference, and \(\tilde{x}\) is the median of elevational difference.

### 2.4. Glacier surface velocity changes and uncertainty

In this study, the annual surface velocities of Weigeledangxiong Glacier from 1989 to 2021 were obtained from Landsat and Sentinel-2 images using a frequency cross-correlation algorithm in the co-registration of optically sensed images and correlation package (COSI-Corr, a visual plug-in in the Environment for Visualizing Images [ENVI] software) (Leprince et al. 2007). This algorithm can obtain glacier surface displacement by automatically tracking similar features between different images, and the accuracy of glacial surface displacement obtained can reach subpixel levels (Heid and Kääb 2012). This process involves two steps: (a) an initial window was used to estimate the shift between images at a multi-pixel scale; (b) a final window was operated to retrieve the subpixel displacement based on the Fourier shift theorem. Considering the maximum velocity of Weigeledangxiong Glacier and the computational efficiency, the initial and final window sizes were set as 32 (96 for Sentinel-2 images) and 8 (24 for Sentinel-2 images) for the Landsat images, respectively. Sam et al. (2015) found that surface velocity estimation can be affected by bandwidths. Considering the effects of atmospheric scattering, near-infrared bands with longer wavelengths shared in different images (Landsat TM/ETM+: band 4,
Landsat OLI: band 5, Sentinel-2: band 8) were used to extract velocities.

After the cross-correlation calculations, the displacement results were filtered by a multi-step filter. First, we excluded the values with low correlation (signal-to-noise ratio <1.6) (Ayoub et al. 2009). Second, each horizontal displacement direction grid and the aspect grid were compared, and the displacement with anomalous flow direction (difference >60°) was removed (Ruiz et al. 2015). Third, the unrealistic magnitudes were removed using the method from Guan et al. (2022).

The uncertainty of glacier velocities was primarily caused by inaccuracies in the image co-registration and surface feature changes over time (Quincey et al. 2011), which are usually assessed using the displacement obtained from the ice-free and stable terrain (Paul et al. 2017). All the surface displacements on ice-free terrain with the slope of <10° around Weigeledangxiong Glacier were analyzed, and the mean uncertainty of displacement was 6.25 m (figure S2).

3. Results

The long temporal span and high resolution of remote sensing data revealed dramatic changes in the frontal position, surface elevation, and velocities of Weigeledangxiong Glacier for the past 48 years. The frontal position retreated by 703 ± 79.6 m during the study period, but the change trend differed or was even opposite (figures 2(a) and S3). The frontal position continuously retreated at 415 ± 85 m from 1973 to 1992. Subsequently, it suddenly advanced to 392 ± 42 m from 1992 to 1994 with a maximum speed reaching 369 m a\(^{-1}\) (figures 2(d) and (e)). The frontal position then continuously retreated to 806 ± 32 m from 1994 to 2017, exhibiting a relatively slow advance after 2017 with a mean speed of 31.5 m a\(^{-1}\) (figures 2(f) and (g)). The area of Weigeledangxiong Glacier decreased 1.03 ± 0.48 km\(^2\) from 1973 to 2021, exhibiting two periods of shrinking and expansion that occurred within the study period.

Weigeledangxiong Glacier exhibited accelerated thinning with the mean rate of \(-0.17 \pm 0.01\) m a\(^{-1}\), and the ice volume continually decreased with the mean rate of \((\sim 22.81 \pm 1.64) \times 10^3\) m\(^3\) a\(^{-1}\) during 2000–2020 (table S2). The changes in the surface elevation of Weigeledangxiong Glacier exhibited different spatiotemporal patterns during 1985–2020 (figures 2(b) and S4). From 1985 to 2000, the glacier clearly thickened at the tongue and in the zone above 5.2 km from the frontal position, where the maximum thickening of 26.2 ± 5.88 m. While the glacier thinned in the middle region, with the mean thinning rate of \(\sim 0.59\) m a\(^{-1}\). From 2000 to 2015, the glacier continued to slightly thin in the zone above 5.2 km from the frontal position, meanwhile, it considerably thinned in the zone below 2 km from the frontal position but the thinning rate gradually decreased. The glacier slightly thickened in the middle region, and the thickening rate gradually decreased until reaching approximately 0 in 2010–2015. From 2015 to 2020, the glacier thinned in the zone above 2 km and below 1.1 km from the frontal position and evidently thickened in 1.1–2 km from the frontal position.

The surface velocities of Weigeledangxiong Glacier exhibited strong spatiotemporal variations during the study period. The surface velocity distributed along the centerline from 1989 to 2021, showing that the rapid flow was primarily clustered in the zone below the equilibrium line altitude (ELA). Moreover, it exhibited several different levels of acceleration, including two accelerations in the lower part and one acceleration–deceleration process in the upper part (figure 2(c)). The first sudden acceleration in the lower part occurred after 1992, following a slight acceleration. Then, the velocities almost stagnated after reaching a maximum velocity during 1993–1994, and the maximum velocity occurred in the zone \(\sim 1\) km from the frontal position, eventually reaching \(350 \pm 9\) m a\(^{-1}\). The zone below 2 km from the frontal position almost stagnated during 1994–2015. However, the velocities exhibited the acceleration–deceleration pattern in the upper part (\(2–5\) km from the frontal position) during this period, with the maximum velocity of \(264 \pm 5\) m a\(^{-1}\) during 2005–2006. The second acceleration in the lower part occurred after 2017, following an acceleration in 2015 in the upper part and passed down gradually, and still flowing rapidly. The duration and velocity of the rapid flow of the second acceleration were substantially longer and lower, respectively, compared to those of the first acceleration. In addition, we found that the velocity almost stagnated before both accelerations in the lower part (figure 2(c)).

4. Discussion

4.1. Glacier evolution and surge identification

The changes in the glacier length, surface elevation, and surface velocity of Weigeledangxiong Glacier revealed two surges triggered in 1992 and 2015. The glacier accelerated abruptly, and large volume of ice was transported from the upper part to the lower part from 1992 to 1994 (figure 2(c)), causing a sudden advance in the glacier frontal position (figure 2(a)) and clear thickening of the ice tongue (figures 2(b) and S4(a)). These results suggest that Weigeledangxiong Glacier entered the active phase in 1992 and the active phase lasted for two years. During the active phase, the zone above the ELA was stagnant and thickened (figure 2(b)), whereas the zone below the ELA flowed rapidly (figure 2(c)) and thinned above 1 km from the frontal position. These phenomena likely indicate that the reservoir zone of 1992 surge was below the ELA.
Weigeledangxiong Glacier flowed rapidly from 1997 to 2010 (figure 2(c)), the zone above the ELA thinned, and the zone below the ELA to 2 km from the frontal position thickened from 2000 to 2015 (figures 2(b) and 54(b)–(d)). These findings suggest that the ice in the accumulation zone was transported to the reservoir zone to replace the mass loss caused by the surges.

The evident acceleration after 2015 suggests that a large amount of ice was transported downward (figure 2(c)), accumulated near 1.5 km from the frontal position (altitude range = 4500–4600 m), and caused a clear thickening. The ice tongue showed thinning, but the rate was less than that in 2000–2015 (figures 2(b) and 54(e)). The frontal position continued advancing after 2017, following the retreat from 1994 to 2017 (figure 2(a)). These phenomena suggest that Weigeledangxiong Glacier surged again in 2015 and that it is still in the active phase in 2021.

4.2. Influence of climate change on surge behaviors

Comparing the characteristics of the two surges of Weigeledangxiong Glacier, the distance and speed of frontal position advancement became shorter and slower during the active phase in the recent surge, and the duration of the active phase became longer (figure 2). Similar phenomena were identified in most surges both in the positive mass balance regions, such as Karakoram (Bhambr et al. 2017) and Pamirs (Goerlich et al. 2020), and in the negative mass balance regions, such as Tien Shan (Mukherjee et al. 2017, Zhou et al. 2021), in the TPs (table S3). These phenomena may be attributed to the increase in air temperature (Flowers et al. 2011).

ERA5 reanalysis data show that the air temperature variations from 1970 to 1997 in the Weigeledangxiong Glacier region, and then increased by ∼0.81 °C from 1997 to 2021 at the rate of 0.34 °C dec−1. The precipitation increased by ∼106.26 mm, with an overall increase of ∼16%, compared to that in 1970 (figure 3). The ground temperatures around Weigeledangxiong Glacier ranged from −3 °C to −6 °C (Obu et al. 2019). Increasing air temperatures cause increases in both englacial and subglacial temperatures, resulting in the reduction of the glacier basal resistance owing to the increased subglacial melt and less frozen areas at the bedrock (Kääb et al. 2018). Thus, less mass in the reservoir
Figure 3. (a) Annual air temperature anomaly and (b) annual precipitation anomaly in the Weigeledangxiong Glacier region from 1970 to 2021 obtained from ERA5 reanalysis data. The dark gray dotted line indicates the air temperature and precipitation trend. The light gray and purple shaded areas represent the quiescent phase and active phase of Weigeledangxiong Glacier, respectively.

zone during the later surge than that during the previous surge could cause the basal shear stress to reach critical levels, breaking the dynamic equilibrium and triggering the surge. Compared to the 1992 surge, the surge energy in 2015 decreased, resulting in a gentler process of slower advance speed and lower peak velocity, and a smaller glacier expansion zone. These results suggest that the frontal position advancement of Weigeledangxiong Glacier in the recent surge would not exceed the maximum zone of the last surge and thus is unlikely to threaten roads near the ice tongue.

Previous studies have shown that subglacial high-pressure water may be the ultimate cause of a surge, and the magnitude of subglacial high-pressure water may control the surge extent (Murray et al. 2003). Therefore, the longer duration of the active phase of 2015 surge (figure 3) was potentially governed by the decrease in subglacial water pressure. The increase in ice temperature likely facilitated the development of the subglacial drainage system during the reorganized subglacial drainage system after entering the active phase. Additionally, rising air and ice temperatures, increasing precipitation, and the development of englacial channels potentially facilitated this process (Usman and Furuya 2018). It seems that water at the bottom of the glacier was discharged by a more developed drainage system, compared to that in the previous surge.

Several surges on the same surge-type glacier generally exhibited a similar magnitude of change during the surge (Kochtitzky et al. 2019). In this study, we found that the characteristics of the two surges of Weigeledangxiong Glacier are different markedly. A similar phenomenon has not been observed in previous studies on surges. The duration of the 1992 surge was relatively short (∼2 years), with rapid acceleration and deceleration, accompanied by rapid advancement of the terminal position. These characteristics suggest that the 1992 surge was similar to the surge affected by hydrological mechanisms. This finding further indicates that the high-pressure water of 1992 surge was primarily originated from surface melting and precipitation, which could not be discharged by an inefficient drainage system (Kamb 1987). However, the 2015 surge showed a long period of stable and fast flow with a relatively low velocity, suggesting that it may have been triggered by a rise in subglacial temperature, and that the surge process was affected by the discharge of subglacial high-pressure water caused by rising temperature. This may mean that the hydrological and thermal conditions were developed simultaneously with increasing temperature and precipitation. Therefore, models exclusively based on the evolution of hydrological or thermal conditions would not be suitable to describe the surges of Weigeledangxiong Glacier. These conjectures about the two surges of Weigeledangxiong Glacier require further investigation using more detailed data.

5. Conclusion

In this study, the evolution of Weigeledangxiong Glacier since 1973 was obtained by detailed changes in length, surface elevation, and surface velocities extracted from 33 Landsat images, seven Sentinel-2 images, two DEMs, and the elevation change database. Two surges of Weigeledangxiong Glacier triggered in 1992 and 2015 were identified, and the 2015 surge was still in the active phase. Over the past few decades, the englacial and subglacial temperature rise caused by rising air temperatures has resulted in a reduction of the glacier basal resistance. Thus, the less mass in the reservoir zone than that in the previous
surge could reach the critical basal shear stress, and the energy was reduced when the surge was triggered. These factors may have resulted in a gentler process of slower advance speed and lower peak velocity, and a smaller expansion zone of the 2015 surge than 1992 surge. The increased temperatures caused conditions under which the subglacial drainage system was easier to develop, and the subglacial water might be discharged through a more developed drainage system than that in the previous surge. This phenomenon likely contributed to the longer duration of the active phase of 2015 surge. Similar phenomena may exist extensively in the TPs. This probably means that the frontal position advancement of Weigeledangxiong Glacier during the recent surge is not expected to threaten roads near the ice tongue. Recently, the hydrological and thermal conditions of glaciers developed simultaneously with increasing temperature and precipitation, hence these additional factors need to be considered in the analysis of the surge process.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This study is financially supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP, Grant No. 2019QZKK0205), National Natural Science Foundation of China (Grant Nos. 42071077 and 42171148). Landsat and Sentinel-2 images were obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/). The C-band and X-band SRTM DEMs were obtained from the USGS and the German Aerospace Center (DLR) (https://download.geoservice.dlr.de/SRTM_XSAR/), respectively. ERA5 reanalysis data was obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 climate reanalysis (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-mean-sea-level-pres?tab=form). A five-year interval (during 2000–2020) glacier surface elevation change database was obtained from the source data from Hugonnet et al. (2021) (https://doi.org/10.6096/13)

Author contributions

Bo Cao, Baotian Pan and Guangjian Wu designed the study. Weijin Guan processed the data and prepared manuscript. Menghan Shi, Jiaimei Cheng and Donghui Shangguan provided assistance for literature search and manuscript editing. Wanqin Guo provided assistance for data analysis. All authors have read and approved the content of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Bo Cao, Baotian Pan and Guangjian Wu designed the study. Weijin Guan processed the data and prepared manuscript. Menghan Shi, Jiaimei Cheng and Donghui Shangguan provided assistance for literature search and manuscript editing. Wanqin Guo provided assistance for data analysis. All authors have read and approved the content of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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