# Disaggregating surface change mechanisms of a rock glacier using terrestrial laser scanning point clouds acquired at different time scales

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**Abstract.** Topographic change at a given location usually results from multiple processes operating over different timescales. However, interpretations of surface change are often based upon single values of movement, measured over a specified time period and in a single direction. This work presents a method to help separate surface change mechanisms related to the deformation of an active rock glacier, drawing on terrestrial lidar monitoring at sub-monthly intervals. We derive 3D topographic changes across the Äußeres Hochebenkar rock glacier in the Ötztal Alps. These are presented as the relative contribution of surface change during a three-week period of snow-free conditions (2018) to the annual surface change (2017-2018). They are also separated according to the direction perpendicular to the local rock glacier surface (using point cloud distance computation) and the direction of rock glacier flow, indicated by movement of individual boulders. In a 1500 m² sample area in the lower tongue section of the rock glacier, the contribution of the three-week period to the annual change perpendicular to the surface is 20 %, as compared to 6 % in the direction of rock glacier flow. This shows that different directions of surface change are dominant at different times of the year. Our results demonstrate the benefit of more frequent lidar monitoring and, critically, the requirement of novel approaches to detecting change, as a step towards interpreting the mechanisms that underlie the surface change of rock glaciers.

## 1 Introduction

Rock glaciers play a key role in understanding the impact of changing environmental conditions on the high-mountain cryosphere. Their deformation, i.e. change in shape and/or size, has shown sensitivity to atmospheric conditions at interannual (Roer et al., 2008; Sorg et al., 2015; Kellerer-Pirkelbauer et al., 2018) and seasonal (Delaloye et al., 2010; Kenner et al., 2017) timescales. Rising permafrost temperatures, which have been observed since the 1980s, have led to an acceleration of rock glacier movement (Kääb et al., 2007; Sorg et al., 2015). Deformation can result from different mechanisms across the rock glacier, such as plastic deformation proximal to the accumulation zone, shearing within distinct

30    layers, mass accumulation and thickening, frost heave, and thaw settlement (Barsch, 1996; Kääb et al., 1997; Krainer et al., 2015; Kenner et al., 2017). While certain processes tend to operate within distinct zones (Kenner et al., 2017), multiple mechanisms may occur in unison at a given point on the surface, with the resulting surface change representing superimposed expressions of these mechanisms.

Disaggregating the changes related to this deformation represents a valuable step in interpreting how rock glaciers move, as

35    well as what drives this movement. Approaches to support these interpretations based on *in situ* monitoring, such as the distribution of electrical resistivity tomography values (Zahs et al., 2019) or ground temperature records from boreholes (Kenner et al., 2017) are also of value. To distinguish changes at the surface, which are assumed to be in the order of a few centimeters within timescales of few weeks, 3D topographic data at high spatial resolution are required. These can be obtained using lidar systems (e.g. Bollmann et al., 2012; Micheletti et al., 2016; Zahs et al., 2019), which provide high-

40    accuracy and high-precision 3D measurements of a surface at centimeter-scale point spacing (generally equating to spatial resolution).

Several studies have relied on two-dimensional raster-based methods, such as the differencing of digital elevation models, to detect rock glacier surface change (Bollmann et al., 2012; Bollmann et al., 2015). These are limited, however, in representing changes to steep and complex morphology (Hodge et al., 2009; Sailer et al., 2014) and provide change in a

45    single direction, typically vertically. The Multiscale Model to Model Cloud Comparison (M3C2) algorithm (Lague et al., 2013) overcomes these limitations by computing point-wise cloud distances in a direction perpendicular to the local surface. While Zahs et al. (2019) have applied this approach to existing datasets of the rock glacier *Äußeres Hochebenkar*, the processes that cause the observed changes may induce movement along different predominant directions. Examining change in multiple directions may therefore be required in order to distinguish these processes.

50    Repeated data acquisitions using lidar have seen increasing use in order to detect and quantify rock glacier surface change (Bollmann et al., 2012; Bollmann et al., 2015; Micheletti et al., 2016; Klug et al., 2017; Zahs et al., 2019). To date, most studies have used monitoring intervals of one year or longer. This is problematic where the aim is to increase the understanding of processes operating over shorter timescales, such as the movement of individual boulders, or the drivers of these processes, such as individual precipitation events. Ideally, monitoring intervals should be short enough to approach the

55    timescale over which changes occur, or the timescale of variability in external drivers; yet this remains difficult to define *in-situ* (e.g. Williams et al., 2019). The point cloud-based assessment of geomorphological activity at the *Äußeres Hochebenkar* conducted by Zahs et al. (2019) demonstrated that deformation processes occurred continuously at the rock glacier's lower tongue over a 12-year period. However, it was shown that there are episodic processes as well, which may be masked by continuous deformation processes at the timescale of a year.

60    In this study, we examine the benefits of interpreting 3D surface change from short interval monitoring in terms of its contribution to annual movement and the drivers behind it. By quantifying surface change based on movements that occur in different directions, we aim to distinguish creep-related processes from other processes of surface change (e.g. surface lowering or surface heave). To achieve this, movements normal to the surface of an active rock glacier, derived from the

M3C2 algorithm, and movements in the direction of rock glacier flow, derived from individual boulder tracking, will be used
(Fig. 1). The contribution of a three-week period to the annual surface change will be assessed by considering this
contribution as a ratio between the surface change occurring during the three-week period and the surface change within one
year. This will enable to disclose the contribution of short-term surface changes to annual surface changes in the context of
superimposed, and hence cumulated, surface changes for the first time.

Three epochs of TLS point clouds

**Three weeks**          **One year**
(heightened activity)

Change normal to rock glacier surface
(M3C2 algorithm)

Change along rock glacier surface
(Boulder movement)

Contribution of change during
three-week period to annual change
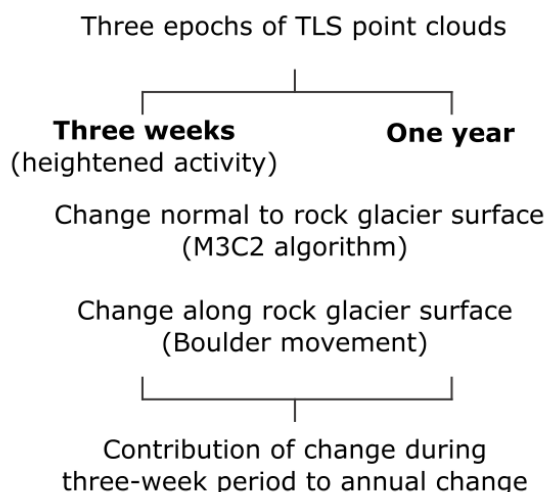
**Fig. 1. Changes to the rock glacier surface in the direction normal to the local surface were calculated using the M3C2 algorithm
over a three-week and a one-year period. The results of the M3C2 algorithm were combined with distances between the centroids
($\mathbb{R}^3$) of corresponding boulders within each point cloud, representing movement in the direction of rock glacier flow. The changes
in both directions are expressed as the percentage contribution of the three-week period to the annual surface change rates.**

## 2 Study Site and Data

Our study site is the lower tongue area of the *Äußeres Hochebenkar* rock glacier (Fig. 2), located near Obergurgl in the
southern Ötztal Alps, Austria (46°50′ N, 11°01′ E). Long-term measurements have shown that the surface velocity of the
rock glacier has increased since the mid-1980s (Schneider, 1999; Kaufmann & Ladstädter 2002; Bollmann et al., 2012; Klug
et al., 2012; Hartl et al., 2016b).
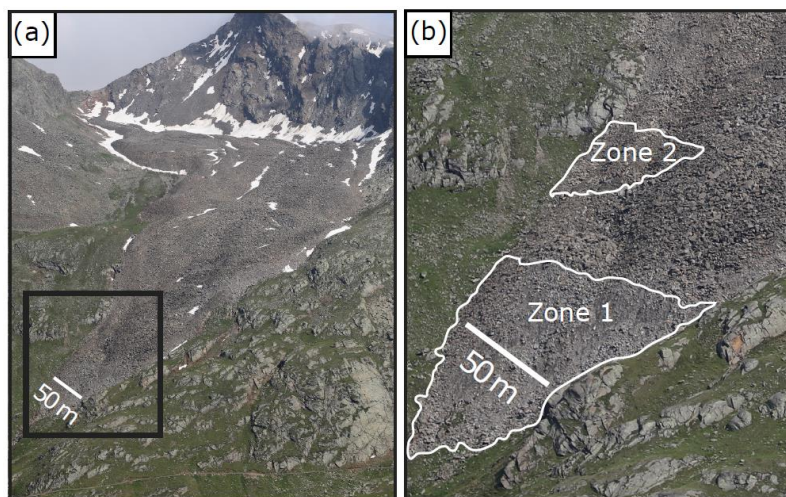
**Fig. 2. Overview of the study area (a). The inset (b) shows the lower tongue area of the Äußeres Hochebenkar rock glacier. Active zone 1 comprises the rock glacier front, while active zone 2 represents a ridge above the rock glacier front exhibiting negative surface change in the direction normal to the surface in both periods. Images: J. G. Williams, 21 July 2019.**

In this paper we report on three Terrestrial Laser Scanning (TLS) datasets, captured on 19 July 2017, 7 July 2018, and 30 July 2018 from seven scan positions (six positions in the dataset of 30 July 2018), located around the lower tongue. The three-week period during July 2018 was selected because it presented snow-free conditions. Riegl VZ-400 (acquisition in 2017) and Riegl VZ-2000i (acquisitions in 2018) TLS instruments were used, capable of range measurement accuracies of ± 5 mm and a precision of ± 3 mm at 100 m scanning range (lower tongue width ~150 m). Accuracy and precision may vary across surfaces with varying target range and geometry. To obtain high point densities for an accurate representation of single boulders, a vertical and horizontal angular resolution between 0.017° and 0.023° was therefore chosen, equating to 3-5 cm point spacing at 100 m range. The resulting mean point density ranges from 436 points m$^{-2}$ to 528 points m$^{-2}$.

## 3 Methods

3D changes to the rock glacier surface were calculated using the M3C2 algorithm over 376 days (herein referred to as one-year) and 23 days (herein referred to as a three-week period), and expressed as the percentage contribution of the three-week period to the annual surface change rates. The results of the M3C2 algorithm were combined with distances between the centroids ($\mathbb{R}^3$) of corresponding boulders within each point cloud, representing movement in the direction of rock glacier flow (Fig. 3b, 2).
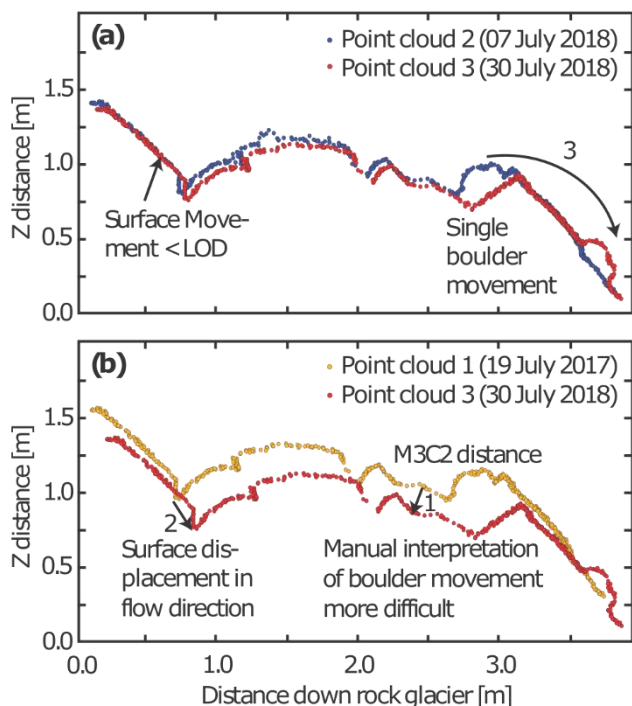
**Fig. 3. Explanation of different types of surface change that can be observed in a three-week period (a) and a one-year period (b).**
100 **While the M3C2 distance refers to surface change in the normal direction (1), the measurements of surface displacement in flow direction reflect the creep-related movement of the rock glacier tongue (2). Additionally, single boulder movement was measured in a sample area of the rock glacier front (3). In the one-year period, manual interpretation of boulder movement is more difficult than in the three-week period. It is easier to distinguish single boulder movement from rock glacier creep in the three-week period, because creep-related surface movement is often below the level of detection (4).**

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Each TLS point cloud was subsampled with a method that selects the point with the highest elevation value within a 3D spherical neighborhood of 0.05 m diameter. Using this subsampling method, no averaging was required and a consistent selection of 3D points within each sphere was performed. The uniform point distribution obtained aided the selection of a single set of parameters for the M3C2 algorithm, which was then used to quantify surface change for both periods. The
110 method calculates signed distances between two point clouds along vectors orthogonal to the local surface, herein referred to as 'surface change in the normal direction' (Fig. 3b, 1) (Lague et al., 2013). This change corresponds to the 3D distance between the average positions of two point clouds, calculated in the direction of the normal vector. The projection radius for the M3C2 algorithm, representing the volume within which average positions are calculated, was set to 1 m. In order to respect the varying roughness values of the study area, a multi-scale normal vector estimation with a minimum normal scale
115 of 8 m was used. This was large enough to ensure that the calculated distances would not be influenced by the local orientation of single boulders, instead aligning approximately perpendicular to the rock glacier surface.

Various sources of uncertainty can affect the accuracy of surface changes quantified using multitemporal lidar; ultimately determining the scale of movement that can be confidently detected (Hodge et al., 2010; Lague et al., 2013; Micheletti et al., 2016). In addition to the systematic measurement errors related to the sensor and the alignment of two datasets, further
120   uncertainty is introduced by varying point density and high roughness in morphologically complex, natural surfaces (Lague et al., 2013; Schürch et al., 2011; Soudarissanane et al, 2011). Therefore, the confidence in the true position of the surface, and hence the distance to itself in successive point clouds, are spatially variable. Although the point clouds were subsampled to a uniform 0.05 m distribution, this process does not eliminate variations in surface roughness across the cloud. To account for this, the M3C2 algorithm performs a confidence assessment by approximating the minimum detectable changes, referred
125   to as the level of detection. This draws on (1) the fit of points within each neighborhood to a plane, with a higher standard deviation of distances resulting in less confidence in the surface's average position within that neighborhood, and (2) the number of points within the neighborhood, with an increase in the number of points generally providing a more robust centroid position. The level of detection is calculated for each point individually across the point cloud (Lague et al., 2013). In order to obtain a uniform threshold value and to make level of detection values of both periods comparable, the 95th
130   percentile of the distribution of level of detection values was calculated for both dataset pairs used for the change analysis. For a pair of datasets, all quantified surface changes exceeding this level of detection threshold value were considered statistically significant.

The ratio of the three-week change to the annual surface change was separated into mean positive and mean negative change. This provided an initial distinction between processes that raise or lower the surface and prevented mean values from
135   clustering around zero where positive and negative changes were proximal. Visual inspection of the distribution of M3C2 values (Fig. 4) enabled us to identify different active zones of the rock glacier based on the direction and magnitude of surface change. In these active zones, displacement of the rock glacier was estimated by measuring the movement of 48 manually identified boulders in the direction of rock glacier flow (Fig. 3b, 2) in both observed periods. Although boulder movement at the rock glacier surface may be influenced by processes such as frost heave or thaw settlement, causing them to
140   move perpendicular to the rock glacier surface, their motion is predominantly in the direction of rock glacier flow.

## 4 Results

The level of detection ($p < 0.05$) is 0.10 m in the three-week period and 0.11°m in the one-year period. The share of significant changes in the three-week period is 7.1 % as compared to 52.1 % in the one-year period. We interpret this as relating to the low magnitudes of surface change (Table 1) relative to the surface roughness. For both the three-week and
145   annual periods, the majority of points exhibit positive surface changes in the normal direction (68.7 % and 61.7 %, respectively), indicative of mass accumulation and thickening. Interestingly, the contribution of the three-week period to the annual positive surface change in the normal direction amounts to 14.8 %, while this ratio is 21.4 % for negative surface change over the same point set. The higher proportion of negative change indicates that surface lowering is more active over

Earth **Surface**
**Dynamics**
Discussions

this period than surface raising. The rate of surface lowering is four times what would be expected if changes observed over

150  the annual period were uniform through the year or, critically, averaged across the year (5.7 %).

**Surface Change 3-Week Period [m]**

| | |
|---|---|
| ■ > 0.2 | ☐ -0.05 - 0.0 |
| ■ 0.1 - 0.2 | ■ -0.1 - -0.05 |
| ■ 0.05 - 0.1 | ■ -0.2 - -0.1 |
| ☐ 0.0 - 0.05 | ■ < -0.2 |

**Surface Change 1-Year Period [m]**

| | |
|---|---|
| ■ > 1.0 | ☐ -0.2 - 0.0 |
| ■ 0.5 - 1.0 | ■ -0.5 - -0.2 |
| ■ 0.2 - 0.5 | ■ -1.0 - -0.5 |
| ☐ 0.0 - 0.2 | ■ < -1.0 |

– – Rock glacier outline
○  TLS scan position (7 July 2018)

Coordinate system: WGS 1984 UTM Zone 32N
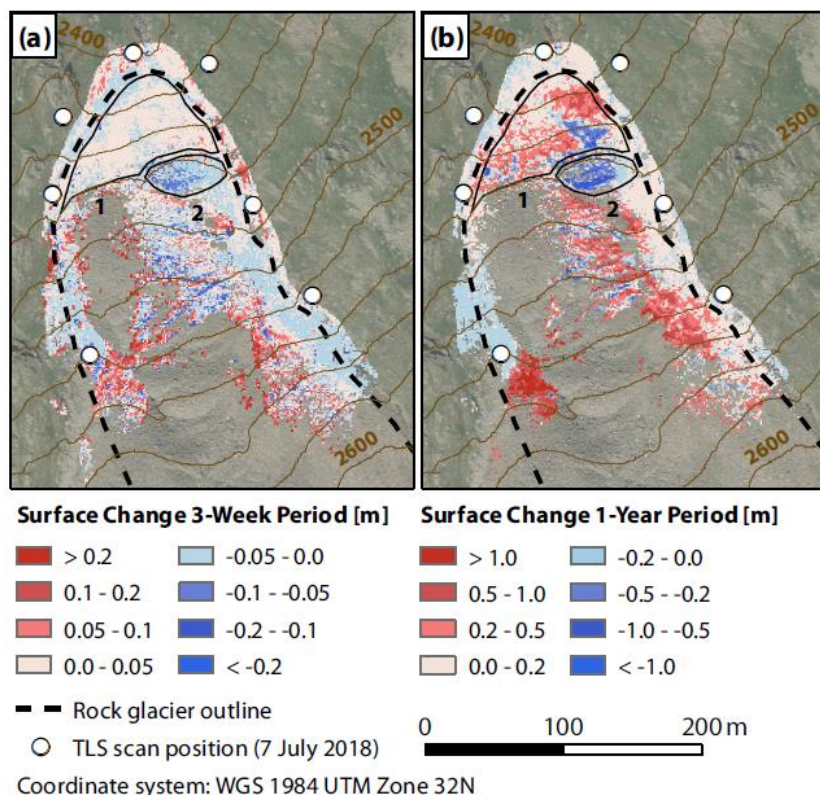
**Fig. 4. Comparison of surface changes normal to local surface orientation in the lower tongue area of the Äußeres Hochebenkar rock glacier computed with the M3C2 algorithm for (a) the three-week period and (b) the one-year period. For a better visibility of the spatial change patterns, the scale of the color ramps is different for the two periods. Active zone 1 comprises the rock glacier**

155  **front, while active zone 2 represents a ridge above the rock glacier front exhibiting negative surface change in both periods. Map Extent: Top left 652769 E, 5189346 N; bottom right 653051 E, 5188937 N (WGS 1984 UTM Zone 32N). Source of base map: Orthophoto Tyrol, Federal State Tyrol - data.tirol.gv.at.**

Table 1: Level of detection threshold values and percentage of M3C2 distance values exceeding these thresholds in the one-year period and in the three-week period

| | One-year | Three-week |
|---|---|---|
| Level of detection threshold value [m] | 0.11 | 0.10 |
| Share of M3C2 distance values exceeding the level of detection threshold value [%] | 52.1 | 7.1 |

160 Surface changes over the course of a year include many small and discrete areas of positive and negative change on the orographic left side of the rock glacier front, between 2420 and 2460 m a.s.l. (Active Zone 1; Fig. 4b). In the three-week period, almost no similar boulder movement is visible in a mostly static rock glacier front (Fig. 4a). Although the change detection over three weeks shows only a few significant surface changes (> 0.10 m), some similarities of surface changes can be identified in both periods (Fig. 4). For example, both periods exhibit positive surface changes in active zone 1, caused by

165 the advance of the rock glacier, and both periods exhibit negative surface change in a ridge above the rock glacier front (active zone 2).

The ratio of distances travelled by individual boulders at the rock glacier front sheds light on how independently they move relative to creep of the rock glacier. In the three-week period, only few single boulder movements (eight were detected) exceed the level of detection, with the magnitudes of their movement differing considerably. The movement of boulders no.

170 1 to 6 in the three-week period is < 1 m (Fig. 5a), which, combined with the direction of this movement, indicates that they move creep-induced, reflecting the advance of the wider rock glacier body. Conversely, movement of boulders no. 7 and 8 is > 5 m (Fig. 5b), indicating that these boulders have moved gravity-induced, i.e. independently from the underlying material. While their movement exceeded 5 m, manual tracking of these boulders was possible within the three-week period because relatively few other observable changes occurred. This discrepancy, which is only possible from the shorter three-week

175 monitoring interval, is important for identifying boulders moving independently from rock glacier creep. Given their independence from overall creep of the rock glacier, these eight boulders were removed from the calculation of boulder movement ratios between the three-week and one-year period.
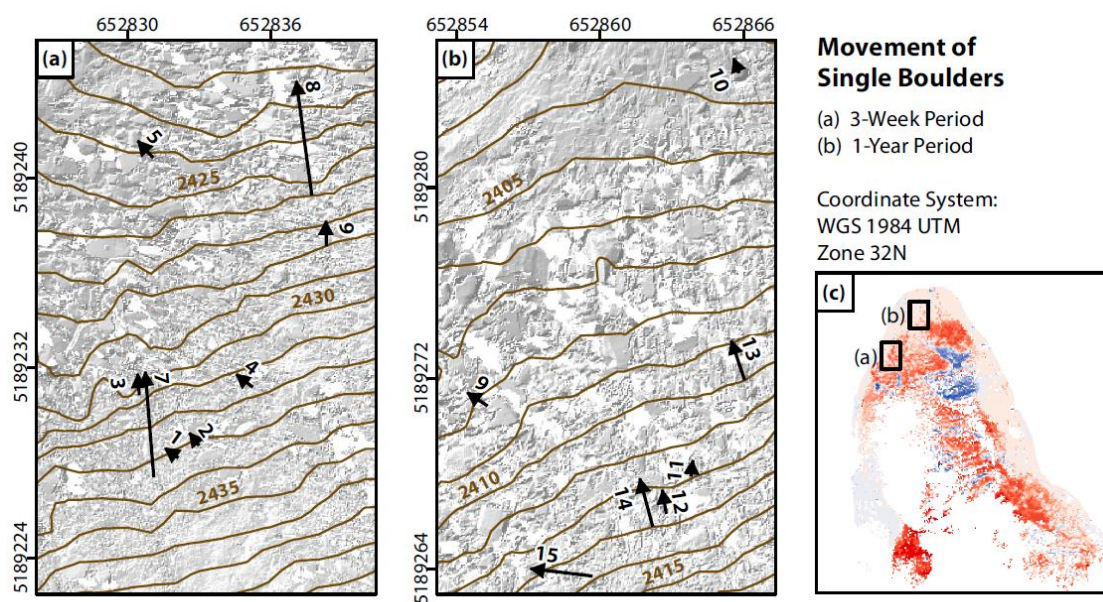
**Fig. 5. Movement of single boulders in two different sub-areas of the rock glacier front during the three-week period (a) and the**

180 **one-year period (b). Boulders are predominantly moving in the direction of rock glacier flow. The distances covered by the moving**

**boulders range from few cm to 6 m in the three-week period, enabling a clear distinction between creep-induced boulder movement (boulders 1 to 6) and gravity-induced boulder movement (boulders 7 and 8). In the one-year period, the magnitudes of the detected single boulder movement are more homogeneous than in the three-week period and remain well below 5 m, indicating that all of these movements are creep-induced.**

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In contrast to the three-week period, the one-year period exhibits a high quantity of single boulder movements at the rock glacier front. As this makes their re-identification between successive point clouds difficult, it is only possible to find corresponding boulders at smaller distances, whose movement is likely to result from rock glacier advance. This is indicated by magnitudes of boulder movement that are more homogeneous than in the three-week period and that are well below 5 m

190  (Fig. 5b). We cannot assume that no boulders in the one-year period are moving independently from the rock glacier advance, but such movements over larger distance (presumably > 5 m) could not be identified visually.

In comparing different change directions, the M3C2 distances illustrate that in active zone 2 (Fig. 4), the three-week period contributes 0.10 m (20 %) to the annual surface change (-0.5 m) in the normal direction (Fig. 6). However, the measurements of boulder displacement indicate that the three-week period contributes 0.08 m (6 %) to the annual surface change of 1.4 m

195  in flow direction in this active zone. Assuming a theoretical constant annual rate, the contribution of a three-week period is 5.7 %. While the movement rate in the normal direction suggests an above-average contribution of the three-week period to the annual surface change, the movement rate from the boulder displacement measurements implies that quantified movement was in-line with the annual average during this three-week period.
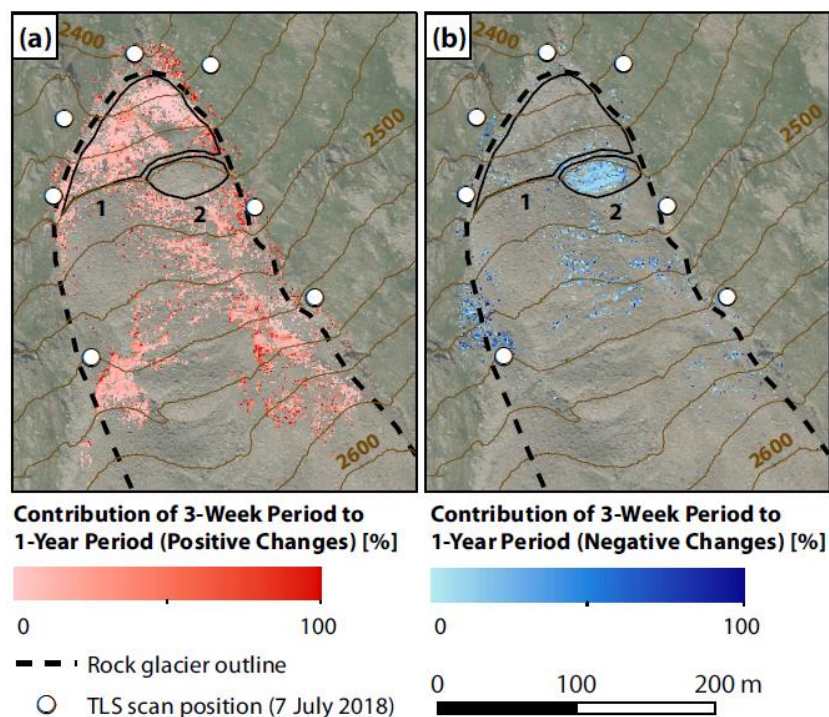
**Fig. 6. Percentage contribution of the three-week period to the annual surface change regarding positive change (a) and negative change (b). If changes observed over the annual period were uniform through the year or, critically, averaged across the year, the three-week period would contribute roughly 6 % to the annual change rates. Red areas are relatively active during the three-week period compared to the rest of the year, while blue areas are relatively stable during the three-week period. Active zone 1 comprises the rock glacier front, while active zone 2 represents a ridge above the rock glacier front exhibiting negative surface change in both periods (d). Map Extent: Top left 652769 E, 5189346 N; bottom right 653051 E, 5188937 N (WGS 1984 UTM Zone 32N). Source of base map: Orthophoto Tyrol, Federal State Tyrol - data.tirol.gv.at.**

## 5 Discussion

Level of detection and implications for monitoring

Uncertainties in measuring the volume of discrete events, such as rockfalls, have been shown to accumulate with short interval monitoring (Williams et al., 2018). This occurs when single events that appear large in less frequent monitoring are in fact the sum of multiple small events, which coalesce over timescales equivalent to those of the short interval monitoring. The result is that more numerous small events are recorded with short interval monitoring, each with a higher volumetric uncertainty relative to its size. However, this differs from displacement monitoring, where the increased proximity of the surface between scans has the effect of lowering the uncertainty in change detection, as noted by Zahs et al. (2019). Our

215 uncertainty analysis corresponds with these findings. We note that the identification and tracking of corresponding boulders between surveys is improved as their distance between surveys (a function of monitoring interval) lowers. However, continuous surface change mechanisms can be better recognized over the one-year period, because the portion of significant M3C2 distance values for this change detection is much higher (52.1 %) than in the three-week period (7.1 %).

Finding an appropriate temporal frequency of data capture has been identified as a key challenge to overcome the invisibility

220 of surface change mechanisms caused by their mutual superimposition (Abellán et al., 2014). The fact that the rates of both lowering and raising of the rock glacier surface are considerably higher over three weeks as compared to the annual average shows that surface change and the drivers behind it vary seasonally. This seasonality makes it near-impossible to separate individual processes and their drivers from low-frequency monitoring. The capacity to resolve episodic processes, such as individual boulder movements, by monitoring at timescales of three weeks as compared to one year may therefore lead to the

225 assumption that even higher monitoring frequency is desirable (e.g. daily or hourly). However, due to the small portion of significant surface changes, and the small quantity of individual boulder movement observable in a three-week period, the benefit of even more frequent monitoring may be limited for processes that are relatively slow-moving, such as rock glaciers.

Implications for rock glacier understanding

230 Studies of other alpine rock glaciers have shown that the surface velocity reacts to seasonal temperature changes (Kääb et al., 2007; Ikeda et al., 2008; Delaloye et al., 2010). This response has been attributed to snow melt (Kääb et al., 2007) and to channeling of meltwater within the rock glacier, reducing the strength of frozen debris and promoting shearing along horizons (Ikeda et al., 2008; Kenner et al., 2017). Long-term measurements of cross-profiles on the *Äußeres Hochebenkar* rock glacier have shown that warm summers with high precipitation generally lead to an increase in surface velocity. At the

235 lower end of the tongue, however, the same atmospheric conditions can lead to a decrease in surface velocity, indicating an ice loss due to high temperatures and a subsequent velocity decrease (Hartl et al., 2016). Our results demonstrate that the contribution of the three-week period to the annual negative surface change in the normal direction is higher than the contribution of the three-week period to the annual positive surface change in the normal direction. This rate (as a function of annual change) is four times the rate that would be derived from a theoretical uniform rate through the course of a year

240 (based on annual monitoring). This indicates that the surface change and its underlying mechanisms, including shearing or plastic deformation, complemented by mechanisms involved in lowering of the surface, show seasonal variation. Given the prevalence of surface lowering that complements down-rock glacier movement during the three-week period, it is likely that this also indicates the occurrence of thaw settlement. The ability of our method to distinguish different seasonal surface change processes by considering both flow direction and normal direction shows that the approach of separating different

245 directions of surface change has considerable potential for increasing rock glacier understanding.

Rock glacier fronts are subject to material gain, caused by the advance of the rock glacier tongue (Micheletti et al., 2016). The presented surface change analysis illustrates that, in both time periods, the majority of M3C2 distances have a positive sign, indicating that the lower tongue area is affected by mass accumulation and thickening in both time periods. Multi-

temporal Ground Penetrating Radar (GPR) measurements have shown that the central part of the rock glacier tongue has

250    thinned since 2000 (Hartl et al., 2016a). At the existing cross-profiles, average surface velocities of 6.37 m a$^{-1}$ at 2570 m a.s.l. (roughly the upper end of our study area) have been measured since 1997, as compared to 1.98 m a$^{-1}$ at the lower end of the tongue (Hartl et al., 2016b). Accounting for these differences in surface velocity as well as the mass accumulation shown by our results, implies that material is being shifted from the central to the lower tongue area. This supports the theory that the lower part of the tongue is separating from the rest of the rock glacier, as it moves into

255    steepening terrain (~2580 m a.s.l.; Schneider & Schneider 2001).

While previous works on the surface change of rock glaciers either measured the surface velocity by tracking objects (Nickus et al., 2015; Bodin et al., 2018) or calculated changes in the normal direction with the M3C2 algorithm (Zahs et al., 2019), this study combines the M3C2 algorithm with manual measurements of boulder displacement in flow direction to separate the two directions of surface change. Seasonal variations in surface change of rock glaciers have been observed

260    (Zahs et al., 2019), but little is known about seasonal changes in the directions of movement. At the Muragl rock glacier in Switzerland, measurements have shown that the surface velocity increases in autumn with a time lag of approximately three months after snow melt and gradually decreases again in winter (Kääb et al., 2007), meaning that in this rock glacier, surface displacement in flow direction is dominant in autumn. This notion of different directions of surface change dominating at different times of the year illustrates that, in order to obtain a comprehensive process understanding of rock glaciers,

265    methods assessing change in multiple directions at each location of the rock glacier are required.

## 6 Conclusion

The aim of this study was to disaggregate different surface change mechanisms related to the deformation of the lower tongue area of an active rock glacier. Drawing on TLS monitoring at sub-monthly intervals, this was achieved by considering change as the ratio of movement during a three-week period compared to the annual deformation of a rock

270    glacier. The analysis indicates that while the signal of continuous surface change is stronger relative to the level of detection in a one-year period, individual boulder movements can only be resolved in the investigated three-week period. Different directions of surface change are dominant at different times of the year, indicating a seasonality of certain surface change mechanisms and the drivers behind them. In a sample area of the rock glacier front, the contribution of the three-week period to the annual surface change in normal direction is 20 %, while the same period only contributes 6 % to the annual surface

275    change in the direction of rock glacier flow as indicated by boulder movements. These findings highlight that, in order to disaggregate different surface change mechanisms related to rock glacier deformation, increased temporal resolution (e.g. bi-weekly to monthly) and multidirectional analyses are needed.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request. They
280 will be released openly following the review of this study.

Multi-temporal terrestrial lidar datasets of the *Äußeres Hochebenkar* rock glacier have been openly published on PANGAEA
(Pfeiffer et al., 2019).

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