Thinning and surface mass balance patterns of two neighboring debris-covered glaciers in southeastern Tibetan Plateau

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Abstract. Debris-covered glaciers are a common feature of the mountain cryosphere in the southeastern Tibetan Plateau. A better understanding of these glaciers change is necessary to reduce the uncertainties of the regional water resource variability, and to anticipate potential cryospheric risks. In this study, we quantify seasonal thinning (d*h*) and surface mass balance(SMB) patterns of two neighboring debris-covered glaciers (23K Glacier and 24K Glacier) in the southeastern Tibetan Plateau with repeated unpiloted aerial vehicle (UAV) surveys and *in-situ* measurements (13th Aug. 2019 - 20th Oct. 2020). We observe that the thinning magnitude of 23K Glacier is ~2-7 times greater than that of 24K Glacier for annual and cold periodsperiod. d*h* pattern of 23K Glacier is distinct from that of 24K Glacier, despite their proximity. The surface velocity of 24K Glacier is higher than that of 23K Glacier (~5-6 times) for all periods. The d*h* magnitude of the 23K Glacier is ~1.4-3.0 times greater than that of the 24K Glacier at all periods, which is mainly driven by the stronger dynamic state of 24K Glacier. The contrasted behaviour between the two glaciers is also valid in the early twenty-first century. In contrast with the thinning patterns, the surface mass balanceSMB patterns of the two glaciers closely agree across the different periods.are generally in agreement at different periods. The debris thickness distribution correlates with the SMB spatial distribution for both glaciers, while the supraglacial ice cliffs and ponds area density distribution is not correlated with SMB spatial distribution. We find that the debris thickness distribution strongly correlates with the spatial distribution of surface mass balance for both glaciers (23K Glacier: r=0.88; 24K Glacier: r=0.82). Ice cliffs and supraglacial ponds are prevalent (~4.4-7.2 ± 0.5 %) and enhance melt overall (enhancement factor: ~–2.5), but do not control the overall surface mass balance pattern of either glacier. This high-resolution comparison study of two neighboring glaciers confirms the significance of both glacier dynamic and debris thickness in controlling the thinning and melt for the different type debris-covered glaciers of the southeastern Tibetan Plateau in the context of climate change.

1 Introduction

Monsoon-influenced glaciers in the southeastern Tibetan Plateau have experienced more significant mass loss than in most other regions of High Mountain Asia in the past two decades (Kääb et al., 2012; Yao et al., 2012; Brun et al., 2017; Shean et al., 2020; Hugonnet et al., 2021). And tTThe percentage of debris-covered area as a proportion of the total glacierised area in the southeastern Tibetan Plateau was estimated at ~17-19%, which exceeds the proportion of debris-covered glaciers at the global scale (~4.4%-7.3%; Scherler et al., 2018; Herreid and Pellicciotti, 2020). Notably, the rate of thinning of debris-covered glaciers is close to that of debris-free glaciers in the southeastern Tibetan Plateau (Neckel et al., 2017; Brun et al, 2019; Ke et al., 2020), therefore a A betterdeeper understanding of the evolution and mass balance patterns of debris-covered glaciers in the southeastern Tibetan Plateau is essential for constrainingunderstanding changes in regional water resources (Zhang et al., 2011; Neckel et al., 2017). Because potentially hazardous glacial lakes can develop on or in front of debris-covered glaciers (Wang et al., 2011; Allen et al., 2019; Racoviteanu et al., 2022), and because glacier thinning may affect slope stability (Kääb et al., 2021; An et al., 2022; Zhao et al., 2022), expanding this knowledge base may also inform understanding of mountain geohazards.and the mechanism of potential glacier-related hazards such as the glacial lake outburst floods (Wang et al., 2011; Allen et al., 2019) or ice-rock avalanches in the southeastern Tibetan Plateau (Kääb et al., 2021; An et al., 2022; Zhao et al., 2022).

The presence of debris can influence the glacial response to climate change due to melt-buffering effect of supraglacial debris cover that exceed a few centimeters in thickness (Østrem, 1959; Nakawo et al., 1999; Nicholson and Benn, 2006; Reid and Brock, 2010; Anderson and Anderson, 2016; Yang et al., 2017)Debris-covered glaciers are globally widespread (Scherler et al., 2018; Herreid and Pellicciotti, 2020)., and their response to climate change is considerably different to that of debris-free glaciers due to the melt-buffering effect of supraglacial debris cover that exceed a few centimeters in thickness (Østrem, 1959; Nakawo et al., 1999; Nicholson and Benn, 2006; Reid and Brock, 2010; Yang et al., 2017). However, some satellite remote sensing studies have found similar thinning rates for debris-free and debris-covered glaciers (Kääb et al., 2012; Gardelle et al., 2013; Pellicciotti et al., 2015; Brun et al., 2019);. tThere is even a higher thinning rate of debris-covered- compared to debris-free glaciers in the Lahaul and Spiti region, Indian Himalaya (Vincent et al., 2013) and several studies also confirm the strong surface thinning of debris-covered glaciers in the southeastern Tibetan Plateau (-0.52- -0.83 $m\ a^{-1}$; Neckel et al., 2017; Ke et al., 2020). This phenomenon has been referred to as the “debris-cover anomaly” (Pellicciotti et al., 2015; Vincent et al., 2016). Ice cliffs and supraglacial ponds could partly explain this anomaly, because they are directly exposed to incoming radiations and therefore act as melt “hotspots” (Sakai, 1998, 2002; Reid and Brock, 2014; Juen et al., 2014; Steiner et al., 2015; Buri et al., 2016; Miles et al., 2016; Miles et al., 2018; Buri et al., 2021). The areas influenced by cliffs and ponds are characterized by high melt rates relative to surrounding debris-covered ice based on the differencing of high-resolution digital elevation models (DEMs) and energy-balance modelling (Thompson et al., 2016; Brun et al., 2018; Miles et al., 2018, 2022; Buri et al., 2016, 2021; Kneib et al., 2022; Sato et al., 2021; Mishra et al., 2021; Miles et al., 2022). However, some studies have found researchers consider that the insulating effect of debris cover has a larger effect on total thinning than the enhanced ice ablation from ice cliffs and supraglacial ponds area (e.g., Hambrey et al., 2008; Vincent et al., 2016; Brun et al, 2018; Anderson et al, 2021a). Additionally, glacier dynamics play an essential role that influences debris-covered glacier elevation change, and the rapid thinning of debris-covered glaciers is speculated to be partly caused by declining ice flow (Nuimura et al., 2017; Brun et al., 2018; Anderson et al., 2021a, 2021b; Rounce et al., 2021). However, to date this has been evaluated with precision at very few sites, none of which are in the southeast Tibetan Plateau. Despite this difference, some studies have found that the debris-covered glaciers and debris-free glaciers possess comparable thinning rates (Kääb et al., 2012; Immerzeel et al., 2013; Gardelle et al., 2013; Pellicciotti et al., 2015; Brun et al., 2019), and this phenomenon has been called the “debris-covered anomaly” (Pellicciotti et al., 2015; Vincent et al., 2016). This anomaly could partly be explained by the presence of ice cliffs and ponds at the surface of these glaciers. Ice cliffs and supraglacial ponds are common features of debris-covered glaciers (Sakai et al., 1998, 2000), they are directly exposed to incoming radiations and therefore act as melt ‘hotspots’ (Sakai, 1998, 2002; Reid and Brock, 2014; Juen et al., 2014; Steiner et al., 2015; Buri et al., 2016; Miles et al., 2016; Miles et al., 2018; Buri et al., 2021). The areas influenced by cliffs and ponds are characterized by high thinning and melt rates (~ 6–10 times) relative to surrounding debris-covered ice in the southeastern Tibetan Plateau (Miles et al., 2022), as revealed by the differencing of high-resolution DEMs and the results of energy-balance modelling (Thompson et al., 2016; Brun et al., 2018; Miles et al., 2018, 2022; Buri et al., 2016, 2021; Kneib et al., 2022; Sato et al., 2021; Mishra et al., 2021). There is a debate on the so-called ‘debris cover anomaly’ phenomenon since some research considers that the insulating effect of debris cover has a larger effect on total thinning than the enhanced ice ablation due to exposed ice cliffs and supraglacial ponds (e.g., Hambrey et al., 2008; Vincent et al., 2016; Brun et al, 2018; Anderson et al, 2021a). Some studies have confirmed the effect of the debris thickness spatial distribution on the physical mechanisms of ablation (Mihalcea et al., 2008; Zhang et al., 2011; Reid et al., 2012; Juen et al., 2014; Gibson et al., 2017; McCarthy et al., 2017). One also needs to take into account the contribution of glacier dynamics on glacier thinning, which could be reduced for long, stagnating debris-covered glacier tongues (Nuimura et al., 2017; Brun et al., 2018; Anderson et al., 2021a, 2021b; Rounce et al., 2021). This has led to the hypothesis that the similar thinning rates of debris-covered and debris-free glaciers in High Mountain Asia is primarily caused by differences in ice dynamics (Nuimura et al., 2017; Brun et al., 2018; Rounce et al., 2021).

These hypotheses therefore need to be supported with very high-precision data to account for the local effects of these melt hotspots. Since ice cliffs and supraglacial ponds tend to have a relatively small area and be very changeabledynamic (Miles et al., 2017; Kneib et al., 2021), it is challenging to accurately track their evolution over time and quantify their contribution to melt (Mishra et al., 2021; Kneib et al., 2022). Because of these challenges, studies which have investigated their spatial distribution, dynamics, and melt contribution have typically utilized unpiloted aerial vehicle (UAV) or very high-resolution optical satellite data (Immerzeel et al., 2014; Brun et al., 2016; Brun et al., 2018; Mölg et al., 2019; Anderson et al., 2021a; Kneib et al., 2021, 2022; Mishra et al., 2021; Sato et al., 2021). These studies confirm the potential for investigating glacier- or sub-glacier-scale domains based on hHigh-resolution data, which can provide detailed observations of local processes (e.g., Westoby et al., 2020). In the meantime， high-resolution data are also required for disentangling the glaciers thinning patterns.

The use of UAVs can overcome some shortcomings associated with in-situ (i.e. ground-based) observation (e.g., limited spatial representation) and satellite remote sensing data (e.g. insufficient resolution and vulnerability to cloudy and rainy weather), which has led to hence the increasing application of UAV technology in glaciological studies worldwide, including in debris-covered glacier settings (Hugenholtz et al., 2013; Immerzeel et al., 2014; Kraaijenbrink et al., 2016; Wigmore and Mark, 2017; Fugazza et al., 2018; Rossini et al., 2018; Bash and Moorman, 2020; Westoby et al., 2020; Cao et al., 2021; Mishra et al., 2021; Xu et al., 2022). High-precision digital elevation models (DEMs) and orthophotos can be obtained relatively easily from UAV images processed using Structure-from-Motion (UAV-SfM) with multi-view stereo photogrammetry (Westoby et al., 2012; Benoit et al., 2019). However, there are few studies that estimate the seasonal or annual surface mass balance (SMB) of debris-covered glaciers based on repeated UAV data.

Here we systematically compare the glacier change patterns of two neighboring debris-covered glaciers, 23K Glacier and 24K Glacier, in the southeastern Tibetan Plateau for the period from 13th August 2019 to 22nd October 2020 by using change detection applied to high-resolution repeated DEMs and orthoimages acquired via UAV-SfM surveys, and *in-situ* measurements. The glaciers are located in the same catchment and climatic setting, but the topography of the glaciers, as well as their dynamic behaviors and supraglacial debris thickness differs varies considerably. The objective of this study is to explore the factors that control the inter-glacier variability in surface thinning (d*h*) and surface mass balance (SMB) patterns of these two glaciers, with a view to advance theadvancing understanding of the key mechanisms that control debris-covered glacier change in the southeastern Tibetan Plateau, and to assess the two different hypotheses at the glacier scale the two different hypotheses (additional melt at from hot spots area or extra thinning from reduced ice supply) that contribute to currently explain the anomalous thinning of debris-covered glaciers.which may have relevance beyond this region of interest.

2 Study area

The southeastern Tibetan Plateau is monsoon-influenced, and has a glacierized area of ~10,000 km^2. 23K (~4 km^2) and 24K (~2 km^2) Glaciers are located in the southeastern Tibetan Plateau (~29.77° N, 95.70° E; Fig. 1). 23K (~4 km^2) and 24K (~2 km^2) Glaciers are located in the southeastern Tibetan Plateau (~29.77° N, 95.70° E; Fig. 1). This region is characterized by steep and complex topography, as well as abundant precipitation, and has a glacierized area of ~10,000 km^2. Meltwater from gGlaciers in the region variously supply meltwater to the Yarlung Tsangpo (the upper stream of the Brahmaputra River) and the Salween River. These monsoon-dominated glaciers are characterized by high accumulation and high ablation rates (Shi et al., 2008). The region is mainly affected by two streams of humid air: the Bay of Bengal Vortex (in Spring) and the Indian Summer Monsoon system (in Summer), respectively (Ye and Gao, 1979; Yang et al., 2013; Yang et al., 2016). Thus, the monthly precipitation distribution exhibits a double-peak type occurring in both spring and summer (Yang et al., 2013). This is significantly different to the temporal patterns of mass gain on the Tibetan Plateau, which are so-called ‘summer accumulation’ type (Fujita et al., 2000; Maussion et al., 2014). Regional geodetic mass balance studies Geodetic mass balance studies conducted at the regional scale indicate that the magnitude of recent ice loss in the region exceeds the average for High

Mountain Asia (Kääb et al., 2012; Yao et al., 2012; Brun et al., 2017; Shean et al., 2020; Hugonnet et al., 2021) in the past 20 years, also affecting debris-covered glaciers. 23K and 24K Glaciers are located on the northern slopes of the Gangrigabu Mountains, ~23 kilometers and 24 kilometers, respectively, from Bomi City (Yang et al., 2017). 23K Glacier spans an altitudinal range of 3,760 to 5,437 m a.s.l. and flows initially toward the south-east before turning to the northeast in the ablation zone (Fig. 1a). In contrast, 24K Glacier flows to the northwest, and spans an altitudinal range of 3,900 to 5,621 m a.s.l. Both glaciers are partly covered by a layer of rock debris (Fig. 1a, 1c) and the debris-covered area represents approximately 34% and 41% of the total area for 23K Glacier- and 24K Glacier- respectively based on satellite data (Pléiades-1A false-color image from 2021-09-20, 2m resolution). The terminus retreat patterns of the two glaciers are also conspicuously different; terminus of 23K Glacier appears largely stagnant and is enclosed by a latero-terminal moraine complex, while the terminus of 24K Glacier takes the formpresents of a large ice cliff, and which is bounded by lateral moraines (Fig. 1c, 1d). Data from an automatic weather station (AWS, 3900 m a.s.l., running between June and September 2016) on 24K Glacier indicates a warm and humid climate, with mean temperature and total precipitation reaching ~9 °C and ~1700 mm, respectively between June and September (Yang et al., 2017; Fugger et al., 2022).

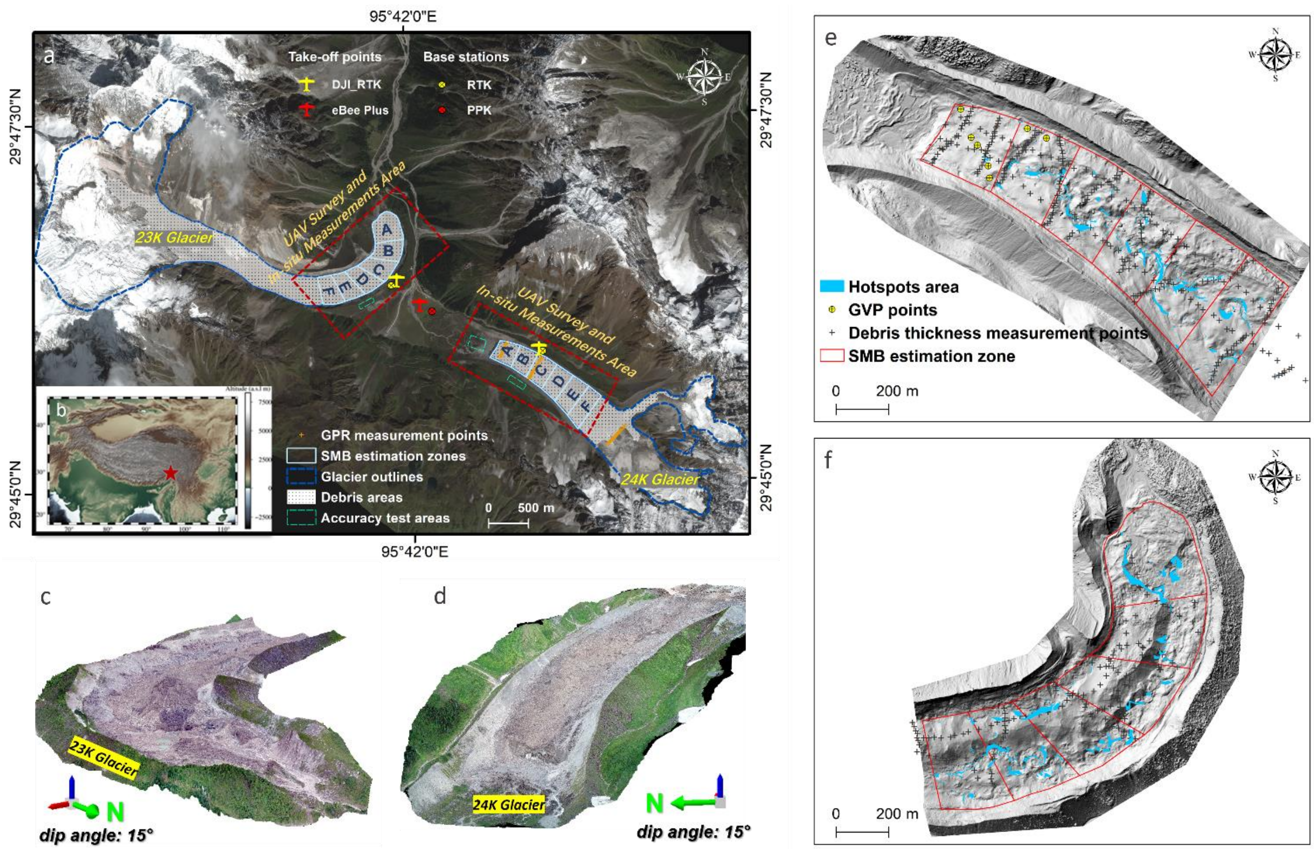


Figure 1: (a) Overview of the 23K Glacier and 24K Glacier basin including the UAV survey area, accuracy test areas, *in-situ* measurement locations (GVPs、GPR、debris thickness measurements), surface mass balanceSMB estimation zones (zones A-F)

and glacier outlines (background image from Pléiades-1A false-color image from 2021-09-20). © CNES 2021, Distribution Airbus D&S. (b) Geographic location of the study area. (c-d) UAV-derived three-dimensional images for the two glaciers. (e-f) Spatial distribution of the surface mass balance~~SMB~~ estimation zones of the two glaciers (e: 24K Glacier; f: 23K Glacier), debris thickness measurement points (in June 2019), and distribution of ice cliffs & supraglacial ponds (based on 2020 orthomosaics).

3 Data and Methods

3.1 UAV flights and data processing

Optical imagery of the glacier surface and its immediate surroundings was acquired using UAVs during four field campaigns were conducted~~that took place~~ between August 13th 2019 and October 22nd 2020 (Table 1). We used an eBee Plus aircraft with built-in GNSS PPK functionality in October 2019, August 2020, October 2020 surveys and DJI Phantom 4 RTK in August 2019 survey to capture the high-resolution~~quality~~ annual ~~l~~and seasonal patterns of glacier thinning and surface displacement~~dynamics~~.

The eBee Plus (Fig.S1a) is a fixed-wing UAV that has a 20-megapixel RGB digital compact camera (SenseFly S.O.D.A.). The flight management software eMotion3® was used for flight planning. The DJI Phantom 4 RTK is a rotary-wing UAV (Fig.S1c) equipped with a 1-inch, 20-megapixel CMOS camera. In this study, all longitudinal and lateral image overlaps were set to 65% and 80%, respectively. The flight lines for the eBee Plus and DJI Phantom 4 RTK maintained a relatively constant survey height above the glacier surface, which resulted in a constant ground resolution for each survey. A Huaxing A10 GNSS GPS was used as a static base station (Fig.S1b; fixed position for different surveys), and these data were attached to EXIF metadata of every geotagged image (Yang et al., 2020) and thereby integrated into a Post-Processed Kinematic (PPK) correction workflow to improve the accuracy of the UAV-SfM reconstruction. The DJI Phantom 4 real-time kinematic (RTK) UAV ~~i~~was permanently connected to a GNSS receiver (D-RTK 2, Fig. S1d), so that each survey image already had~~s~~ its high-precision position information embedded (i.e., no post-processing required). The geotagged UAV images were used to create orthomosaics and DEMs using the SfM-based photogrammetric software Pix4Dmapper version 4.3.31.

To assess the final positional accuracy of the UAV-derived DEMs and outputs, seven ground validation points were laid out in the vicinity of *in-situ* measurements (Fig.1a) on the surface of 24K Glacier in October 2020 (synchronized with the October 2020 UAV survey). We used a Huaxing A10 dGPS system to measure the position (XYZ) of each ground validation point. The horizontal accuracy of the dGPS is ± 8 mm and the vertical accuracy is ± 15 mm. ~~Seven ground validation points (GVPs) were deployed during our UAV-SfM survey in October 2020 and their positions were measured with a dGPS system (section 3.2).~~ By comparing the ground validation point~~GVP~~ measurements with the UAV-derived orthomosaics and DEMs, we obtain absolute XYZ accuracies for the October 2020 UAV-SfM survey product (Table 2). While ground validation points~~GVPs~~ were not used for the other UAV-SfM surveys, the accuracies of all UAV-SfM products were indirectly assessed by comparing the horizontal (XY) and vertical errors (Z) between all orthomosaics and DEMs (Table 3). The horizontal (XY) error was estimated by measuring the displacements of 25 benchmark boulders located on stable off-glacier terrain. For the vertical (Z) error, we calculated the elevation difference over stable terrain, as outlined in Figure 1a.

Table 1: UAV photogrammetric flights used for acquisition of glacier image.

Time	Flight type	Glacier	Number of Images	Flight altitude above ground (m)	Ground resolution (cm)	Coverage area (km^2)	Flight time (Beijing time)
13th Aug. 2019	RTK	23K	558	298	7.0	2.3	13:29-14:14
		24K	468	315	7.4	2.0	17:00-18:22
12th Oct. 2019	PPK	23K	743	243*	6.9	6.9	11:25-12:34
		24K	445				10:13-11:03
20th Aug. 2020	PPK	23K	128	434	10.2	3.1	12:07-12:26
		24K	160	536	12.6	3.7	11:11-11:35
22nd Oct. 2020	PPK	23K	188	344	8.1	2.4	10:37-10:59
		24K	346	374	8.8	3.8	8:57-9:37

3.2 *In-situ* observations and measurements

To evaluate the role of debris on surface mass balance~~SMB~~ patterns of both glaciers, debris thickness was manually measured by digging pits at selected sites in June 2019 (Fig. 1d, 1e). For 23K Glacier, a total of 157 locations were measured within the elevation range of 3,740-3,880 m a.s.l.. For 24K Glacier, we measured a total of 349 points from the glacier terminus to 4,250 m a.s.l.. The uncertainty in the manual measurement of the debris thickness was assumed to be 2 cm.

~~To assess the final positional accuracy of the UAV-derived DEMs and outputs, seven ground validation points (GVPs) were laid out in the vicinity of *in-situ* measurements (Fig.1a) on the surface of 24K Glacier in October 2020 (synchronized with the October 2020 UAV survey). We used a Huaxing A10 dGPS system to measure the position (XYZ) of each GVP. The horizontal accuracy of the dGPS is ± 8 mm and the vertical accuracy is ± 15 mm.~~

In October 2019, three ice thickness cross-sections (two in the debris-covered area and one in the debris-free area, Fig.1a and Fig. S2) were measured on 24K Glacier using a Kentech ground penetrating radar (GPR) monopulse transmitter with 2.5 MHz antennas. The *in-situ* ice thickness measurements were used to correct ~~(using a linear regression)~~ the 24K Glacier distributed ice thickness ~~dataset~~ from Farinotti et al. (2019) using linear regression (Fig. S2; Kneib et al., 2022). ~~No *in-situ* ice thickness measurements exist for 23K Glacier; therefore, we directly used the consensus ice thickness from Farinotti et al. (2019) for this glacier.~~

~~*In-situ* observations from an on-glacier automatic weather station (AWS) in 24K Glacier (29.765° N, 95.713° E, 3900 m a.s.l.) was gathered for analysing air temperature differences between different survey periods.~~

3.3 Thinning (d*h*) patterns, glacier dynamics and glacier driving stress

We compared the thinning(d*h*) and velocity patterns of 23K and 24K Glaciers on an annual and on a seasonal timescale. The period between August 2019 and August 2020 (373 days, mean temperature at~~of~~ AWS: 1.66 ℃) was selected for the annual timescale analysis. ~~The annual rates were adjusted according to the ratio of days (366/373).~~ The annual rates were adjusted according to the ratio of days (366/373) to make this result (13th Aug. 2019 - 20th Oct. 2020, 373 days) closer to that of the natural year (366 days). For the seasonal analysis, we refer to the period October 2019-August 2020 (313 days, mean temperature: 0.42 ℃) as the 'cold period' and the period August 2020-October 2020 (63 days, mean temperature: 8.68 ℃) as the 'warm period'. We applied the Post-Processed Kinematic (PPK) and real-time kinematic (RTK) GPS correction technologies and ensured that the static base stations were fixed at the same location for different surveys, which lead to DEMs with only very small minor offsets in XYZ (Yang et al., 2020). Therefore, we did not perform the co-registration of DEMs for the thinning (d*h*) calculation. For each period the thinning pattern was obtained by 2.5D DEM differencing in ArcGIS 10.4.

~~Glacier surface velocity is a good indicator of glacier dynamics (Kääb et al., 2003; Van, 2013) linked to the driving stress (e.g. Dehecq et al., 2019).~~ A spatially distributed estimate of XY surface displacements was obtained for each period by applying a Normalized Cross Correlation algorithm to the multidirectional 0.15 m-resolution DEM hillshades using ImGRAFT (Messerli and Grinsted, 2015). A search window of 10 × 10 pixels (1.5 × 1.5 m) was used to compute the magnitude and directions of the displacement vectors. The surface displacements greater than 30 m were considered as noise and were filtered out. Due to the high-resolution velocity data and the small number of gaps (<5%), we interpolated the velocity values in the data gaps using nearest neighbor interpolation.~~We removed surface displacement values above 30 m (noise) and interpolated the surface velocity at these locations in ArcGIS 10.4 using nearest neighbors.~~

The glacier driving stress was calculated as (Cuffey and Paterson, 2010):

$$D_{stress} = \rho_i \cdot g \cdot h \cdot sin\, \alpha_s, \qquad (1)$$

where D_{stress} is the glacier driving stress, ρ_i is the density of ice (917 kg m^3), g is the gravitational acceleration (9.81 m s^{-2}), h is the ice thickness (in m), and α_s is the glacier slope obtained from the AW3D30 (30 m-resolution) DEM (Tadono et al., 2014) smoothed with a Gaussian filter (8 pixels window) to~~for~~ remove~~ing any~~ effects from local variations in surface topography (Brun et al., 2018)~~smoothed with a Gaussian filter (8 pixels window)~~. ~~The consensus ice thickness product by Farinotti et al. (2019) is likely to have large errors in the accumulation area of 24K glacier due to inaccurate RGI 6.0 glacier outlines that encompass the glacier headwall. However, in the ablation area, we applied a local correction using GPR measurements (section 3.2), which reduces the errors considerably.~~

3.4 Surface mass balance (SMB) of UAV survey area

To investigate the magnitude and the distribution of the surface mass balance~~SMB~~, each glacier was divided into six zones (A-F) and each zone was used as a separate section for the surface mass balance~~SMB~~ estimation. Each surface mass balance~~SMB~~ estimation zone was outlined manually, perpendicular to the main glacier flow line and with a similar area (Fig. 1a). To extract the melt contribution from the ice cliffs and ponds, we flow-corrected the DEMs following Brun et al. (2018). To perform the flow correction, we used orthomosaics and DEMs from the August 2020 UAV-SfM surveys as a reference for each glacier, to which the August 2019, October 2019 and October 2020 UAV-derived data were flow-corrected. Corrections in XY were made using the ArcGIS georeferencing tool to manually track the surface flow for each given period by using surface tie points (mainly large boulders). For each correction period, the number of tie points was sufficiently large (> 75) and were well-distributed across the glacier surface to ensure a spatially representative correction, ~~which took the form of~~using a spline-based transformation. The resulting XY flow-corrected elevation change (dh_c, in m) is therefore equal to the sum of the surface mass balance ($\dot{b}$, negative value in the ablation area, in m) and mean vertical displacement (ω, in m):

$$dh_c = \dot{b} + \omega, \quad (2)$$

~~The ω can be expressed as:~~

$$\omega = \omega_s + \omega_e\ , \quad (3)$$

~~Where ω_s (in m) corresponds to the elevation change resulting from the horizontal flow-correction of the DEMs:~~

$$\omega_s = u_s \cdot tan\ (\alpha_m)\ , \quad (4)$$

~~Where u_s (in m) is the mean horizontal surface displacement and α_m (in °) is the mean surface slope of a given zone. ω_e (in m) corresponds to the flux divergence, which can be expressed as:~~

$$\omega_e = \frac{\Delta q}{A}\ , \quad (5)$$

~~Where A (in m^2) is the area of the zone and Δq (in m^3) is the ice flux difference at a given period:~~

$$\Delta q = q_{n+1} - q_n, \quad (6)$$

~~Where q_{n+1} and q_n are the ice flux entering and leaving the estimation zone at a given period. q (in m^3) is the ice flux through a glacier cross-section, given by:~~

$$q = \mu \cdot h_q \cdot v \cdot l \;, \quad (7)$$

Where ω_s (in m) corresponds to the elevation change resulting from the horizontal flow-correction of the DEMs. Where u_s (in m) is the mean horizontal surface displacement and α_m (in °) is the mean surface slope of a given zone. ω_e (in m) corresponds to the flux divergence. Where A (in m^2) is the area of the zone and Δq (in m^3) is the ice flux difference at a given period. Where q_{n+1} and q_n are the ice flux entering and leaving the estimation zone at a given period. q (in m^3) is the ice flux through a glacier cross-section. Where μ is a coefficient to convert the surface velocity into a depth-averaged velocity which we assumed to be equal to 0.9 following Miles et al. (2018), h_q (in m) is the ice thickness for the corresponding cross-section, v (in m) is the surface displacement component normal to the cross sections line, l (in m) is the width of the cross-section.

The following equation was used to evaluate the uncertainty of surface mass balance~~SMB~~ ($\sigma_{\dot{b}}$) for each zone:

$$\sigma_{\dot{b}} = \sqrt{{\sigma_{dh_c}}^2 + {\sigma_\omega}^2}, \quad (8)$$

The uncertainties of dh_c and u_s (also for v) were obtained by calculating the mean surface elevation difference and displacement the non-glacial test areas. They were determined as 0.09 m and 0.25 m respectively by averaging the values over all periods.

The below equations were applied in the uncertainty of vertical component of velocity (σ_ω):

$$\sigma_\omega = \sqrt{{\sigma_{u_s}}^2 + {\sigma_{\alpha_m}}^2 + {\sigma_{\omega_e}}^2} \quad (9)$$

~~Where:~~

$$\frac{\sigma_{\omega_e}}{\omega_e} = \sqrt{\left(\frac{\sigma_{\Delta q}}{\Delta q}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2}, \quad (10)$$

For the uncertainty associated with the slope correction, we assumed a 2° uncertainty in the slope (α_m). We assumed the~~assessed the~~ uncertainty of zone area （A） ~~by expanding the glacier area boundary by~~ to be ± 20 m from the outlines with the buffer method (Bolch et al., 2010; ~~Miles et al., 2016;~~ Miles et al., 2018).~~(Miles et al., 2016).~~ The uncertainty of ice flux difference ($\sigma_{\Delta q}$):

$$\sigma_{\Delta q} = \sqrt{{\sigma_{q_{n+1}}}^2 + {\sigma_{q_n}}^2}, \tag{11}$$

σ_q (m^3) is the uncertainty of ice flux through a glacier cross-section, given by:

$$\frac{\sigma_q}{q} = \sqrt{\left(\frac{\sigma_v}{v}\right)^2 + \left(\frac{\sigma_\mu}{\mu}\right)^2 + \left(\frac{\sigma_{h_q}}{h_q}\right)^2}, \tag{12}$$

Where the uncertainty of ratio μ (column-averaged velocity/surface velocity) is assumed as 0.1 (Cuffey and Paterson, 2010; Miles et al., 2018). The uncertainty in h_q is ~10-35 m (26%) for 23K Glacier (Farinotti et al., 2019) and is assumed to be equal to 12 m for the corrected 24K Glacier (Fig. S2a) ice thickness uncertainty.

3.5 Ice cliffs and supraglacial ponds outlines and melt contribution

In this study, the proportion of ice cliffs and supraglacial ponds areas within each surface mass balance~~SMB~~ estimation zone was calculated to better understand the surface mass balance~~SMB~~ patterns on both glaciers~~ during the ablation period~~. We manually extracted ice cliffs and supraglacial ponds outlines from the flow-corrected orthomosaics (August 2020 and October 2020; August 2019 and August 2020; October 2019 and August 2020). The outlines of the ~~'hotspots' ~~ice cliffs and supraglacial ponds area for each zone was established by taking the union of ~~summing ~~the areas of these features~~were obtained by merging two-phase outlines~~ (Brur~~r~~n et al., 2018)~~, and the total hotspots area for each zone was established by summing the area of these features~~. In this way, we can effectively measure surface change in these ice cliffs and supraglacial ponds area~~hotspots zone~~s, thereby providing us with an upper-bound estimate of the total contribution of ice cliffs and ponds to the surface mass balance (~~Mishra et al., 2021; ~~Kneib et al., 2022; Mishra et al., 2022). We assumed the uncertainty of areas density of ice cliffs and supraglacial ponds to be equal to 0.5%. The enhancement factor was calculated to quantify such difference in melt ~~efficiency~~enhancement between the two glaciers' ice cliffs and supraglacial ponds area and sub-debris area during all periods, which we define as the ratio of the ice cliffs and supraglacial ponds area surface mass balance rate to the sub-debris area surface mass balance rate (Brun et al., 2018, Buri et al., 2021, Miles et al., 2022).

4 Results

4.1 UAV products accuracy

The results from Oct. 2020 UAV-SfM products and GVPs measurements revealed that the mean absolute deviation in the X, Y and Z directions are 0.14 ± 0.11 m, 0.09 ± 0.11 m, and 0.24 ± 0.18 m respectively (Table 2). The vertical uncertainty is twice as high as the horizontal uncertainty, which is in agreement with the findings of other studies (James et al., 2017; Li et al., 2019).

Table 2: XYZ geolocation accuracy of UAV-SfM orthomosaic and DEM (22nd Oct. 2020) for the two glaciers, based on the dGPS measurements of the 7 GVPs.

		X (m)	Y (m)	Z (m)
23K&24K	Mean	0.14	0.09	0.24
Glaciers	Std	0.11	0.11	0.18

The average XY errors for three survey pairs (Aug. 2019 *vs* Oct. 2019, Oct. 2019 *vs* Aug. 2020 and Aug. 2020 *vs* Oct. 2020) are 0.07 ± 0.06 m and 0.08 ± 0.06 m respectively (Table 3). The relative vertical (Z) errors between DEMs were ≤0.09 m for all pairs, which is appropriate for resolving fine-scale surface change for glaciological analysis.

Table. 3: XYZ errors between different orthomosaics/DEMs for the two glaciers using the fixed benchmark boulders and validation areas.

		23K&24K Glaciers		
		Aug. 2019-Oct. 2019	Oct. 2019-Aug. 2020	Aug. 2020-Oct. 2020
X (m)	Mean	0.07	0.08	0.07
	Std	0.06	0.07	0.06
Y (m)	Mean	0.06	0.09	0.09
	Std	0.04	0.06	0.05
Z (m)	Mean	0.09	0.08	0.09
	Std	0.07	0.04	0.08

4.2 Spatio-temporal variability of thinning (d*h*) patterns

The thinning~~d*h*~~ during ~~distribution of~~ different periods ~~(annual, cold, warm)~~ (annual: Aug. 2019-Aug. 2020, cold: Oct. 2019-Aug. 2020, warm: Aug. 2020-Oct. 2020) for the two glaciers is shown in Figure 2 and Table 4. The annual thinning~~d*h*~~ rate of ~~the~~ 23K Glacier in the survey area ~~is~~ was -2.3 ± 0.1 m a^{-1}, whereas the thinning~~d*h*~~ rate of 24K Glacier ~~is~~ was -1.2 ± 0.1 m a^{-1} (Fig. 2a, d). During the cold period (October 2019-August 2020), the average thinning~~d*h*~~ ~~in~~ over ~~the~~ 23K (resp. 24K) Glacier survey area ~~is~~ was -1.5 ± 0.1 m (-0.2 ± 0.1 m), with an average daily thinning~~d*h*~~ of -0.5 ± 0.03 cm d^{-1} (-0.1 ± 0.03 cm d^{-1}) (Fig. 2b, 2e). During the warm period (August 2020-October 2020), the ~~mean~~ magnitude of the thinning of both glaciers was very similar~~d*h* for each glacier is more comparable to the other~~; for 23K (resp. 24K) Glacier it ~~is~~ was -0.7 ± 0.1 m (-1.0 ± 0.1 m), with an average daily thinning~~d*h*~~ of -1.2 ± 0.03 cm d^{-1} (-1.6 ± 0.03 cm d^{-1}) (Fig. 2c, 2f).

Table. 4: Total thinning and its daily rate for 23K & 24K Glaciers during different periods.

		Aug. 2019- Aug. 2020	Oct. 2019-Aug. 2020	Aug. 2020-Oct. 2020
23K Glacier	Thinning (m)	-2.3 ± 0.1	-1.5 ± 0.1	-0.7 ± 0.1
	Daily rate (cm d^{-1})	-0.6 ± 0.03	0.5 ± 0.03	-1.2 ± 0.03
24K Glacier	Thinning change (m)	-1.2 ± 0.1	-0.2 ± 0.1	-1.0 ± 0.1
	Daily rate (cm d^{-1})	-0.3 ± 0.03	-0.1 ± 0.03	-1.6 ± 0.03

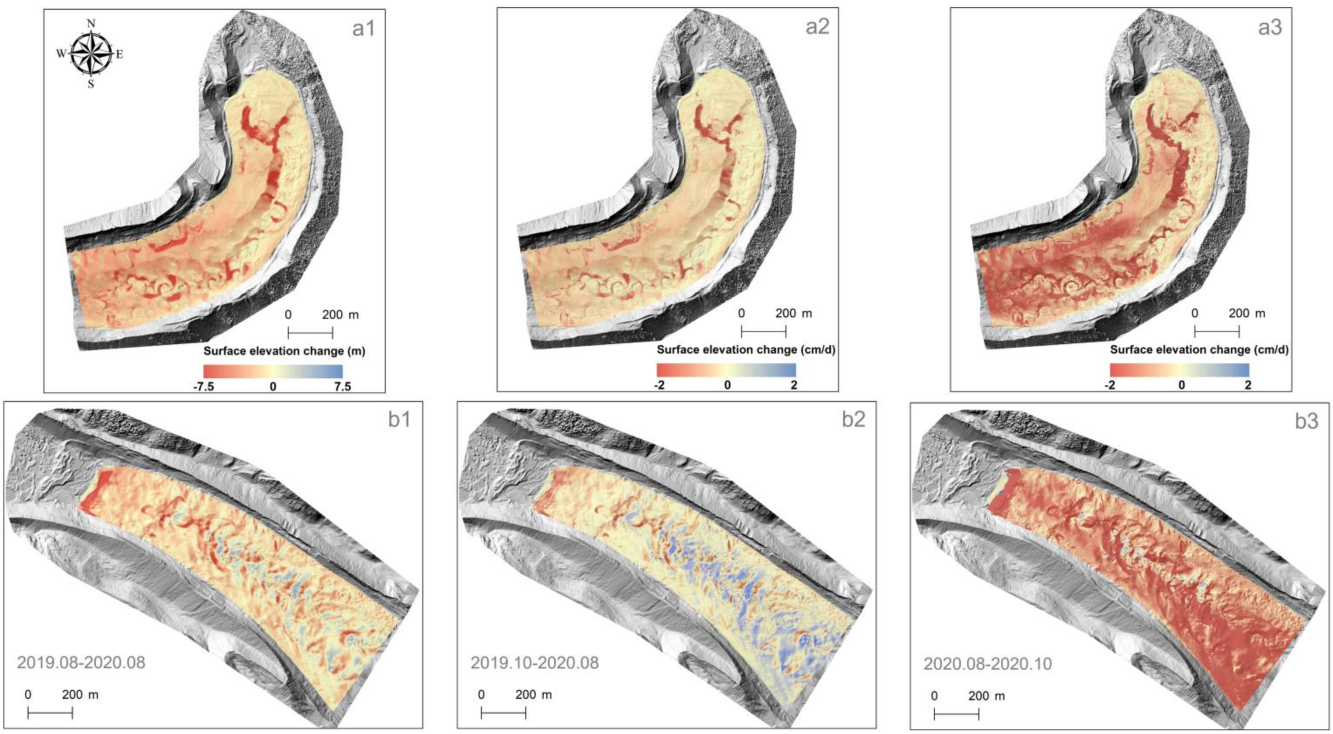
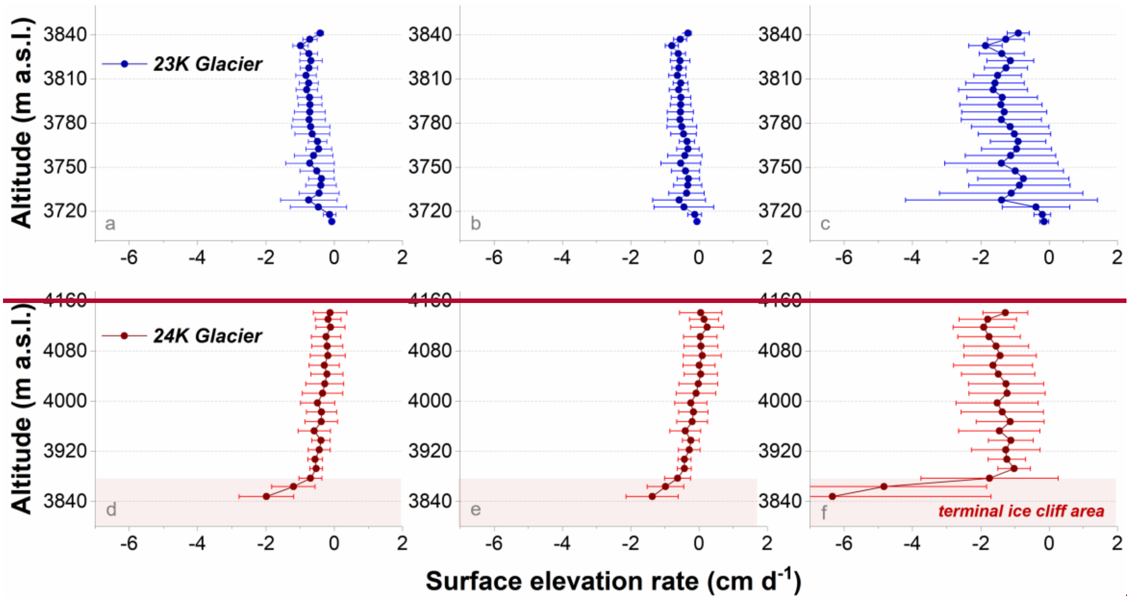


Figure 2: Annual surface elevation changes between UAV-derived DEMs for August 2019-August 2020 (a1, b1), the surface elevation change/thinning rates of the cold period (a2, b2) and the warm period (a3, b3) for the 23K Glacier (upper panels) and 24K Glacier (lower panels).

We present the relationships between thinning~~*dh*~~ rates and altitude for each glacier at 5 m and 15 m intervals (Fig 3). The relationships between thinning~~*dh*~~ rates and altitude show that the absolute thinning~~*dh*~~ of 23K Glacier increases with altitude based on the Mann-Kendall test (i.e., a negative gradient; Z value: -3.75 - -3.25~~~-1 to -2 cm d^{-1} 100 m^{-1}~~) for every analysis period, while the thinning~~*dh*~~ of 24K Glacier decreases with altitude in the annual scale and cold period (positive gradient; Z value: +3.65 - +3.69~~~+0.5 cm d^{-1} 100 m^{-1}~~). In particular, the thinning~~*dh*-altitude gradient~~ of 24K Glacier in the warm period shows~~follow~~ the opposite altitudinal trend to its annual scale and cold period~~'s~~ (i.e., consistent with 23K Glacier~~'s~~; Z value:

-0.77), with the gradients of ~-2 cm d^{-1} 100 m^{-1} at 23K Glacier and ~-1 cm d^{-1} 100 m^{-1} at 24K Glacier (ignoring the effect of the terminal ice cliff).



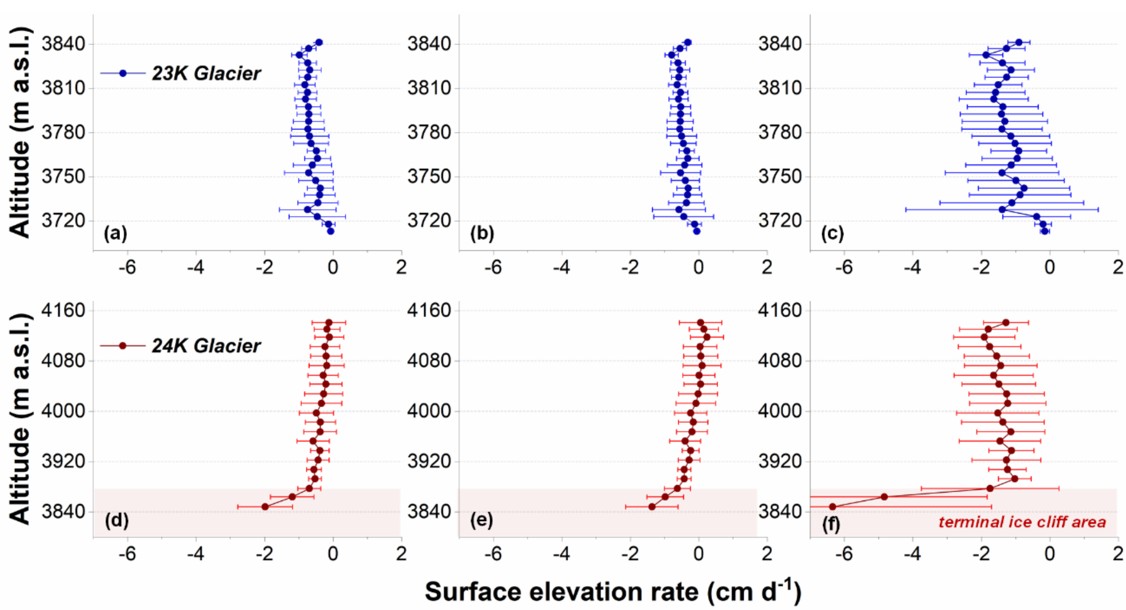
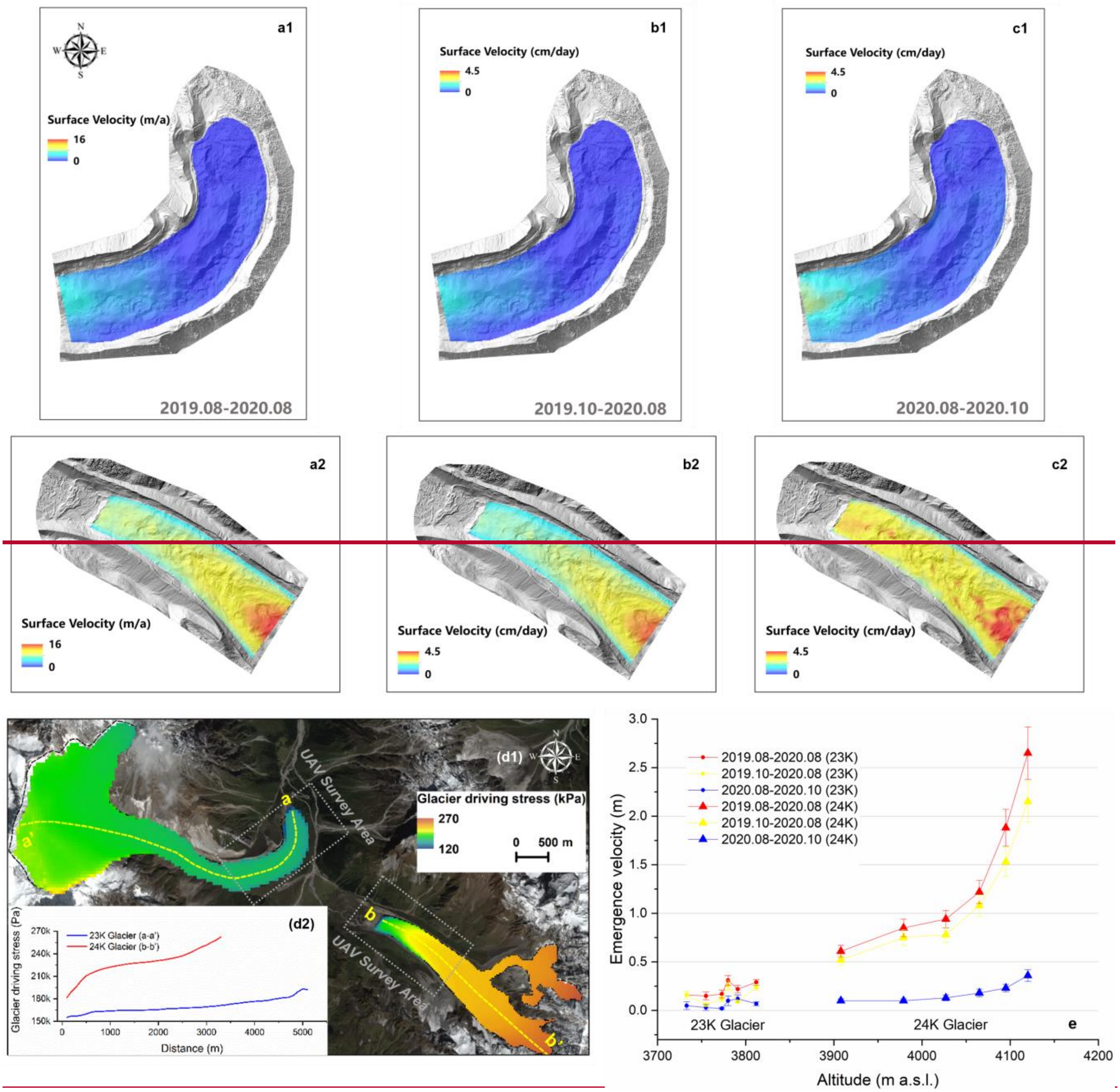


Figure 3: Annual average glacier surface elevation rates within 5-m (23K Glacier)/15-m (24K) elevation bands (dots) with the corresponding standard deviations (horizontal error bar) for August 2019-August 2020 (a, d), the cold period (b, e) and the warm period (c, f) across the monitoring area of the two glaciers. The red shadowed sections represent the terminal ice cliff at of the 24K Glacier.

4.3 Glacier dynamics

Between August 2019 and August 2020, the mean surface velocity ~~is~~ was 1.7 ± 0.2 m a^{-1} for 23K Glacier and 9.2 ± 0.2 m a^{-1} for 24K Glacier (Fig. 4a1, a2). There is a zone of stagnation at the terminus of 23K Glacier where the surface velocity is less than 2 m a^{-1} (from terminus to 900 m up-glacier, Fig. 4a1). ~~The mean surface velocities were also calculated for the cold and warm periods of both glaciers (Fig. 4b, 4c).~~ During the cold period, the mean surface velocity of 23K Glacier ~~is~~ was 0.4 ± 0.03 cm d^{-1}, while it was ~~24K Glacier is~~ 2.4 ± 0.08 cm d^{-1} for 24K. During the warm period, the mean surface velocity for 23K Glacier and 24K Glacier ~~are~~ were 0.6 ± 0.14 cm d^{-1} and 3.0 ± 0.40 cm d^{-1} respectively. For the UAV survey area, the mean driving stress of 23K Glacier ~~is~~ was 1.6 × 10^{5} Pa and for 24K Glacier ~~is~~ was 2.1 × 10^{5} Pa. The driving stress in the survey area for 24K Glacier ~~is~~ was ~30% higher than for 23K Glacier (Fig. 4d). The estimated emergence velocities agreed with the insight from surface velocities and driving stress, with 24K Glacier having significantly higher emergence velocities than 23K Glacier at any period (Fig. 4e). In this case, the annual emergence of 23K (resp. 24K) Glacier ~~is~~ was 0.18 ± 0.04 m (1.36 ± 0.14 m), and 24K Glacier ~~is~~ was approximately 7.6 times higher than 23K Glacier. The mean emergence of cold period for 23K (resp. 24K) Glacier ~~is~~ was 0.16 ± 0.03 m (1.14 ± 0.11 m), the warm period emergence velocity for 23K (resp. 24K) Glacier ~~is~~ was 0.07 ± 0.03 m (0.18 ± 0.04 m). ~~The relationship between emergence and altitude for 23K Glacier was not remarkable for all periods, whereas the magnitude of emergence for 24K Glacier increased with altitude for all periods.~~ 24K Glacier hads consistently higher emergence velocity than 23K Glacier during all periods.


a1
Surface Velocity (m/a)
16
0
2019.08-2020.08
b1
Surface Velocity (cm/day)
4.5
0
2019.10-2020.08
c1
Surface Velocity (cm/day)
4.5
0
2020.08-2020.10
a2
Surface Velocity (m/a)
16
0
b2
Surface Velocity (cm/day)
4.5
0
c2
Surface Velocity (cm/day)
4.5
0
(d1)
UAV Survey Area
Glacier driving stress (kPa)
270
120
0 500 m
(d2)
23K Glacier (a-a')
24K Glacier (b-b')
Glacier driving stress (Pa)
Distance (m)
2019.08-2020.08 (23K)
2019.10-2020.08 (23K)
2020.08-2020.10 (23K)
2019.08-2020.08 (24K)
2019.10-2020.08 (24K)
2020.08-2020.10 (24K)
Emergence velocity (m)
23K Glacier
24K Glacier
e
Altitude (m a.s.l.)

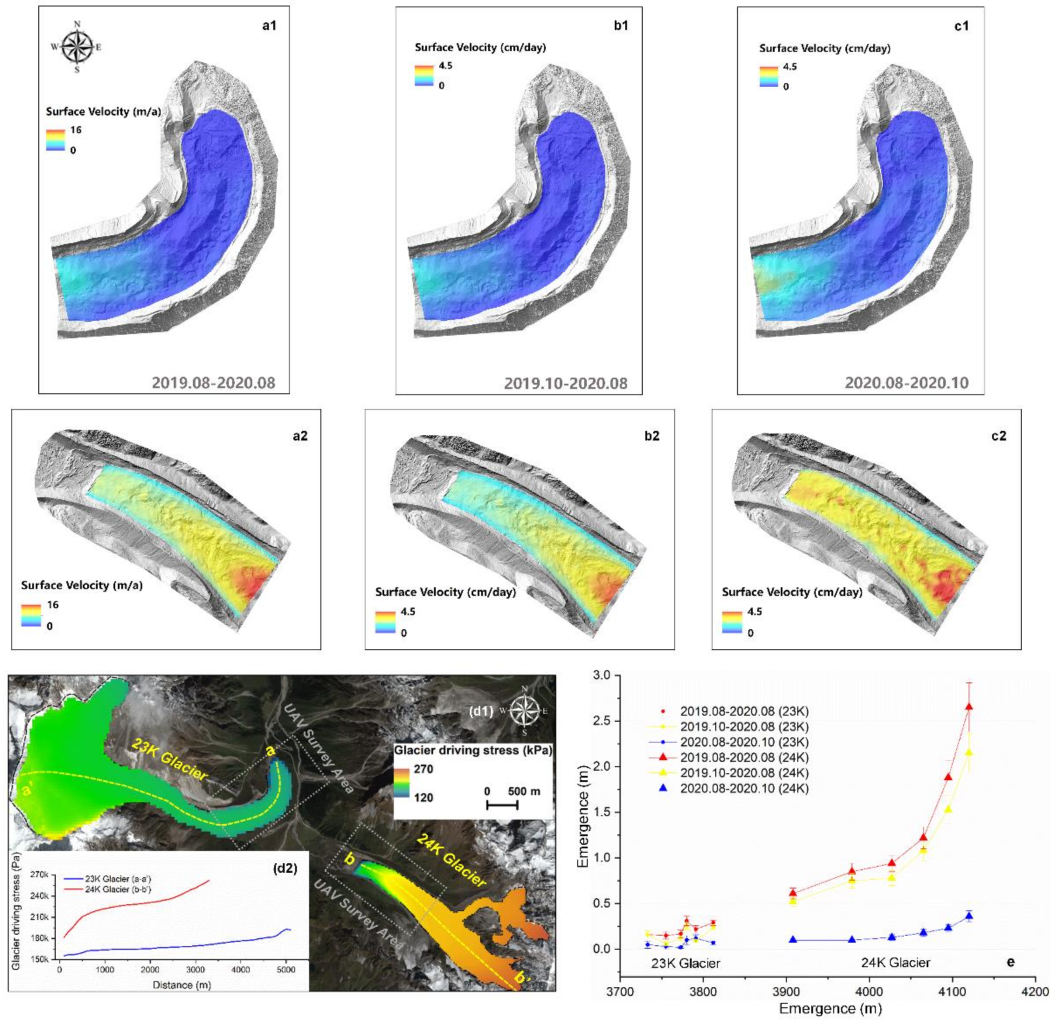


Figure 4: Average surface velocity for August 2019-August 2020 (a1, a2), the cold period (b1, b2) and the warm period (c1, c2). Spatial distribution of driving stresses (August 2019-August 2020) of the two glaciers (d1) and central flowlines (a-a' and b-b') driving stresses (d2), the grey dashed rectangular box (b1) represents the UAV aerial survey area, and we consider the confidence in the driving stress values of these parts to be higher than that of the upper part of the glacier, background image is a Pléiades-1A false-color image from 2021-09-20, which was used to derive the glacier outlines. © CNES 2021, Distribution Airbus D&S. The gradients between emergence velocity and altitude for two glaciers (e).

4.4 Surface mass balance (SMB) patterns

At the annual scale, the mean surface mass balanceSMB for 23K Glacier and 24K Glacier survey areas weare -2.5 ± 0.1 m w.e. a^{-1} and -2.8 ± 0.3 m w.e. a^{-1} respectively and are therefore not significantly different (Fig. 5). During the 'cold' period, the glacier mass balance wais -0.5 ± 0.03 cm w.e. d^{-1} for 23K Glacier and -0.4 ± 0.09 cm w.e. d^{-1} for 24K Glacier (Fig. 5). In contrast, during the warm period, the mass balance of 23K Glacier wa~~i~~s -1.3 ± 0.15 cm w.e. d^{-1}, while for 24K Glacier it wa~~i~~s -1.9 ± 0.18 cm w.e. d^{-1}; the surface mass balance~~SMB~~ during the warm period for 24K Glacier is thus ~46% ~~higher~~ larger than for 23K Glacier (Fig. 5). The surface mass balance~~SMB~~ values of each mass balance zone (A-F) for both glaciers exhibit a weak decreasing trend with altitude in all periods (Fig. ~~6~~7; Fig. S3).

To better evaluate the role of emergence velocity replenishment on thinning, we calculated the ratio of emergence velocity to surface mass balance (Table. 5). ~~The greater of the~~A higher absolute value of this ratio indicates ~~the~~a greater impact of emergence velocity replenishment on thinning ('-1' indicates perfect compensation of ablation by ice flow). The ratio of annual emergence velocity and annual surface mass balance for 23K (resp. 24K) Glacier is -0.09 (-0.49). The ratio values for 23K (resp. 24K) Glacier during cold and warm periods are -0.11 (-0.87) and -0.09 (-0.15), respectively. The ratio absolute values for 24K Glacier are always higher than those for 23K Glacier, and this is especially evident in the non-ablation period.

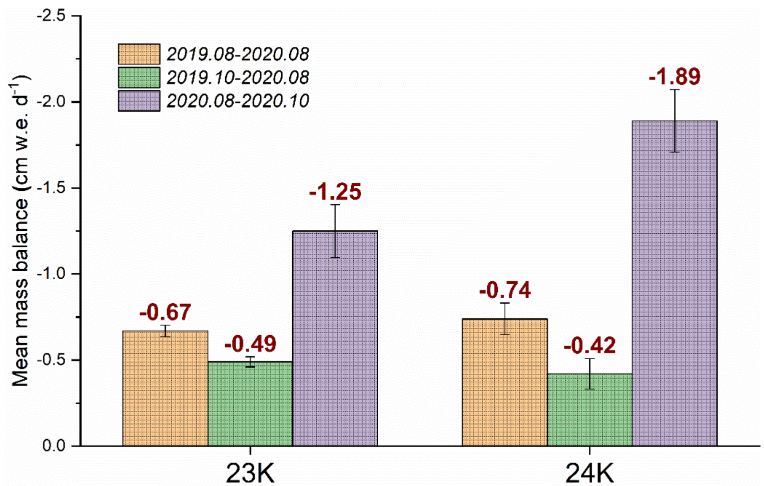


Figure 5: Mean surface mass balance~~SMB~~ rates and their uncertainties for both UAV survey domains during the annual observation period (2019.08-2020.08), the cold period (2019.10-2020.08) and the warm period (2020.08-2020.10).

Table 5: Emergence velocity, surface mass balance~~SMB~~ and the ratio of above two in all periods for both glaciers.

Time	Glacier	Emergence velocity (m w.e.)	Surface mass balance~~SMB~~ (m w.e.)	Ratio of emergence velocity to surface mass balance~~SMB~~
Aug. 2019-Aug. 2020	23K	0.22 ± 0.04	-2.50 ± 0.11	-0.09
	24K	1.36 ± 0.14	-2.76 ± 0.34	-0.49
Oct. 2019-Aug. 2020	23K	0.16 ± 0.03	-1.53 ± 0.09	-0.11
	24K	1.14 ± 0.11	-1.31 ± 0.25	-0.87
Aug. 2020-Oct. 2020	23K	0.07 ± 0.03	-0.79 ± 0.09	-0.09

24K	0.18 ± 0.04	-1.19 ± 0.11	-0.15

The density of ice cliffs and supraglacial pondshotspots area for 23K Glacier is 6.8-7.2% and it is 4.4-5.1% for 24K Glacier (Table. 64). There are few ponds (~5, area > 100 m^2) on 23K Glacier, while there is no ponded area on 24K Glacier. Most ice cliffs on 24K Glacier are located in the center of the survey domain, while they are more homogeneously distributed on 23K Glacier (Fig. 1e, 1f). The average debris thickness in the UAV survey area of 23K Glacier and 24K Glacier is 47.1 ± 2 cm and 24.2 ± 2 cm respectively. The debris thickness of both glaciers decreases with increasing altitude in the UAV survey area (23K Glacier: ~ -57 cm 100 m^{-1}; 24K Glacier: ~ -9 cm 100 m^{-1}). To disentangle the influence of the sub-debris area and the ice cliffs and supraglacial pondshotspots area for the surface mass balanceSMB pattern respectively, we extracted the surface mass balanceSMB rates of the area of ice cliffs and supraglacial ponds hotspots area and the sub-debris area in both glaciers for all periods (Table. 64). As shown in Table 64, the surface mass balanceSMB rates in the ice cliffs and supraglacial pondshotspots area of both glaciers are higher than the sub-debris area during all periods (i.e., the ice cliffs and supraglacial pondshotspots area possess the higher melt efficiency). The enhancement factor was calculated to quantify such difference in melt efficiency between two glaciers' hotspots area and sub-debris area during all periods, which we define as the ratio of the hotspots area SMB rate to the sub-debris area SMB rate (Brun et al., 2018, Buri et al., 2021, Miles et al., 2022). In this study, the enhancement factors for the two glaciers range from 1.6 to 4.4 during all periods. It is also found that The enhancement factors were consistently higher inat 23K Glacier than atin 24K Glacier (~1.5-1.8 times). We note that Tthe enhancement factors for the two glaciers are significantly higher in the warm period than in the annual scale (23K: ~2.0 times；24K: ~1.6 times) and cold period (23K: ~1.7 times；24K: ~1.5 times), indicating that the 'hotspots' effect' is more pronounced during the ablation period. By extracting the ablation contribution of the ice cliffs and supraglacial ponds (Fig. 7), we found that the total melt from ice cliffs and supraglacial ponds areas accounted for 31.5 ± 2.2% of the total ablationmelt in the UAV survey area for 23K Glacier and 11.4 ± 1.3% for 24K Glacier during the warm period.

Table 64: Ice cliffs and supraglacial pondsHotspots area proportion, mean ice cliffs and supraglacial pondshotspots area and sub-debris area surface mass balanceSMB, ice cliffs and supraglacial pondshotspots area enhancement factors in all periods for both glaciers.

Time	Glacier	Ice cliffs and supraglacial pondsHotspots area proportion (%)	Mean ice cliffs and supraglacial pondshotspots area surface mass balanceSMB (cm w.e. d^{-1})	Mean sub-debris area surface mass balanceSMB (cm w.e. d^{-1})	Ice cliffs and supraglacial pondsHotspots area enhancement factors (-)
Aug. 2019-Aug. 2020	23K	6.8 ± 0.5	-1.3 ± 0.03	-0.6 ± 0.03	2.2
	24K	5.1 ± 0.5	-1.1 ± 0.1	-0.7 ± 0.1	1.6

Oct. 2019-Aug. 2020	23K	7.1 ± 0.5	-1.1 ± 0.03	-0.4 ± 0.03	2.6
	24K	4.9 ± 0.5	-0.7 ± 0.1	-0.4 ± 0.1	1.7
Aug. 2020-Oct. 2020	23K	7.2 ± 0.5	-4.1 ± 0.2	-0.9 ± 0.2	4.4
	24K	4.4 ± 0.5	-4.4 ± 0.2	-1.7 ± 0.2	2.6

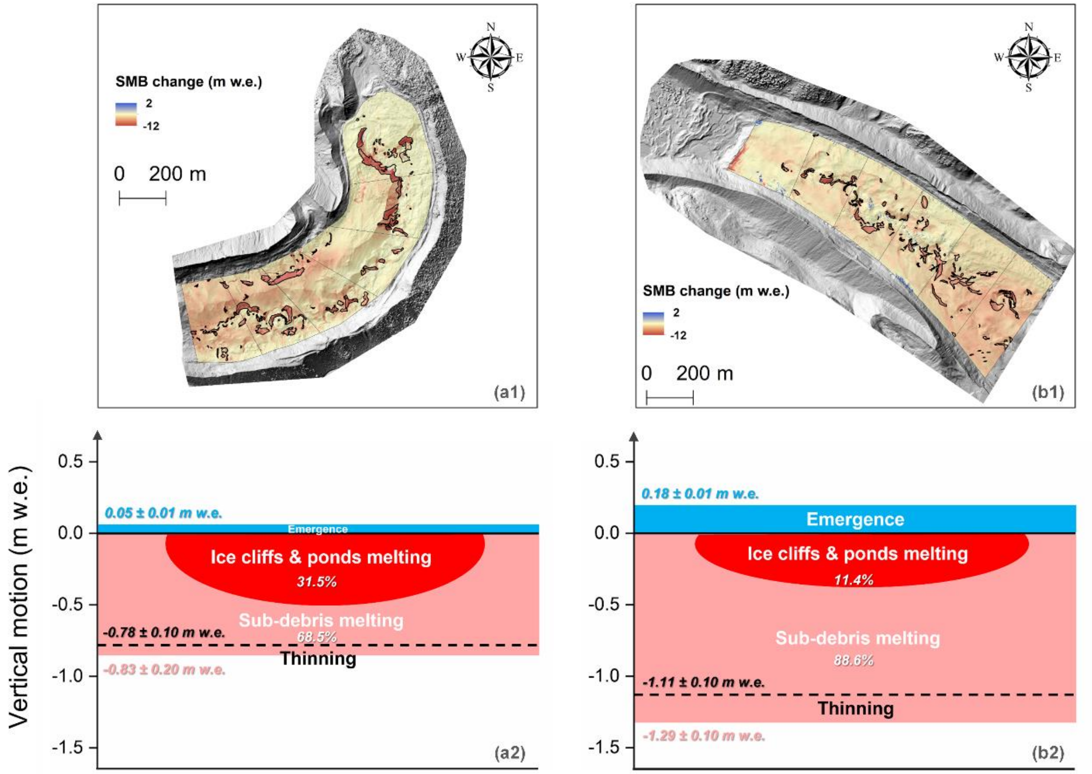


Figure 7: Spatial distribution of surface mass balance during ablation period for the UAV survey domains of 23K Glacier and 24K Glacier (a1, b1). The a2 and b2 are the conceptual diagrams of vertical motion components for 23K Glacier and 24K Glacier.

To better disentangle the effects of debris thickness and ice cliffs and supraglacial pondshotspots areas on glaciers melt, we compared the mean debris thickness, the percentage of ice cliff and supraglacial ponds area and the mean melt rate dur-ing the warm period in each of the six zones (A-F) of each glacier (Fig. 86). We assessed the correlations of the zonal surface mass balanceSMB in the warm period with the zonal debris thickness and ice cliffs and supraglacial ponds density based on six points for each glacier. For 23K Glacier, the correlation coefficient , *r* (95% confidence interval), between debris thickness and surface mass balanceSMB during the warm period is 0.88 (*p*--value = 0.02), indicating that the debris thickness is highly correlated with the melt. In contrast, the correlation coefficient between the percentage of ice cliff and supraglacial ponds area, and the surface mass balanceSMB, is -0.29 (*p*-value = 0.58), indicating the absence of a strong correlation. During the warm period, 24K Glacier also exhibits a strong relationship between the debris thickness and melt, where *r* is 0.82 (*p*--value = 0.05). The Iice cliffs and supraglacial pondsHotspots area is weakly correlated with the glacier melt (*r* = -0.48, *p*--value = 0.36).

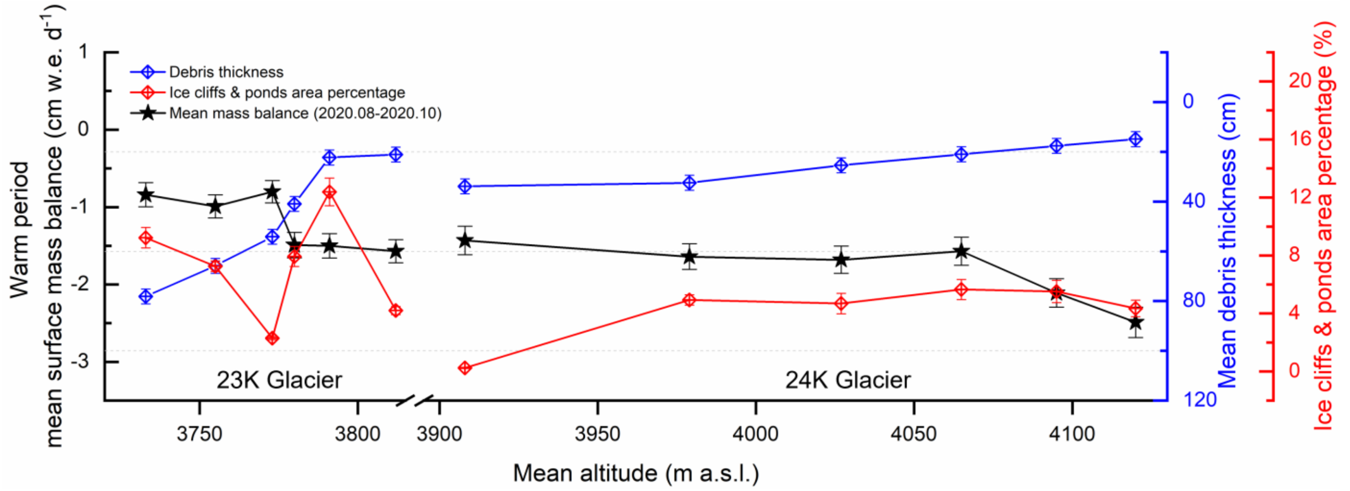


Figure 86: The Ddaily SMB surface mass balance and during the warm period (black solid line), the mean debris thickness (blue solid line) and the mean percentage of the ice cliffs and supraglacial ponds area (red solid line) for the individual zones of two glaciers.

4.5 Glacier change in the early twenty-first century

The thinning of 23K Glacier tongue was greater than that of 24K Glacier since 2000 (Hugonnet et al., 2021; Fig. 9), which is generally in agreement with the thinning patterns we derived from the UAV surveys. We found that the thinning rates of bBoth glaciers (UAV survey domains) show the inverted relationship of thinning against altitude at all periods of over the last two decades. Both glaciers have experienced increases in thinning rates over this time period (increase rate for 23K: +77%; 24K: +100%). However, although the increase rate of 24K Glacier tongue is slightly lower than that of 23K Glacier over the last decade (23K: +44%; 24K: +20%).

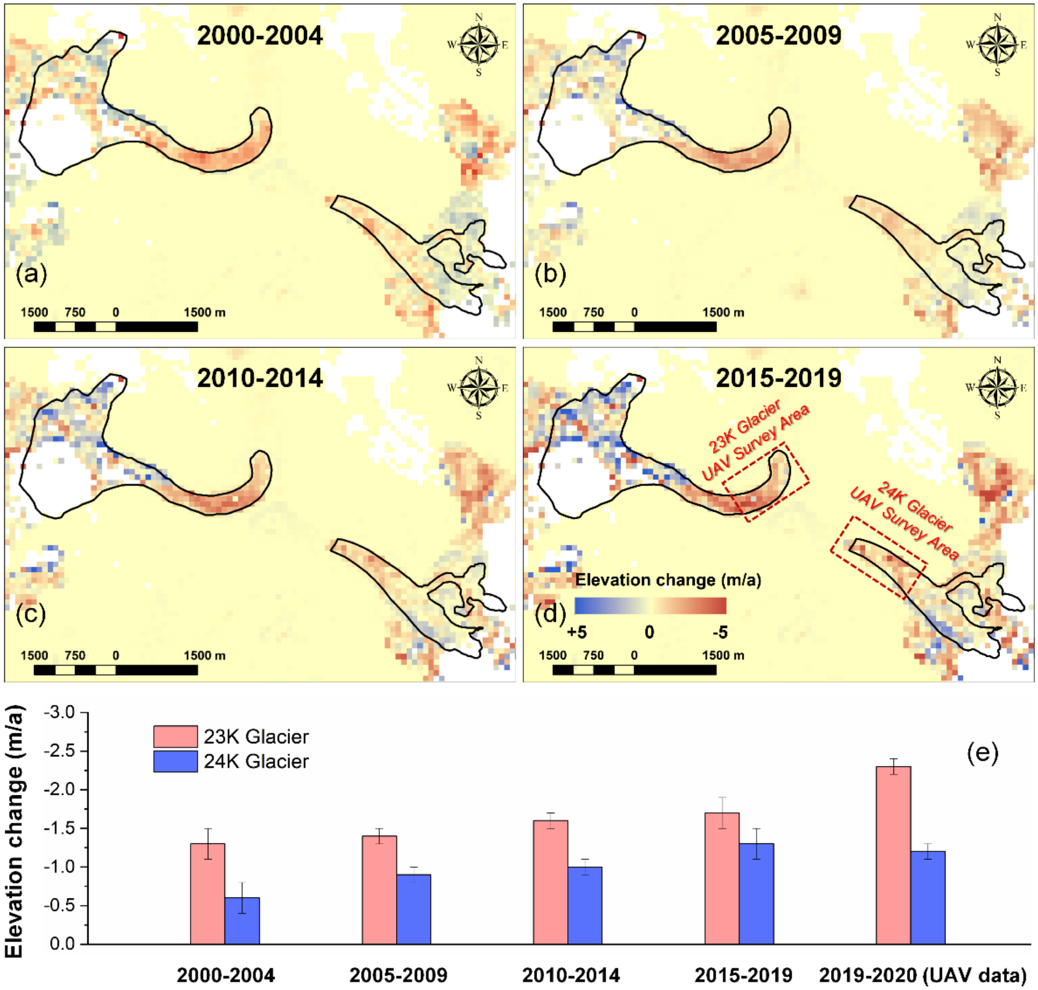


Figure 9: Annual surface elevation changes for 2000-2004 (a), 2005-2009 (b), 2010-2014 (c), 2015-2019(d) for the 23K Glacier and 24K Glacier (red dashed rectangular box represents the UAV aerial survey area). Annual surface elevation changes and their uncertainties for both UAV survey domains at different periods (e).

We explore changes in the glaciers' dynamic state change by analysing the surface velocities over the last two decades (Dehecq et al., 2015; Fig. 10). It is found that the surface velocities of both glaciers (UAV survey domains) decreased significantly in the first fifteen years of this century with the surface velocities of 1999-2003 and 2013-2015. During this period, the surface velocity of 23K and 24K Glaciers decreased on average by 84% and 54% respectively. However, the velocity magnitude and pattern for 2013-2015 corresponds to our UAV results. In contrast, there is no clear decreasing trend in the surface velocity of the two glaciers in the last five years (2015-2020). The 24K Glacier tongue is still replenished by ice flux at present, which compensates for its higher melt due to its thinner debris thickness. We expect ice supply to continue to deteriorate as these glaciers thin (Dehecq et al., 2019) and Iit is necessary weto carry out continuous, high-precision surface velocity observations to understand these glaciers' its future fate.

A prior study analyzed the ~~The~~ mean surface mass balance for ~~both~~the ~~UAV~~ survey domains from 2000-2016 based on regionally-available datasets (Miles et al., 2021), estimating ~~were~~ -1.5 ± 0.7 m w.e. a^{-1} (23K) and -1.6 ± 1.1 m w.e. a^{-1} (24K)~~(Miles et al., 2021),~~. ~~they~~These values are lower than our results for~~the magnitude of surface mass balance in~~ 2019-2020, which might be attributed to warming or to changes in precipitation timing in the Southeast Tibetan Plateau (e.g. Jouberton et al., 2022)~~is mainly driven by the global warming~~. From 2000-2016, the magnitude of surface mass balance was slightly greater on 24K Glacier than on 23K Glacier, which is consistent ~~similar~~ with ~~the~~ our ~~recent~~ surface mass balance results for ~~(~~2019-2020~~)~~ derived from the UAV data.

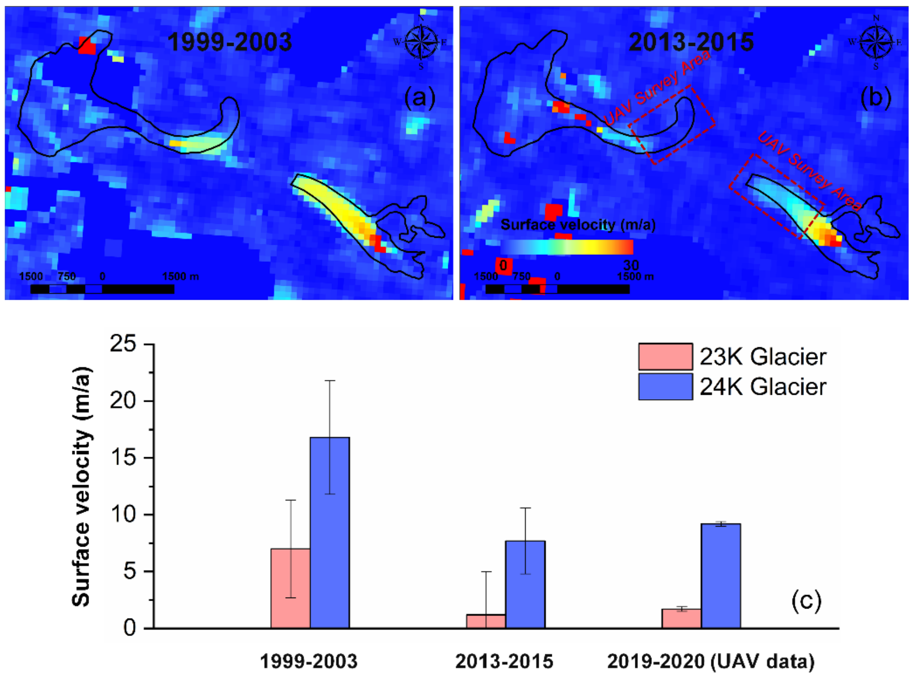


Figure 10: Annual surface velocity for 1999-2003 (a), 2013-2015 (b) for the 23K Glacier and 24K Glacier (red dashed rectangular box represents the UAV aerial survey area). Annual surface velocities and their uncertainties for both UAV survey domains at different periods (c).

5 Discussion

5.1 Controls ~~of~~ on the thinning (d*h*) patterns

The thinning~~d*h*~~ patterns of the two glaciers are ~~very~~ different at the annual scale and during the cold period, as indicated by their ~~its~~ magnitude and spatial distribution (Fig.2). The annual thinning~~d*h*~~ rate of 23K Glacier is approximately twice ~~than~~ that of ~~the~~ 24K Glacier, but the rate at which surface mass balance~~SMB~~ evolves with altitude exhibits less variation between the two glaciers (Fig. 6, Figure S3). Some studies have highlighted ~~show~~ that ~~the~~ large differences ~~These large difference~~ in thinning can be~~d*h* between two glaciers are mainly~~ caused by different dynamic states (Fig. 4; Brun et al., 2018; Anderson et al., 2021a, 2021b; Rounce et al., 2021). In this study, the emergence velocity replenishment is consistently higher on 24K Glacier than on 23K Glacier for all~~in any~~ periods (Fig. 4e)~~, and the estimated surface velocities and driving stress results support this conclusion~~ (Fig. 4a~~, b, c, -~~d). The replenishment of ice into the ablation area by ice flow~~motion~~ is crucial to the glaciers' long-term sustainability, and net annual ablation exceeds ice resupply for the study areas of both glaciers. We therefore assess the ratio of emergence velocity to surface mass balance as an indicator of the local balance between ablation and ice supply (a direct local metric of glacier health), and this study illustrates that glacier health can vary greatly even over small distances (Table~~.~~ 5)~~The dynamic state of a glacier is a clear indicator of its health (Miles et al., 2021), and this study illustrates that glacier health can vary greatly even over small distances~~. 23K and 24K Glaciers experience the same climatic forcing, but their~~have a~~ distinct geometries~~y~~ lead to different expressions of ice dynamics. For instance, ~~We found that~~ the mean longitudinal gradient of 24K Glacier (~0.18) is consistently higher than that of 23K Glacier (~0.08), which explains the higher driving stress (Fig. S8) and, consequently, faster surface velocity of 24K Glacier~~ due to higher driving stress (Fig. S8)~~. In addition, the different glacier geometries may lead to~~ possibly~~ distinct~~ive~~ dependence on avalanche and rockfall mass supply, which could also lead to marked differences in mass supply to the glacier terminus. ~~23K and 24K Glaciers may be thought to experience the same climatic forcing, yet their distinct geometry, and possibly distinctive dependence on avalanche and rockfall mass supply, has led to marked differences in mass supply to the glacier terminus.~~ Using the ratio of emergence to surface mass balance, we can identify, for each season, whether ice resupply or surface mass balance is the main factor leading to the thinning rates. In Table 5, we clearly see that at 23K Glacier, ice supply is considerably smaller (-0.11) than surface mass balance for all periods, indicating that surface mass balance is directly responsible for contemporary thinning patterns. 24K Glacier also exhibits a strong imbalance between ice emergence and surface mass balance over the warm period (-0.15), but emergence nearly compensates for surface mass balance during the cold period (-0.87). Thus, 24K Glacier exhibits a healthier cold-season and annual balance between ablation and ice supply than 23K Glacier.~~However, the d*h* magnitude and spatial distribution of 24K Glacier are similar to that of 23K Glacier during the warm period (Fig. 2, Fig. 3), due to the fact that the ablation determines the d*h* pattern and dilutes the emergence velocity contribution of 24K Glacier during this period. For 23K Glacier, the ablation consistently determines its d*h* patterns due to the weak emergence velocity replenishment during all periods (Fig. 4e)~~. In contrast to the annual and cold period, the thinning patterns of the two glaciers are similar during the warm period (i.e., the magnitude of thinning increases with altitude). In this period, the 24K Glacier emergence velocity only represents a small fraction of the -melt~~ is little compensated by the emergence velocity~~ (Table 5), and the pattern of surface mass balance is clearly driven by the spatial distribution of debris thickness. Therefore, during the warm period, the thinning pattern of 24K Glacier goes from being controlled primarily by ice dynamics (for the annual and cold period) to being controlled by debris thickness.

~~To better evaluate the role of emergence velocity replenishment on d*h*, we calculated the ratio of emergence velocity to SMB (Table. 5). The greater of the absolute value of this ratio indicates the greater impact of emergence velocity replenishment on d*h*. The ratio of annual emergence velocity and annual SMB for 23K (24K) Glacier is -0.09 (-0.49). The ratio values for 23K~~

~~(24K) Glacier during cold and warm periods are -0.11 (-0.87) and -0.09 (-0.15), respectively. The ratio absolute values for 24K Glacier are always higher than those for 23K Glacier, especially evident in the non-ablation period. Hence, the survey area on 23K Glacier is weakly replenished by the upstream ice flux while the stronger upstream ice flux for 24K Glacier serves to restrain the annual surface thinning signal (Fig.4).~~ Fu et al. (2022) also conducted thinning~~d*h*~~ observations for a debris-covered glacier (Hailuogou Glacier) in the southeastern Tibetan Plateau. They revealed that the tongue area showed a considerable thinning~~d*h*~~ (-2.81 m) during an ablation period (June. 2018-Oct. 2018) and that its ice resupply ~~dynamic state~~ is very weak, similar to what we observe for 23K Glacier. He et al. (2023) have also observed the tongue area of a debris-covered glacier (Zhuxi) in the southeastern Tibetan Plateau by UAV from 2020-2021. The tongue part of this glacier is similarly characterised by high rates of thinning (>1 m a^{-1}) and slow movement (< 7 m a^{-1}). Other studies concerning the mass balance of Himalayan debris-covered glaciers also report on glaciers which possess a high thinning~~d*h*~~ rate (~-0.9-1.8 m a^{-1}) and weaker dynamic state (Vincent et al., 2016; Nuimura et al., 2017; Brun et al., 2018; Rowan et al., 2021), and which possess thinning~~d*h*~~ patterns which are consistent with that of 23K Glacier. In summary, the thinning~~d*h*~~ pattern for 23K Glacier appears to conform to that of other Himalayan debris-covered glaciers, whilst that of 24K Glacier ~~is exceptional~~ is perhaps more anomalous due to its relatively healthy ice supply all the way to the terminus.

~~**Table 5: Emergence velocity, SMB and the ratio of above two in all periods for both glaciers.**~~

~~Time~~	~~Glacier~~	~~Emergence velocity (m w.e.)~~	~~SMB (m w.e.)~~	~~Ratio of emergence velocity to SMB~~
~~Aug. 2019-Aug. 2020~~	~~23K~~	~~0.22 ± 0.04~~	~~-2.50 ± 0.11~~	~~-0.09~~
	~~24K~~	~~1.36 ± 0.14~~	~~-2.76 ± 0.34~~	~~-0.49~~
~~Oct. 2019-Aug. 2020~~	~~23K~~	~~0.16 ± 0.03~~	~~-1.53 ± 0.09~~	~~-0.11~~
	~~24K~~	~~1.14 ± 0.11~~	~~-1.31 ± 0.25~~	~~-0.87~~
~~Aug. 2020-Oct. 2020~~	~~23K~~	~~0.07 ± 0.03~~	~~-0.79 ± 0.09~~	~~-0.09~~
	~~24K~~	~~0.18 ± 0.04~~	~~-1.19 ± 0.11~~	~~-0.15~~

In-situ ~~Field~~ observations show that the terminus type differs between each glacier (Fig. 1c, 1d, Fig. S4), which can have a strong influence on ice dynamics for debris-covered glaciers (Anderson and Anderson, 2016). The terminus of 23K Glacier appears largely stagnant and is enclosed by a latero-terminal moraine complex, while the terminus of 24K Glacier exhibits a large ice cliff~~, and which is~~ bounded by lateral moraines. The mass of 24K Glacier is lost due to progressive melt, and episodic 'dry' calving promotes glacier retreat. Such terminal-cliff debris-covered glaciers are less well studied but have been noted in a variety of settings (e.g., Ferguson and Vieli, 2021). Terminus type can have an important influence on debris-covered glacier geometry (King et al., 2019) and may thus influence glacier geometric evolution in a warming climate. Our investigations suggest that 24K Glacier exhibits reduced climatic-geometric imbalance than 23K Glacier, possibly because it has responded to climate warming with progressive retreat, rather than thinning. ~~These differences likely reflect this difference in ice~~

~~dynamics and emphasize their contrasting position within the glacier-debris-covered glacier-rock glacier continuum (Anderson et al., 2018). The terminus of 23K Glacier is largely stagnant with a low d*h* rate, a suppressed dynamic state, and the presence of supraglacial ponds which, combined, are consistent with observations of stagnating debris-covered glaciers in other glacierised regions globally (e.g., Benn et al, 2012).~~ In addition, the ablation area of 23K Glacier is largely stagnant with a low thinning rate (> -0.5 m a^{-1}) and the lower mean surface velocities and reduced driving stress, which favor the presence of supraglacial ponds that enable the persistence of relatively large pond-influenced cliffs (Quincey et al., 2007; Sakai and Fujita, 2010; Miles et al., 2017; Kneib et al., 2023). On the contrary, due to a steeper longitudinal gradient and stronger ice flux, 24K Glacier is characterized by thinner debris which, combined with the steeper gradient, allows for the development of supraglacial streams and corresponding stream-influenced cliffs (Mölg et al., 2020; Kneib et al., 2023).~~In contrast, 24K Glacier has a steep longitudinal gradient with a smooth surface and has developed a sizable terminal ice cliff (Fig. S4); this feature, where mass is lost due to progressive melt, and episodic 'dry' calving promotes glacier retreat. Such terminal-cliff debris-covered glaciers are less well studied but have been noted in a variety of settings (e.g., Ferguson and Vieli, 2021). Terminus type can have an important influence on debris-covered glacier geometry (Anderson et al., 2016) and may thus influence glacier geometric evolution in a warming climate. Our investigations suggest that 24K Glacier exhibits reduced climatic-geometric imbalance than 23K Glacier, possibly because it has responded to climate warming with progressive retreat.~~

5.2 Possible reasons for surface mass balance (SMB) patterns

The ~~existence~~ presence of a debris cover and its influence on ablation typically causes surface mass balance ~~SMB~~ patterns for debris-covered glaciers to differ from those of largely debris-free glaciers due to the melt-buffering effect of supraglacial debris cover that exceed a few centimeters in thickness (Ostrem, 1959; Nakawo et al., 1999; Nicholson and Benn, 2006; Reid and Brock, 2010; Anderson and Anderson, 2016; Yang et al., 2017).~~,~~ ~~and o~~Our results show inverted melt-season surface mass balance~~SMB~~ profiles for both 23K and 24K Glaciers. In addition, debris-covered glaciers tend to develop ice cliffs~~ and supraglacial ponds~~ which enhance melt locally, even relative to clean ice (Sakai, 1998, 2002; Reid and Brock, 2014; Juen et al., 2014; Steiner et al., 2015; Buri et al., 2016, 2021; Miles et al., 2016, 2018, 2022; Kneib et al., 2022). Overall, the annual surface mass balance~~SMB~~ of 23K Glacier and 24K Glacier are similar, but the rate of mass loss is higher for 24K Glacier during the warm period due to its thinner debris cover. During all periods, the magnitude of ablation increases with elevation for both glaciers, with the same spatial distribution (Fig. ~~6~~8, Fig. S3). We find that the correlation between the melt and the debris thickness distribution is strong for both glaciers (23K: r=0.88; 24K: r=0.82) during the warm period, while there is little correlation between the melt and the ice cliffs and supraglacial ponds~~hotspots~~ area distribution (23K: r=-0.29; 24K: r=-0.48). Prior~~Some~~ studies have also identified~~confirmed~~ the effect of the debris thickness spatial distribution on the physical mechanisms of ablation (Mihalcea et al., 2008; Zhang et al., 2011; Reid et al., 2012; Juen et al., 2014; Zhang et al., 2016; Gibson et al., 2017; McCarthy et al., 2017).

With the relationship between surface mass balanceSMB and debris thickness established for the two glaciers during the ablation period, we found that the mean residuals sourced from surface mass balanceSMB-debris thickness relationship of 23K Glacier were larger than the 24K Glacier (47.1 *vs* 24.2). Although there is no direct clear correlation between surface mass balanceSMB and ice cliffs and supraglacial pondshotspots, the above nearly double residual difference is hypothesized to be based on the large difference in ice cliffs and supraglacial pondshotspots area enhancement factors of two glaciers (23K: 4.4, 24K: 2.6; ~1.7 times), and. It reflects some of the influence of ice cliffs and supraglacial pondshotspots area on surface mass balanceSMB/melt pattens. By extracting the ablation contribution of the ice cliffs and supraglacial ponds (Fig. 7), we found that the total melt from hotspots areas accounted for 31.5 ± 2.2% of the total melt in the UAV survey area. For 24K Glacier, the ablation in hotspots areas accounts for 11.4 ± 1.3% of the total melt in the survey area for this glacier.

Based on UAV and time-lapse camera observations, Kneib et al. (2022) carried out high-precision observation of a single ice cliff on the 24K Glacier, and measured the daily cliff melt during the ablation period atis 3.9-5.1 cm day^{-1}. In this study, the daily melt of the 24K Glacier ice cliffs and supraglacial pondshotspots areas during the warmduring warm period was estimated to be 4.4 ± 0.2 cm w.e. d^{-1} (~4.9 cm day^{-1}), which is similar to the observed value for a single ice cliff. The role of ice cliffs and supraglacial pondshotspots area is not negligible, as glacier ablation in the survey areas would be underestimated by 24.5 ± 1.7% (23K) and 7.0 ± 0.7% (24K), respectively, if the ice cliffs and supraglacial pondshotspots areas were not taken into account when carrying out the two glaciers mass balance modelling work. Other studies have observed and simulated the contribution of ice cliffs to be 17-26% of the total ablation, which is in agreement with our results (Brun et al., 2018; Anderson et al., 2021a; Buri et al., 2021). However, the areal proportion of ice cliffs and supraglacial pondshotspots areas (23K Glacier: 7.2 ± 0.5 %, 24K Glacier: 4.4 ± 0.5 %) is much smaller than that of the sub-debris melt area for each glacier. This has the overall effect that enhanced melt in these regions does not have a marked effect on glacier-scale surface mass balanceSMB profiles, but rather leads to an increase in ablation throughout the debris-covered area. We note that in this study the outlines of ice cliffs and supraglacial pondshotspots area as digitized for warm periods were obtained based on the merged outlines (Brun et al., 2018), which may lead to an overestimation of the extent of the ice cliffs and supraglacial pondshotspots area (Kneib et al., 2022). In other words, the actual ice cliffs and supraglacial pondshotspots area may represent a lower proportion of the UAV survey area. Though the ice cliffs and supraglacial pondshotspots are local controls of melt patterns, the debris thickness is the dominant control on the altitudinal surface mass balance pattern for both 23K and 24K Glaciersarea is recognized as local controls of melt patterns, the debris thickness is the dominant altitudinal control the glacier scale for 23K Glacier and 24K Glacier, similar to the conclusion at Kennicott Glacier in Alaska (Anderson et al, 2021a).

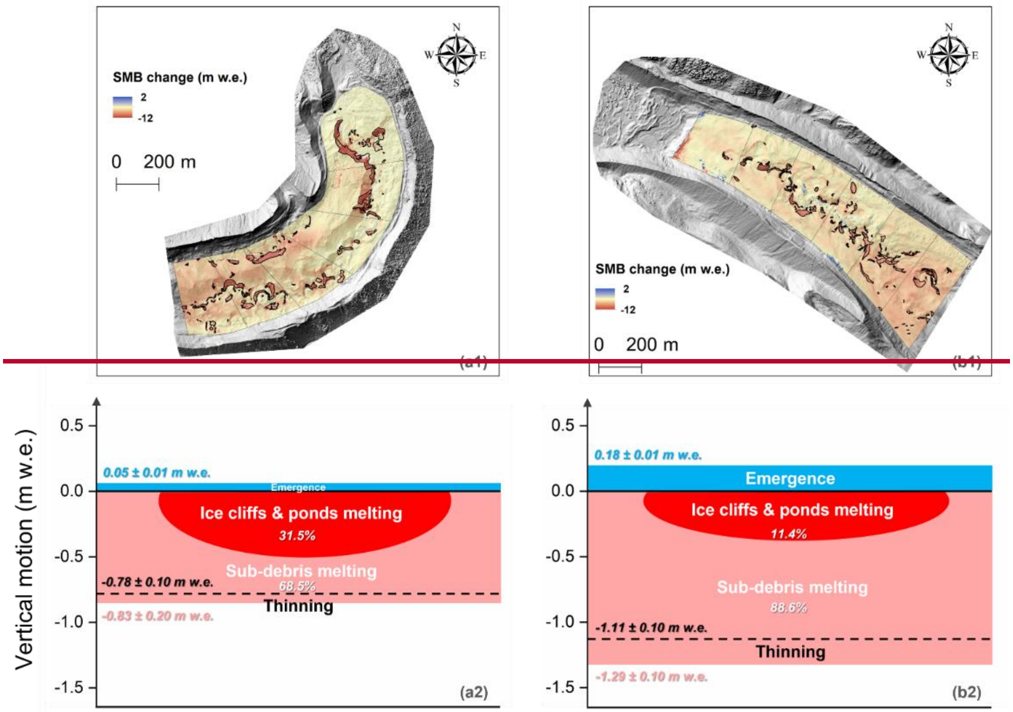


Figure 7: Spatial distribution of surface mass balance during ablation period for the UAV survey domains of 23K Glacier and 24K Glacier (a1, b1). The a2 and b2 are the conceptual diagrams of vertical motion components for 23K Glacier and 24K Glacier.

TIn this study , it gives us insight into the clear controlling role of the debris thickness on ablation melt patterns of debris-covered glaciers. In future research, it will beis beneficial to improve our understanding of the responses of debris-covered glaciers to climate change to by focusing on the debris supply and evacuation differences etc. According toBased on field photography (Fig. S5), we also found that paraglacial slope failure (PSF) events have occurred in the catchment of 23K Glacier recently and may be the result of complex interactions between geologic structure and stress-related slope response to glacier mass loss (Zhong et al., 2022). Such events may become an increasingly important component of the debris supply and transport cascade for these land systems, with implications for the future development of supraglacial debris cover, glacier mass balance, and flow dynamics; large rock avalanches which emplace in supraglacial environments have led to melt suppression and glacier advance in other locations (e.g., McSaveney, 1975; Shugar and Clague, 2011), and, if sufficiently thick, this event could thus temporarily rejuvenate the emergence velocity into the terminus area.

5.3 Glaciers change in the early twenty-first century

The thinning of 23K Glacier tongue is greater than that of 24K Glacier since 2000 (Hugonnet et al., 2021; Fig. 8), which is generally in agreement with the current d*h* pattern. It is found that the thinning rates of both glaciers show the accelerated increase over the last two decades (23K: +77%; 24K: +100%). However, the increase rate of 24K Glacier tongue is slightly lower than that of 23K Glacier over the last decade (23K: +44%; 24K: +20%).

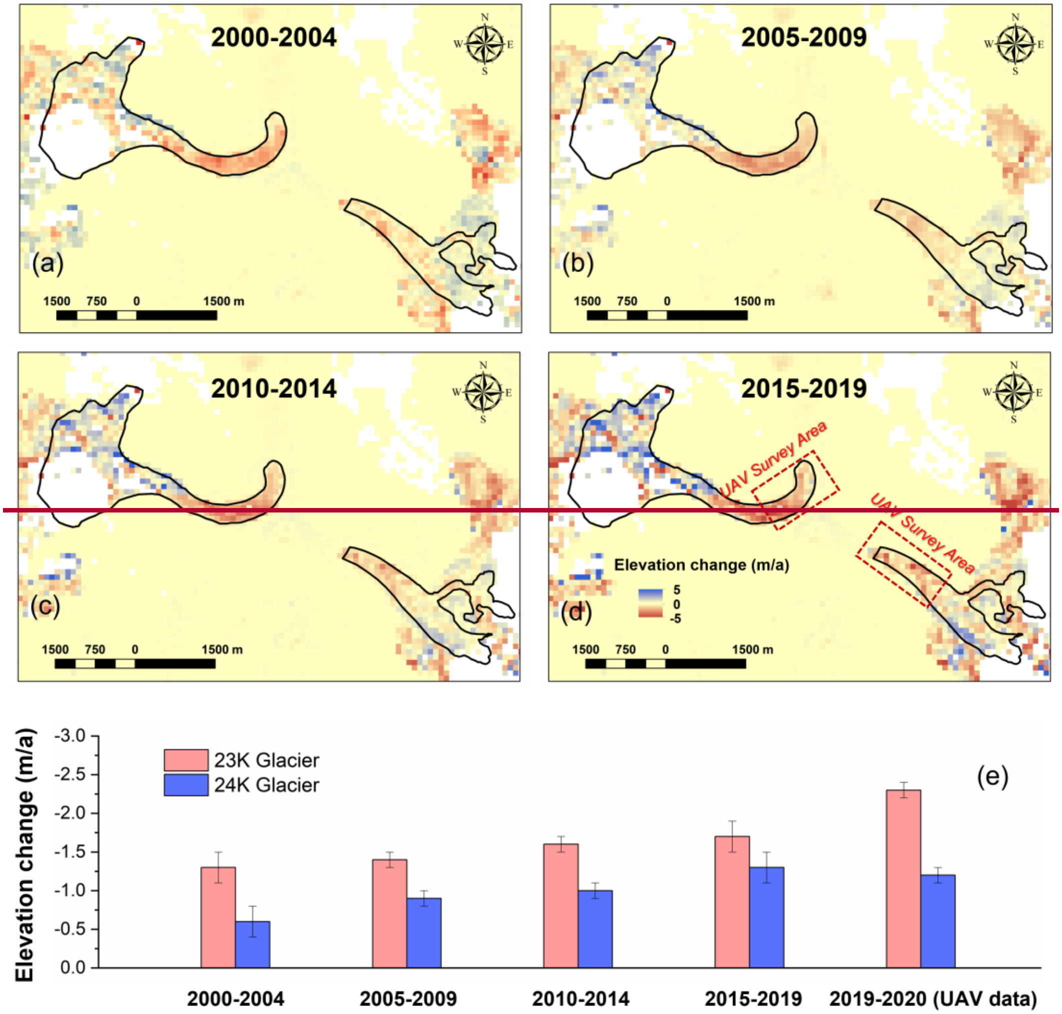
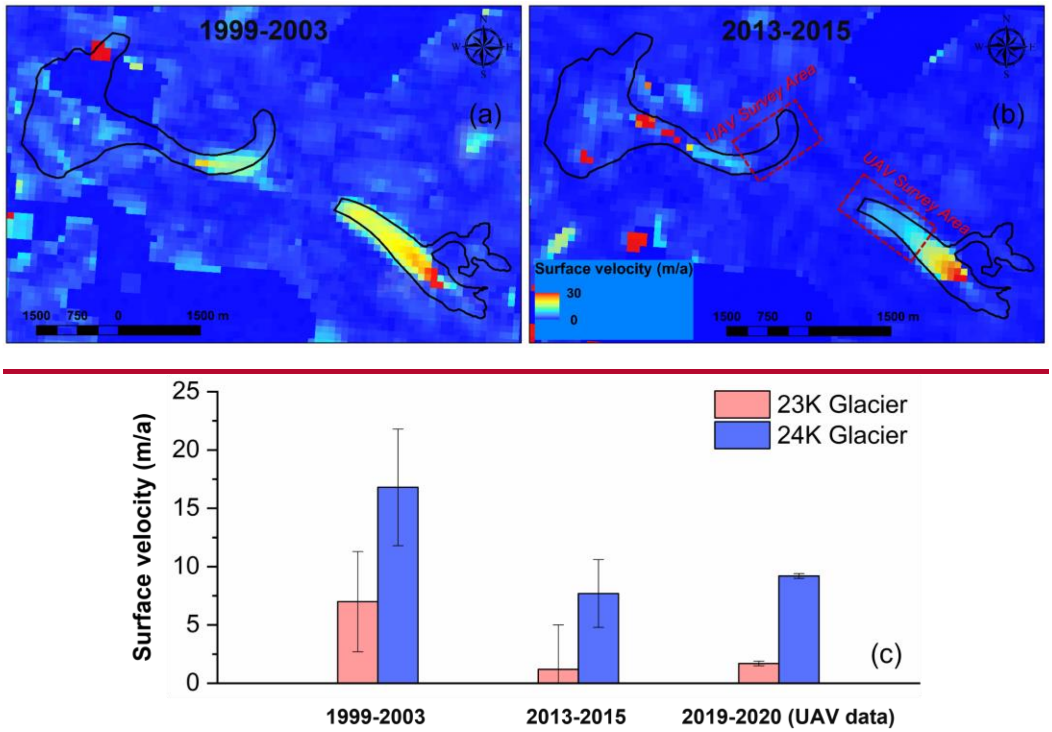


Figure 8: Annual surface elevation changes for 2000-2004 (a), 2005-2009 (b), 2010-2014 (c), 2015-2019(d) for the 23K Glacier and 24K Glacier (red dashed rectangular box represents the UAV aerial survey area). Annual surface elevation changes and their uncertainties for both UAV survey domains at different periods (e).

We explore the glaciers dynamic state change by analysing the surface velocities over the last two decades (Dehecq et al., 2015; Fig. 9). It is found that the surface velocities of both glaciers decreased significantly in the first fifteen years of this century with the surface velocities of 1999-2003 and 2013-2015. During this period, 23K and 24K Glaciers decrease by 84% and 54% respectively. In contrast, there is no clear decreasing trend in the surface velocity of two glaciers in the last five years (2015-2020). The 24K Glacier tongue is still replenished by ice flux at present, which compensates for its higher melt

~~due to its thinner debris thickness. It is necessary for 24K Glacier to carry out continuous, high-precision surface velocity observations to understand its future fate.~~

~~The mean SMB for both UAV survey domains from 2000-2016 were -1.5 ± 0.7 m w.e. a^{-1} and -1.6 ± 1.1 m w.e. a^{-1} (Miles et al., 2021), they are lower than the magnitude of SMB in 2019-2020, which is mainly driven by the global warming. From 2000-2016, the magnitude of SMB was slightly greater on 24K Glacier than on 23K Glacier, which is similar with the recent SMB results (2019-2020) derived from the UAV data.~~



~~**Figure 9: Annual surface velocity for 1999-2003 (a), 2013-2015 (b) for the 23K Glacier and 24K Glacier (red dashed rectangular box represents the UAV aerial survey area). Annual surface velocities and their uncertainties for both UAV survey domains at different periods (c).**~~

Conclusions

We have used multi-temporal high-resolution UAV-SfM surveys combined with *in-situ* observations to quantify seasonal thinning (d*h*) and surface mass balance (SMB)~~ patterns~~ of two neighboring, but contrasting, debris-covered glaciers in the southeastern Tibetan Plateau. The conclusions are summarized as follows：

1) The thinning (d*h*)~~d*h*~~ patterns of the two glaciers display distinct characteristics at annual scale. The annual thinning~~d*h*~~ of 23K Glacier UAV survey area is 1.9 times greater than that of 24K Glacier. The magnitude of 23K Glacier thinning~~d*h*~~ increases with altitude, similar to many other debris-covered glaciers, whereas 24K Glacier shows the opposite pattern, except during

the melt season. These contrasting patterns are mainly driven by the stronger dynamic state of 24K Glacier, which has a much higher down valley~~ward~~ emergence velocity replenishment. However, the thinning pattern of ~~the~~ 24K Glacier is similar with that of ~~the~~ 23K Glacier during the warm period (i.e., the magnitude of thinning increases with altitude). In this period, the thinning of 24K Glacier is mainly controlled by melt.

2) The surface mass balance (SMB)~~SMB~~ patterns of the two glaciers are generally in agreement. The magnitude of surface mass balance~~SMB~~ on both glaciers increases with altitude in the ablation period, exhibiting melt inversion which is attributable to the debris thickness distribution (which decreases with altitude). Due to the low areal proportion of ice cliffs and supraglacial ponds area (melt hotspots), sub-debris ablation accounts for the majority of the total ablation. ~~Debris thickness variations show a clear control on zonal surface mass balanceSMB. The cliffs and ponds melt enhancement factor which ranges between 2.6 and 4.4 during warm period, ice cliffs and supraglacial pondshotspots area's melt contribution is still considerable.~~

3) ~~Based on the analysis of the elevation and surface velocity changes over the last two decades,~~ both glaciers experience accelerated thinning and reduced flow in their ablation area. ~~Both glaciers experience accelerated thinning and their surface velocities are decreased by analysing the elevation and surface velocity changes over the last two decades.~~ 23K Glacier possesses the higher thinning~~*dh*~~ rate and ~~its dynamic state~~ is in a weaker dynamic state than ~~the~~ 24K Glacier, a pattern that is confirmed on the longer term. ~~The magnitude of the annual surface mass balanceSMB for both glaciers has the increasing trend from in 2000-2016 is lower than theto 2019-2020. The surface mass balance magnitude of results (from UAV data), but 24K Glacier is consistently slightly higher than 23K Glacier. (2000-2016: -1.5 m w.e. a^{-1} (23K), -1.6 m w.e. a^{-1} (24K); 2019-2020: -2.5 m w.e. a^{-1} (23K), -2.8 m w.e. a^{-1} (24K)).~~

4) ~~Such a h~~High-resolution and comparative observation gives a rare perspective into the controls of the thinning and melt of two debris-covered glaciers. We provide evidence that the rate of mass loss on such glaciers can be highly dependent on dynamic state, and that the relatively thin debris on these glaciers is the main control of the glacier surface ablation patterns, with supraglacial cliffs and ponds primarily serving to enhance mass loss.

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Data availability

The UAV-derived orthomosaics and DEMs of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.7350479. The above data will be available when this paper is final published in TC.

Author Contributions

CZ, WY, ESM, MW, MK, FP designed the study and completed the data analysis. WY supervised the study. WY, CZ, ESM, MW, MK, YW, ZH conducted the fieldwork. All authors contributed to the writing and revision of the paper.

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Competing interests

The authors have the following competing interests: At least one of the coauthors is a member of the editorial board of The Cryosphere.