Dear Wolfgang,
dear colleagues,

Thank you for taking the time to review our manuscript. Since we have already replied to the general points of reviewer 1 in our initial response and reviewer 2 has raised similar concerns, we will provide a short response to these issues followed by a more detailed reply to the specific comments. Note that given line numbers refer to the document with tracked changes.

Please do not hesitate to contact us directly via email if any questions or concerns arise,

Bernhard Höfle and Veit Ulrich on behalf of all authors

General Points

Linking spatial patterns of change to drivers (precipitation etc.) and/or subsurface information

We agree with your main assessment that our objective and argument with respect to drivers behind the observed change and the "causal" disaggregation of processes could be misunderstood. Our objective is to develop and explore a method for multidirectional 3D change analysis over different (overlapping) periods, which can be used for any 3D point clouds - not only lidar. The findings in our paper will help in developing future observation networks, where our approach centres on analysing the 3D surface change signal over time. We aim to separate and identify the changes in different directions but have to leave the explanation open due to lack of dense, long-term monitoring data of surface, subsurface and environment conditions.

To make it clearer that our focus lies on the disaggregation of different types of change rather than the assessment of underlying mechanisms, we have improved the title of the manuscript to:
"Disaggregating surface change types of a rock glacier using terrestrial laser scanning point clouds acquired at different time scales"

We have adapted the abstract, introduction, and conclusion in this respect as well, in doing so also acknowledging that our work represents a step towards rock glacier observation networks focusing on the analysis of 3D surface change:

- "This work presents a method to help separate surface change types that occur at different time scales related to the deformation of an active rock glacier, drawing on terrestrial lidar monitoring at sub-monthly intervals." (lines 12 ff.)

- "Our results demonstrate the benefit of more frequent lidar monitoring and, critically, the requirement of novel approaches to quantifying and disaggregating surface change, as a step towards rock glacier observation networks focusing on the analysis of 3D surface change over time." (lines 23 ff.)

- "We examine the benefits of interpreting 3D movement at sub-monthly intervals in relation to annual movement, here in the context of superimposed, and hence cumulative, surface changes. We quantify surface change based on movements that occur in different directions: 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. The contribution of short-term surface changes to annual surface changes will be derived for the first time, here as a ratio between the surface change occurring during a three-week period and that over one year." (lines 65 ff.)

- “The aim of this study was to develop a method for multidirectional 3D change analysis drawing on terrestrial lidar monitoring at a sub-monthly interval. By considering change as the ratio of movement during a three-week period compared to the annual deformation, different surface change types related to the deformation of the lower tongue area of an active rock glacier can be disaggregated.” (lines 319 ff.)

- “These findings highlight that multidirectional analyses at an increased temporal resolution (e.g. bi-weekly to monthly) will play an important role in the setup of future observation networks, because they can help to disaggregate different surface change types related to rock glacier deformation.” (lines 330 ff.)

Discussing drivers of change in more detail, adding complementary data

The results of our paper are methods and insights that will provide suitable input for comparison and statistical analysis of rock glacier surface change components over space and time with environmental data. This will then aid the interpretation and explanation of the relation between movement and external drivers by users. The ultimate goal is that our methods can be used to establish 3D surface monitoring networks along with environmental, subsurface and wider catchment data (e.g. headwall). In our specific study case, we were working on the method development and proving that what is gained from the 3D surface analysis can be used and has increased value for further rock glacier mechanism understanding. We believe this is clearly shown in our results. We therefore improved the discussion to emphasise the “implications for rock glacier understanding” and also other geomorphological processes. Working on the drivers for the AHK rock glacier would be a different research focus and paper objective, which could make use of our disaggregated information as one important data source.

Clearing up inconsistency of boulder movement interpretation

We examine two main areas exhibiting two different types of boulder movement. At the rock glacier front (active zone 1), there is both gravitative movement of single boulders and boulder movement in flow direction, i.e. movement that reflects rock glacier creep. On the rock glacier surface (active zone 2), there is only boulder movement reflecting rock glacier creep, which is why we can use boulder movements in this zone as an indicator for change in the flow direction. To more clearly distinguish between these two areas, the different types of boulder movement in these areas, and also the way we use the boulders as indicators for rock glacier flow, we have added the following paragraph to the methods section:

“In these active zones, the movement of 48 manually identified boulders was measured in both observed periods. For both periods, boulders rotating strongly and revealing a different geometry could not be re-identified and were not included. Active zone 1 is located at the front of the rock glacier tongue (Fig. 4), where the movement of individual boulders must not necessarily reflect rock glacier creep but may also be gravitative. In this active zone the goal of the boulder movement measurements was to separate gravitative boulder movement (Fig. 3b, 3) from boulder movement reflecting rock glacier creep. Active zone 2 is located at the top of the rock glacier body (Fig. 4). Although boulder movement at the rock glacier surface may be influenced by processes such as frost heave or thaw settlement, causing them to move perpendicular to the rock glacier surface, their motion is predominantly in the direction of rock glacier flow (Fig. 3a, 2). The aim of the boulder movement measurements in active zone 2 was to estimate the displacement of the rock glacier in both observed periods, with the selected boulders distributed evenly across the zone. In active zone 1, it was not possible to reach an even distribution of boulders since boulders often rotate during their movement in this active zone. Here, the correspondence between both epochs could be verified visually for a limited number of boulders only.” (lines 164 ff.)

Specific comments reviewer 1

Independent checks of data registration accuracy

We inserted information about the checks of data registration accuracy into the "study site and data" section:

"Data registration accuracy was checked independently by determining the alignment error between all point clouds used in the analysis. Plane-based distances were measured between the point clouds in stable areas (rock faces in max. distance from scan positions between 11-284 m) outside the rock glacier tongue and achieved a standard deviation of residual distances of 2.4 cm for the three-week period and 3.3 cm for the one-year period." (lines 106 ff.)

A clear definition of rock glaciers and their relation to debris covered glaciers for example would help.

We inserted a definition of rock glaciers in the beginning of the paper:

"They are bodies of unconsolidated debris which move downslope by creep of supersaturated mountain permafrost cohesive flow, creating special landforms as a visible expression (Barsch, 1992)." (lines 29 f.)

Lines 52 – 59 need to be clarified, the implication that Zahs et al. (2019) found deformation processes occurred 'continuously' over a 12 year period is at odds with their data that showed: 'active and variable spatial and temporal surface dynamics'. Continuous movement over a 12-year period would indeed be surprising but this does not appear to be what was found, though I'm happy to be corrected by the author!

To clarify that not all deformation processes are occurring continuously and to acknowledge that the magnitudes of the continual processes are variable, we changed the statement to "part of the deformation processes such as flow-induced rock glacier advance and longitudinal compression occurred throughout over a 12-year period at the rock glacier's lower tongue, although with variable magnitudes" (lines 61 f.).

Line 60 – define 'short-interval', presumably it's application specific.

We used 'short-interval' instead of 'three-week period' here, because the short interval could also be two or four weeks. We replaced the term with 'sub-monthly intervals' to show the approximate timescale we are implicating (line 65).

Line 86: these three weeks were the only snow free conditions? Seems strange if so, and if not this does not justify why these three weeks (described in Fig. 1 as 'heightened activity').

We have removed this sentence, because this three-week period was not the only snow-free period and the statement was unclear (lines 97 f.).

Line 88: what were the ranges involved? Did you have to consider any range thresholds when combining the scans, what were the registration errors between scans and was the laser beam size at the maximum range relative to your sampling resolution? Was view angle/perspective (i.e. lots of very oblique measurements) an issue? These are potentially important points as you are calculating centroids of boulders – are you confident in the coverage and accuracy all around the used boulders? Are errors induced as a boulder turns, revealing a different geometry? A statement to clarifying specific error potential would help, how accurate/repeatable is the calculation of the centroids spatially across the rock glacier?

We included information on the ranges involved, the data acquisition settings and the registration errors of the scans:

- “The measurement range over the rock glacier was up to 300 m, with accuracy and precision varying across surfaces with different target range and geometry.” (lines 101 f.)

- “To obtain high point densities for an accurate representation of individual boulders, a vertical and horizontal angular resolution between 0.017° and 0.023° was chosen, which corresponds to the maximum sampling resolution without obtaining an overlap between beams, considering the beam divergence of the TLS instrument. The resulting mean point density from all overlapping scan positions ranges from 436 points m^{-2} to 528 points m^{-2}. Data registration accuracy was checked independently by determining the alignment error between all point clouds used in the analysis. Plane-based distances were measured between the point clouds in stable areas (rock faces in max. distance from scan positions between 11-284 m) outside the rock glacier tongue and achieved a standard deviation of residual distances of 2.4 cm for the three-week period and 3.3 cm for the one-year period.” (lines 102 ff.)

For both periods, only boulders that could be identified in both epochs were included in the boulder tracking. These were only boulders that did not rotate much, so that their centroids hardly changed. We included a sentence concerning this in the methods section:

- “For both periods, boulders rotating strongly and revealing a different geometry could not be re-identified and were not included.” (lines 165 f.)

Line 138 presumably the boulders were selected to represent and even coverage of the site? Comment on their distribution.

We added a brief description on their distribution in lines 172 ff.:

“The aim of the boulder movement measurements in active zone 2 was to estimate the displacement of the rock glacier in both observed periods, with the selected boulders distributed evenly across the zone. In active zone 1, it was not possible to reach an even distribution of boulders since boulders often rotate during their movement in this active zone. Here, the correspondence between both epochs could be verified visually for a limited number of boulders only.”

Line 140 Do boulders not interact with each other complicating this simple flow parallel movement at the centimetre scale you are considering?

While interaction of boulders with each other while moving as part of creep on the rock glacier surface cannot be fully excluded, we observe relative positions of boulders to remain similar and therefore consider interaction between them to be negligible for the detected changes.

Line 142 – 3 Clarify what is meant by ‘The share of significant changes’

We adapted the phrase to “The proportion of changes exceeding the level of detection” (lines 182 f.).

Line 148 The surface lowering is relatively more active in the 3-week period, but you also show the total amount of lowering is much lower that the amounts of accumulation – you detect mass accumulation and thickening overall, so caution should be exercised in the interpretation of these results, it might help to put these rates in absolute terms.

We added mean absolute rates and adapted the phrasing to make this element more concise:

"Interestingly, the mean positive surface changes are 0.04 m in the three-week period (one-year period: 0.27 m) and the mean negative surface changes are -0.03 m (one-year period: -0.14 m). 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 apart from the dominant process of mass accumulation and thickening affecting both periods, surface lowering is more active over the three-week period than surface raising." (lines 186 ff.)

Line 149 what is the difference between 'rates made uniform over the year' and 'average across the year'? Furthermore, this assumption is clearly not appropriate for an alpine rock glacier which we would not expect to record uniform rates through a yearly cycle.

The aim here is to show in simple terms that the rate of surface lowering during the three-week period is clearly above-average. We also want to highlight that a lot of detail is missed when change rates are averaged over a year due to a large survey interval. To point this out more clearly, we improved the phrasing to:

"The rate of surface lowering is four times what would be expected if changes observed over the annual period were uniform through the year or, critically, if variable changes were averaged across a year by the user due to an annual survey interval (5.7 %)." (lines 192 ff.)

Line 160 – 161 This is rather confusing. As I understand it, your 'orographic left' would be the reader's right? In this area I can't see 'small and discrete areas of positive and negative change' that you infer as 'boulder movement' but rather large (nearly half of zone 1) coherent blocks of negative (upslope) and positive (downslope) change. The change is very patchy throughout the annual change, particularly on the margins, is this registration error between scans? It seems strange to have reversed patterns of change on either side of the slope with accretion high upslope and lowering downslope in patches on the left of image 4b and the opposite in the right of zone 1, more explanation is needed. Again perhaps combining with drivers of change or underlying bedrock might help.

The readers' left corresponds to the orographic left (flow direction is appr. North). We realize the ambiguity in this paragraph and have included an arrow showing the direction of creep in Fig. 4 to clarify.
We interpret the mentioned coherent blocks of negative and positive changes to stem from a large chunk of material that has melted out of the rock glacier body and slid downslope. They are not addressed in the paper, but we agree that such events and processes would be very interesting to investigate with more in-situ data in future campaigns.

Line 189 I'm not sure the movement data in 5a are 'more homogenous', the directions seem to differ significantly, perhaps consider rephrasing around localised but coherent directions. It seems evident that independent boulder movement must have occurred but just haven't been detected, as you point out how difficult this is in the annual data in Fig. 3b – it should be framed in this context rather than 'cannot assume they didn't'.

We changed the section to:

"This is indicated by magnitudes of boulder movement that are all well below 5 m (Fig. 5b). Boulders in the one-year period moving independently from the rock glacier advance (presumably over distances > 5 m) could not be identified visually, because they likely could not be re-identified between successive point clouds due to the many occurrences and large distances of boulder movement." (lines 231 ff.)

Line 193 What does a 0.10 m contribution to -0.5 m actually mean? Do you mean a -0.1 m contribution or did it offset the negative change by 0.1 m?

We corrected this typo to "-0.1 m" (line 238).

Line 234 What do you mean by an 'increase in surface velocity'? Make sure it reconciles against the final line of the results 'movement was in-line with the annual average'.

Based on your comment, we acknowledge that the general surface velocity increase during warm summers is not relevant for our argument regarding thaw settlement. We therefore changed the sentence to:

"Long-term measurements of cross-profiles on the *Äußeres Hochebenkar* rock glacier (Hartl et al., 2016) have shown that warm summers with high precipitation can lead to a decrease in surface velocity at the lower end of the tongue, indicating an ice loss due to high temperatures and a subsequent velocity decrease." (lines 284 ff.)

Line 248 - 255 This is the first we hear of really valuable site data. It seems a shame that this was not introduced earlier and made much more use of. Surely it is relevant to the site context and selection of zones and then interpretation of results (note the comment above on Fig. 3 for example) – and much more could be made of the spatial patterns identified if better contextualised with this previous data.

For context, we inserted the existence of the GPR data into the study site section (lines 87 f):
"Ground penetrating radar (GPR) has been applied to determine the depth of the bedrock, with estimates of mean thickness between 30-40 m (Hartl et al., 2016a)."

We pick up on these external site data in the discussion to put the merit of our results into context with existing geomorphic research of rock glacier dynamics. As discussed above our main focus of this study is the development of the method to derive input (including datasets, how to set up the system and perform the 3D data analysis) for those follow-up studies analysing the drivers and increasing the understanding of the site-specific mechanisms.

Technical corrections

Strictly speaking raster based change detection is not 2D as inferred in line 42-3, they are typically able to identify surface change in X, Y, and Z directions, and should probably be referred to as 2.5D to distinguish from full 3D analysis because the z component is assumed normal to the raster X,Y grid (as noted in Williams et al., 2018).

We changed the statement to "2.5D" (line 46).

Line 67: Reword 'This will enable to disclose' to better grammar.

We rephrased the sentence to:

"The contribution of short-term surface changes to annual surface changes will be derived for the first time, here as a ratio between the surface change occurring during a three-week period and that over one year." (lines 71 ff.)

Line 142 correct: 0.11_m

We corrected this accordingly (line 182).

Line 171 ‘move creep-induced’ needs rephrasing

We changed the phrase to “that their movement is induced by creep” (line 214).

Line 268 Should read ‘at a sub-monthly interval’ as you on used one three-week period.

We adapted the phrasing as suggested (line 320).

Figure 1
It’s unclear what the ‘three epochs of TLS point clouds’ are? Provide dates, as it is unclear how these relate to the changes claimed until later in the paper or switch the order and present it after line 84 and it possibly should be in the Methods section anyway. It is also unclear how you know the monitored 3-week period is one of ‘heightened activity’? Is this written in retrospect or do you have more data and have selected this 3-week period as that of heightened relative activity?

The figure has been inserted into the methods section and is now Fig. 2. We have provided the dates and removed ‘heightened activity’ from the figure as it can indeed not be known before the analysis of the given data.

Figure 2
An inset map for context would help locate the study.

We inserted an inset map showing the location of the study site in Austria (now Fig. 1).

Fig. 3 Minor point, but it makes more sense to have the wider context and first survey done first – so I suggest swapping a and b around. Where is this profile on the slope? The movement of the boulder is intriguing, appearing to rise up and over a slope crest, is there an underlying ridge present? Some indication of the rock base would be very useful if available (I appreciate it may not but perhaps inferences could be made from the adjacent ridgelines). State ‘Level of detection (LOD)’ as you use it in the figure. (4) appears to be missing? Also I’m not sure Z – displacement is the correct title for the Y-axis as you have expressly stated M3C2 distance is not just in the Z direction, I would advise this should just be ‘Distance’.

We swapped “a” and “b” in the figure to have the wider context first and to have the numbering of the different processes in the figure in a logical order. Fig. 3 is not intended as example of processes occurring at a certain location, but a schematic representation showing the types of surface change that can be observed on the rock glacier. It is therefore not possible to interpret any specific underlying processes from this figure.
We changed the axis labels to “Vertical Distance” and “Horizontal Distance” and added the number 4, corresponding to “Surface Movement < LOD”, to the figure.

Fig. 4 The orientation of zones 1 and 2 are inverted and different to Fig. 2 making interpretation difficult – flow direction is now up the figure, you can work it out from the contours but it is not intuitive. Seems odd to put the map coordinate system extent in the caption but I presume this due to journal figure sizing restrictions.

To facilitate interpretation of the maps, we inserted an arrow showing the flow direction. We added coordinate ticks to the maps and included the coordinate system information into the map legend.

Fig. 5 It would help to have similar lines in 5c denoting the glacier extent and zones to enable comparison with other figures. Not sure the hillshade background adds anything, why are the colored changes not shown to help interpretation? Why are we being shown different areas? Isn't the whole point to be able to interpret annual change better with the higher temporal resolution of the 3 week period? Therefore, we should be able to see what difference the higher frequency data make to the annual analysis.

We have removed the hillshade background. The M3C2 distances are not shown in this figure because they often do not match individual boulder movement. The reason why two areas are shown is that in the three-week period, area a is the only area where single boulder movement was visible, all other areas were unchanged, i.e. not exhibiting any movement above the level of detection. In the one-year period, the movement was large enough that no boulders could be re-identified in the annual point clouds. Since it was possible to re-identify boulders in other areas, we chose to include another area for the one-year period. As only boulders having moved short distances (well below 5 m) could be re-identified, we learn that a sub-monthly temporal resolution is necessary to identify both types of boulder movement: induced by the creep of the rock glacier and gravity-induced. For these reasons, we feel that this figure conveys the message that we need a sub-monthly resolution to detect different kinds of boulder movement better than using the same areas in the two periods.

Is boulder 9 the same boulder in both subsections? Presumably not so perhaps 6 is upside down?

As the numbers in the figure were not easily visible, we adjusted the layout to display all numbers at the arrows horizontally (Fig. 5). The boulders were not the same, the "6" was difficult to read in the previous layout.

Specific comments reviewer 2

- Please provide more information on rock glaciers in general.

We added a definition of rock glaciers in the introduction and are pointing to the relevant literature: "They are bodies of unconsolidated debris which move downslope by creep of supersaturated mountain permafrost cohesive flow, creating special landforms as a visible expression (Barsch, 1992)." (lines 29 f.)

- Please adapt the aims of the study (drivers of topographic change).

We changed the description of aims to the following (lines 65 ff.), rendering them more concise to the content of the paper:

"We examine the benefits of interpreting 3D movement at sub-monthly intervals in relation to annual movement, here in the context of superimposed, and hence cumulative, surface changes. We quantify surface change based on movements that occur in different directions: 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. The contribution of short-term surface changes to annual surface changes will be derived for the first time, here as a ratio between the surface change occurring during a three-week period and that over one year."

Please provide at least some more basic information on the (intensely studied) rock glacier (e.g., size, orientation, area, state of activity, etc.) and the study site in general.

We added the following information about the rock glacier:

- “Our study site is the lower tongue area of the *Äußeres Hochebenkar* (Fig. 1), an active talus rock glacier located ~4.3 km SSW of Obergurgl in the southern Ötztal Alps, Austria (46°50′ N, 11°01′ E). The rock glacier is 1550 m long and has a width of 160 m in the lower tongue area and up to 470 m in the upper part (Krainer, 2015). Situated at a NW-oriented glacial cirque, the rock glacier is surrounded by the near-vertical slopes of Hangerer (3021 m a.s.l.) and Hochebenkamm (3149 m a.s.l.), which are up to 300 m high. Long-term measurements have shown a continual movement of the rock glacier since measurements started in 1938, with an increase of the surface velocity since the mid-1980s” (lines 80 ff.)

- “Ground penetrating radar (GPR) has been applied to determine the depth of the bedrock, with estimates of mean thickness between 30-40 m (Hartl et al., 2016a).” (lines 87 f.)

I recommend shifting the second paragraph with details on data acquisition (Lines 84-91) to chapter 3 (methods) and rename the chapter to “Study Site”.

To avoid shifting the focus to a site-specific study, we limit the “study site” section to a subsection of the methods. While the study site is an excellent use case for the development and applicability of our method, the approach can be applied to other geomorphic settings where information can be gained from combining different periods of 3D change analysis and differentiated multi-directional change. We have extended the discussion regarding this aspect of transferability (lines 272 ff.).

Delete “therefore” (Line 90).

We adapted the sentence as suggested (line 103).

- Line 172: I think the reference to Fig. 5b should refer to Fig. 5a, right?

We corrected the typo to “Fig. 5a” (line 215).

- Line 175-177: How many boulders were removed from the calculation of movement ratios (8 or 2)? Think about shifting this sentence to chapter 3 (Methods).

All eight boulders were removed from the calculation of movement ratios. As it is now stated earlier in the paper that only the boulders in active zone 2 (at the top of the rock glacier body) are used to estimate rock glacier movement (lines 172 ff.), we removed this sentence.

- It would be interesting to discuss the pattern of relative change in more detail (e.g. why does the 3-week period contribute apparently much to the annual negative change in Zone 2 but not in Zone 1, where the annual data also shows strong negative values directly north of Zone 2. Probably this is due to an event that took place during the year before the 3-week period? The positive values north of this area (see Fig. 4b) might support this idea, since the 3-week contribution to positive change in this area seems to be rather low as well.

We consider the coherent blocks of negative and positive changes to have stemmed from a large body of material that has melted out of the rock glacier body and slid downslope. These are not addressed in the paper, but we agree that such events and processes would be interesting to investigate with more in-situ data in future campaigns.

- Line 212: Correct “more numerous”.

The phrase was changed to “The result is that a larger number of small events are recorded with short interval monitoring” (lines 254 f.)

I suggest expanding the discussion with respect to different geomorphic systems, appropriate monitoring frequencies, and the benefit of differentiating multi-directional change. For an active rock glacier setting (that is typically characterized by both, “continuous” creep and “episodic” rock and boulder fall events), you presented the benefits of both, short-term TLS interval data (e.g. displacement of single boulders can be better reconstructed) and long-term data (e.g. more robust creep rates, better signal to noise ratios). This shows that a combined approach using overlapping time series and differentiated multi-directional change analyses optimizes data interpretation and the understanding of rock glacier systems. To what extent could this also apply to other geomorphic systems, or not?

We have included a paragraph expanding the discussion with respect to the applicability to other geomorphic systems into the discussion section (lines 272 ff.):

“Other applications involving the disaggregation of discrete changes at multiple temporal resolutions can benefit from our approach. Quantifying the contribution of a shorter time period to the changes of a longer time period and differentiating change in various directions can help to increase the understanding of the spatial and temporal distribution of coastal erosion (Westoby et al., 2018; Benjamin et al., 2020) or the development of glacial calving events (Petlicki & Kinnard 2016). Landslide analyses (e.g. Crepaldi et al., 2015) can also gain information about the local velocity of movement in different time periods by combining calculations of elevation difference with object tracking in flow direction. When applying our method, the temporal distribution must be adapted to the specific use case.”

Besides the question of whether drivers of topographic change are addressed (what I would find useful), think about providing additional (mesh or raster based) volumes of mass gain and loss to get an idea about how much material is transported towards the investigated lower tongue area over time.

We agree that volumes of mass gain and loss would be very interesting. To derive a proper complete volume estimate of the rock glacier surface change, 3D datasets with complete coverage would be necessary, as could be acquired by UAV-based laser scanning, for example. Due to occlusions with terrestrial LiDAR, it is not straightforward and would require a clever approach to interpolate the gaps. We decided to skip it rather than presenting estimates with high uncertainty which are not essential to understand our results.

Figure 1
- I suggest terming the figure “workflow of the study” and recommend shifting the figure to chapter 2.
- Change the term “epochs” and include dates.
- “Heightened activity” should be removed in this schematic diagram showing the workflow of the study (How can you know before?).
- Consider to change “boulder movement” to “boulder tracking” and “contribution to change during three-week period to annual change” to “contribution of a three-week period to annual change”.

We termed the figure (now Fig. 2) ‘Workflow of the study’ (in the caption) and, following the suggestion of reviewer 1, moved it to section 3, since it depicts the methods more than the study site/data. All of the other suggested changes were made.

Figure 2 (now Fig. 1):
- Please provide an overview map.
- Integrate information on orientation in the images (e.g. “view to XY”).
- Boundaries of zone 2 do not match with Fig. 4 (gap between the zones in Fig. 2b).

We have inserted an inset map showing the location of the study site in Austria and integrated information on the orientation of the images. The extents of zones 1 and 2 were corrected in the figure to correspond with their extents in Fig. 4.

Figure 3:
- I suggest changing “Z distance” against “M3C2 distance”.
- Where are the profiles located? Does the single boulder movement (3) relate to one of the boulders shown in Fig. 5a?
- Point (4) mentioned in the caption is missing in the figure - I suggest to delete this aspect in Fig. 3 and the corresponding lines 102-104 anyway (content does not refer to methodology but interpretation/ discussion).

The M3C2 distance is always measured in the direction of the local surface normal, so its direction varies across the dataset. It is not, therefore, represented by the z-axis. We changed “Distance down rock glacier” to “Horizontal Distance” because this is more exact and “Z Distance” to “Vertical Distance” to correspond to the label of the y-axis. The purpose of Fig. 3 is not to be an example of processes occurring at a certain location. Instead, it is a schematic representation showing the different kinds of surface change that can be observed on the rock glacier in general. Hence, it is not possible to draw any conclusions from this figure regarding specific underlying processes.
We also added the number 4, corresponding to “Surface Movement < LOD”, to the figure.

Figure 5:
- Why did you choose two areas AND two periods (limited comparability)?
- Think about including information on geomorphic change instead of (or on top of) the hillshades (Fig. 5a and b).
- Please extend Fig. 5c with zone 1 and 2 from Figs. 2 and 4.
- Provide scales.

We have included zone 1 and 2 in Fig. 5c and provided a scale. We have addressed your other remarks in the response to reviewer one (see above)

Figure 6:
- Lines 201/202: “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.” I suggest to either deleting this sentence, or to add the information, that the observed 3-week contribution is higher (21.4 % for negative values and 14.8 % for positive values), if I understood correctly (Line 146-148).

We have removed the sentence from the caption to include only the information relevant to understand the figure, as the detailed and therefore more concise information is given in the text (lines 192 ff.).

Disaggregating surface change types~~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~~ or in a single direction. This work presents a method to help separate surface change types that occur at different time scales related to the deformation of an active rock glacier, drawing on terrestrial lidar monitoring at sub-monthly intervals.~~to help separate surface change mechanisms related to the deformation of an active rock glacier, drawing on terrestrial lidar monitoring at sub-monthly intervals.~~ To this end, ~~W~~we derive 3D topographic changes across the Äußeres Hochebenkar rock glacier in the Ötztal Alps. These changes 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 spatially variable direction perpendicular to the local rock glacier surface (using point cloud distance computation) and ~~the~~a single main 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. Viewing change in this way, ~~This~~ ~~In this way~~ our approach ~~enables~~provides ~~shows to give~~estimates of ~~that different directions of~~ surface change in different directions that 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~~ quantifying and disaggregating surface change, as a step towards rock glacier observation networks focusing on the analysis of 3D surface change over time. ~~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. They are bodies of unconsolidated debris which move downslope by creep of supersaturated mountain permafrost cohesive flow, creating special landforms as a visible expression (Barsch, 1992). 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 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.

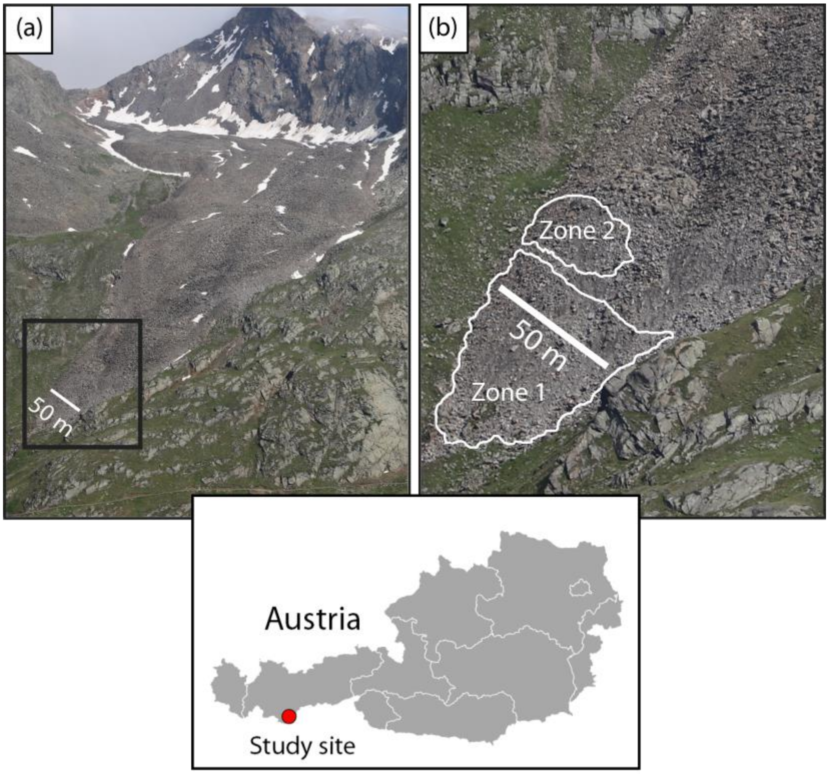
Disaggregating the changes related to ~~this~~ these deformation mechanisms represents a valuable step in interpreting how rock glaciers move, as well as what drives this movement. Approaches to support these interpretations based on *in situ* monitoring, such as the distribution of electrical resistivity 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-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~~ 2.5D 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 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 different types of surface change.~~these processes.~~

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 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 part of the deformation processes such as flow-induced rock glacier advance and longitudinal compression occurred ~~continually~~throughout over a 12-year period at the rock glacier's lower tongue~~ over a 12-year period~~, although with variable magnitudes. 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.

~~In this study,~~ W~~w~~e examine the benefits of interpreting ~~-~~3D ~~surface change~~movement at sub-monthly intervals in relation ~~from short interval~~ ~~a sub-monthly interval~~ ~~monitoring in terms of its contribution toas a function of~~to annual movement, here in the context of superimposed, and hence cumulative, surface changes ~~and the drivers behind it~~. ~~By~~ We ~~aim to~~ quantify~~ing~~ 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 short-term surface changes to annual surface changes ~~contribution of a three-week period to the annual surface change~~ will be ~~assessed~~ derived for the first time, here ~~by considering this contribution~~ as a ratio between the surface change occurring during ~~the~~ a three-week period and ~~the surface change~~that ~~within~~ over one year~~. This will enable~~. ~~Following this approach~~ ~~As a result, it will be possible~~ ~~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.~~

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~~ Our study site is the lower tongue ~~tongue~~ area of the ~~active tongue-shaped, talus rock glacier~~ *Äußeres Hochebenkar* (Fig. 1), an active talus rock glacier located ~~about~~ ~~~-~~4.3 km SSW of Obergurgl in the southern Ötztal Alps, Austria (46°50′ N, 11°01′ E). The rock glacier is 1550 m long and has a width of 160 m in the lower tongue area and up to 470 m in the upper part (Krainer, 2015). Situated at a NW-oriented glacial cirque, the rock glacier is surrounded by the near-vertical slopes of Hangerer (3021 m a.s.l.) and Hochebenkamm (3149 m a.s.l.), which are up to 300 m high. Long-term measurements have shown a continual movement of the rock glacier since measurements started in 1938, with an increase of the surface velocity since the mid-1980s (Schneider, 1999; Kaufmann & Ladstädter 2002; Bollmann et al., 2012; Klug et al., 2012; Hartl et al., 2016b). Ground penetrating radar (GPR) has ~~also~~ been applied to determine the depth of the bedrock, with estimates of mean thickness between 30-40 m (Hartl et al., 2016a).

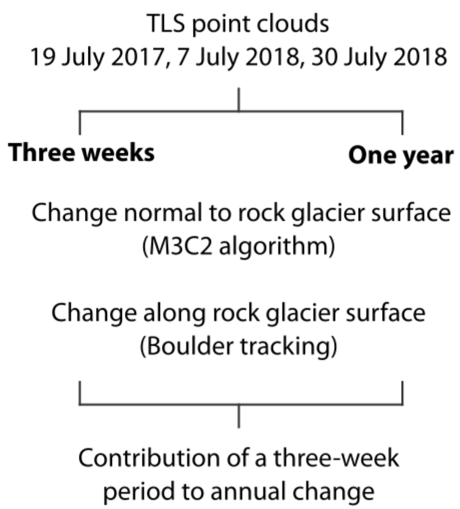


Figure~~.~~ 1. The *Äußeres Hochebenkar* rock glacier. (a) View ~~to~~of Hochebenkamm across the ~~Äußeres Hochebenkar~~ rock glacier ~~(south direction~~(looking south) from the opposite~~ng~~ side of the Gurgler valley~~ (a)~~. (b) Inset showing~~The inset (b) shows~~ the lower tongue area. Active Z~~z~~one 1 comprises the rock glacier front, while ~~a~~Active Z~~z~~one 2 represents a ridge above the rock glacier front, which exhibits~~ing~~ negative surface change in the direction normal to the surface in both periods. Map data: GADM database (www.gadm.org), v.~~ersion~~ 2.5, July 2015. Images: 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), ~~-~~distributed 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, operating in the near-infrared at 1550 nm and capable of range measurement accuracies of ± 5 mm and a precision of ± 3 mm at 100 m scanning range (lower tongue width ~150 m). The ~~range of~~ measurement range~~s~~ ~~across~~over the rock glacier was up to 300 m, with~~. A~~ accuracy and precision ~~may~~ varying across surfaces with ~~varying~~ different target range and geometry. To obtain high point densities for an accurate representation of ~~single~~ individual boulders, a vertical and horizontal angular resolution between 0.017° and 0.023° was ~~therefore~~ chosen, which corresponds to the maximum sampling resolution without obtaining an overlap between beams, considering the beam divergence of the TLS instrument~~equating to 3-5 cm point spacing at 100 m range~~. The resulting mean point density from all overlapping scan positions ranges from 436 points m^{-2} to 528 points m^{-2}. Data registration accuracy was checked independently by determining the alignment error between all point clouds used in the analysis. ~~measuring~~ Plane-based ~~cloud~~ distances were measured between the point clouds in stable areas (rock faces in max. distance from scan positions between 11~~-~~-284~~-~~ m)~~rock faces)~~ outside the rock glacier tongue and achieved a standard deviation of residual distances of 2.4 cm for the three-week period and 3.3 cm for the one-year period.

3 Methods

~~The workflow of the study is shown in Fig. 2.~~ 3D changes to the rock glacier surface were calculated using the M3C2 algorithm over 376 days (~~herein~~ hereafter referred to as one-year) and 23 days (~~herein~~ hereafter referred to as a three-week period), and expressed as the percentage contribution of the three-week period to the annual surface change rates (Fig. 2). 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~~3a, 2).



Figure~~.~~ 2. Workflow of the study. Changes to the rock glacier surface in the direction normal to the local surface were computed 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 that represent 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.

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 within each sphere. 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 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~~3a, 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 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.

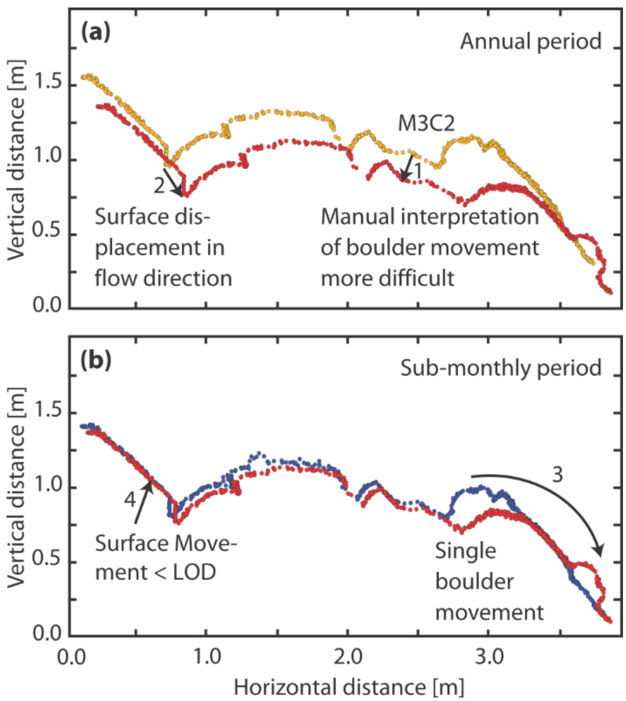


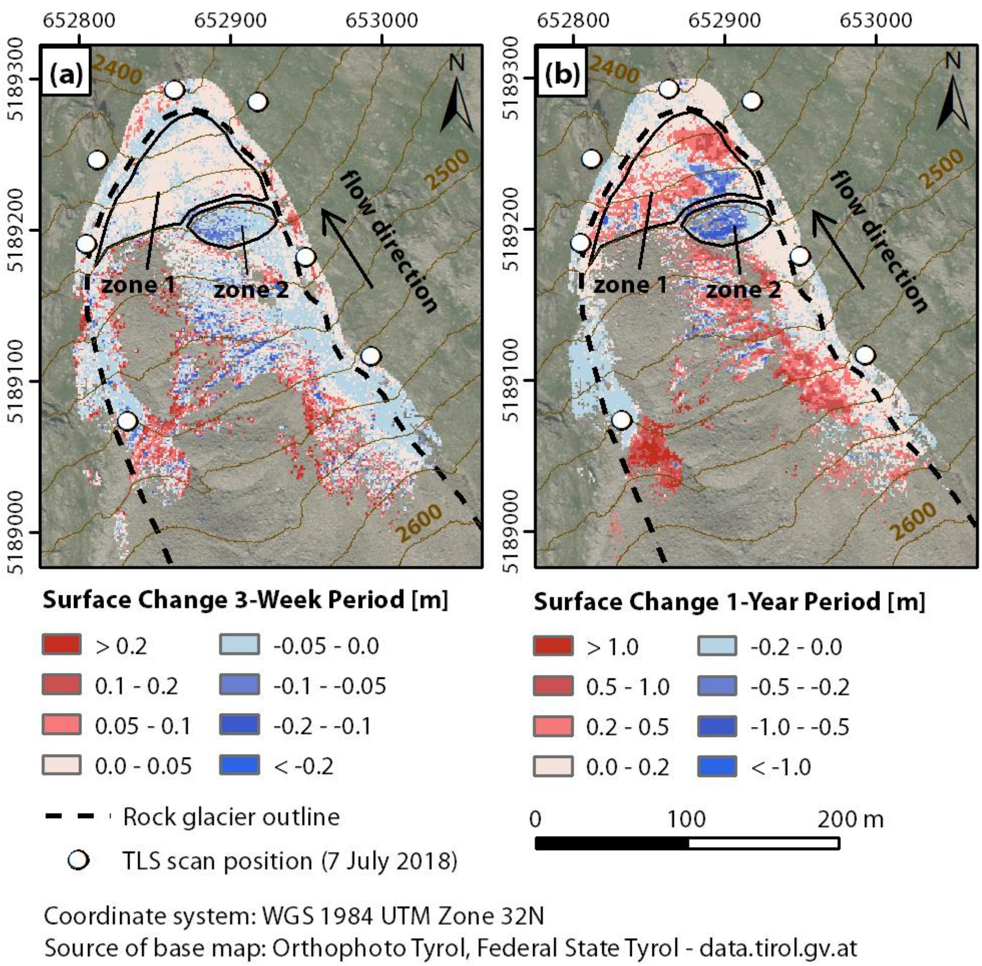
Figure 3. Schematic representation of different types of surface change that can be observed in an annual period (a) and a sub-monthly period (b). While the M3C2 distance refers to surface change in a ~~normal~~ direction ~~orthogonal~~normal (i.e., perpendicular) to the surface (1), the measurements of surface displacement in flow direction reflect the creep-related movement of the rock glacier tongue (2). Additionally, individual boulder movement may occur (3). In longer, annual periods, boulder movement is more difficult to identify because of overlap with creep-related surface movement. In the sub-monthly period, individual boulder movement is easier to distinguish, because creep-related changes are small and often below the level of detection (4).

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 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, t~~ The confidence in the true position of the surface, therefore, 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 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 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 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, the movement of 48 manually identified boulders was measured in both observed periods. For both periods, boulders rotating strongly and revealing a different geometry could not be re-identified and were not included. Active zone 1 is located at the front of the rock glacier tongue (Fig. 4), where the movement of individual boulders must not necessarily reflect rock glacier creep but may also be gravitative. In this active zone the goal of the boulder movement measurements was to separate gravitative boulder movement (Fig. 3~~a~~b, 3) from boulder movement reflecting rock glacier creep. Active zone 2 is located at the top of the rock glacier body (Fig. 4). Although boulder movement at the rock glacier surface may be influenced by processes such as frost heave or thaw settlement, causing them to move perpendicular to the rock glacier surface, their motion is predominantly in the direction of rock glacier flow (Fig. 3~~b~~a, 2). The aim of the boulder movement measurements in active zone 2 was to estimate the ~~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.~~in both observed periods, with~~. Although boulder movement at the rock glacier surface may be influenced by processes such as frost heave or thaw settlement, causing them to move perpendicular to the rock glacier surface, their motion is predominantly in the direction of rock glacier flow. T~~ the selected boulders ~~in active zone 2 are ~~distributed evenly across the ~~active ~~zone. In active zone 1, it was not possible to reach an even distribution of boulders since boulders often rotate during their movement in this active zone. Here, the correspondence between both epochs could be verified visually for a ~~small~~limited number of boulders only.

4 Results

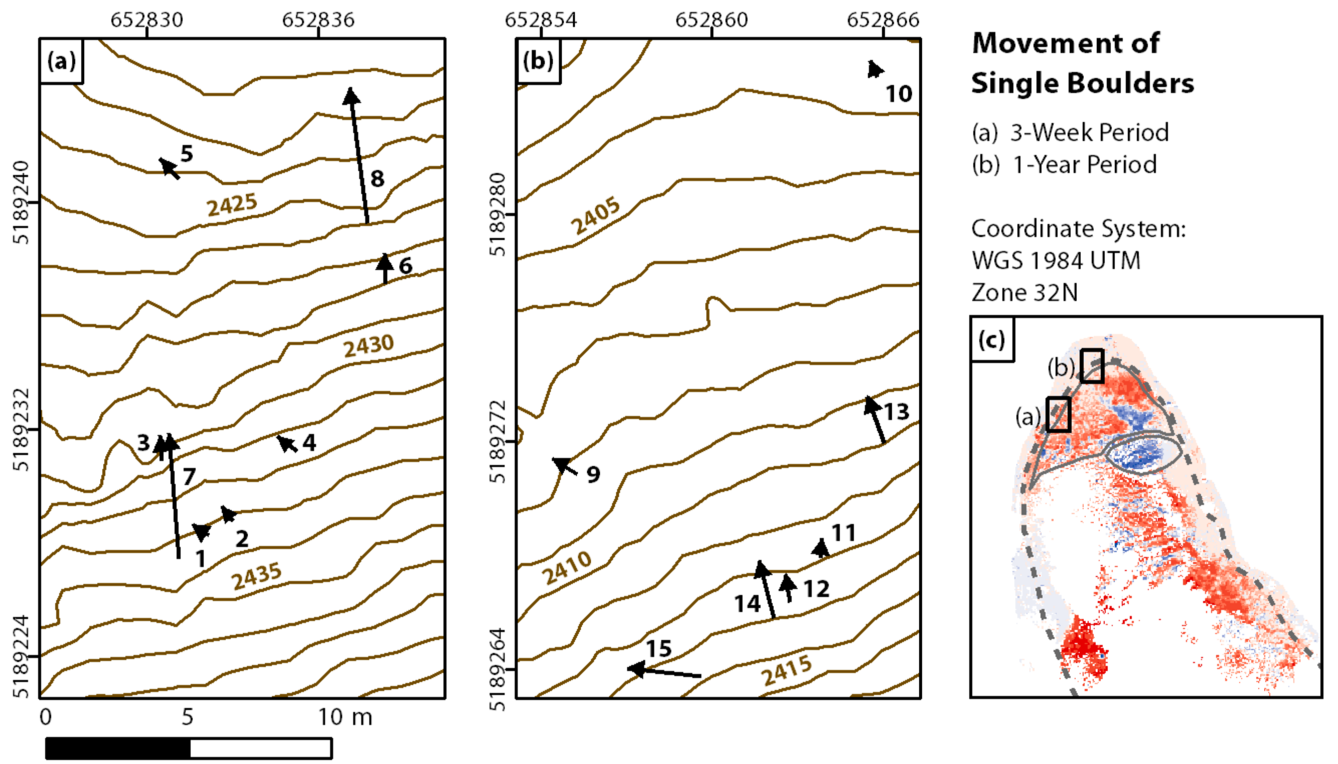
The level of detection ~~($p < 0.05$)~~ is 0.10 m in the three-week period and 0.11 ~~°~~m in the one-year ~~period~~period ($p < 0.05$). The ~~share~~ proportion of ~~significant~~ changes exceeding the level of detection in the three-week period is 7.1 % as compared to 52.1 % in the one-year period. 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 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 mean positive surface changes are 0.04 m in the three-week period (one-year period: 0.27 m) and the mean negative surface changes are -0.03 m ~~in the three-week period~~ (one-year period: -0.14 m). ~~t~~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 apart from the dominant process of mass accumulation and thickening affecting both periods, surface lowering is more active over the three-week ~~this~~ period than surface raising. The rate of surface lowering is four times what would be expected if changes observed over the annual period were uniform through the year or, critically, ~~averaged across the year~~if variable changes were averaged across a year by the user due to an annual survey interval (5.7 %).~~.~~



Figure~~.~~ 4. Comparison of surface changes perpendicular 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 front, while active zone 2 represents a ridge above the rock glacier front exhibiting negative surface change in both periods.

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

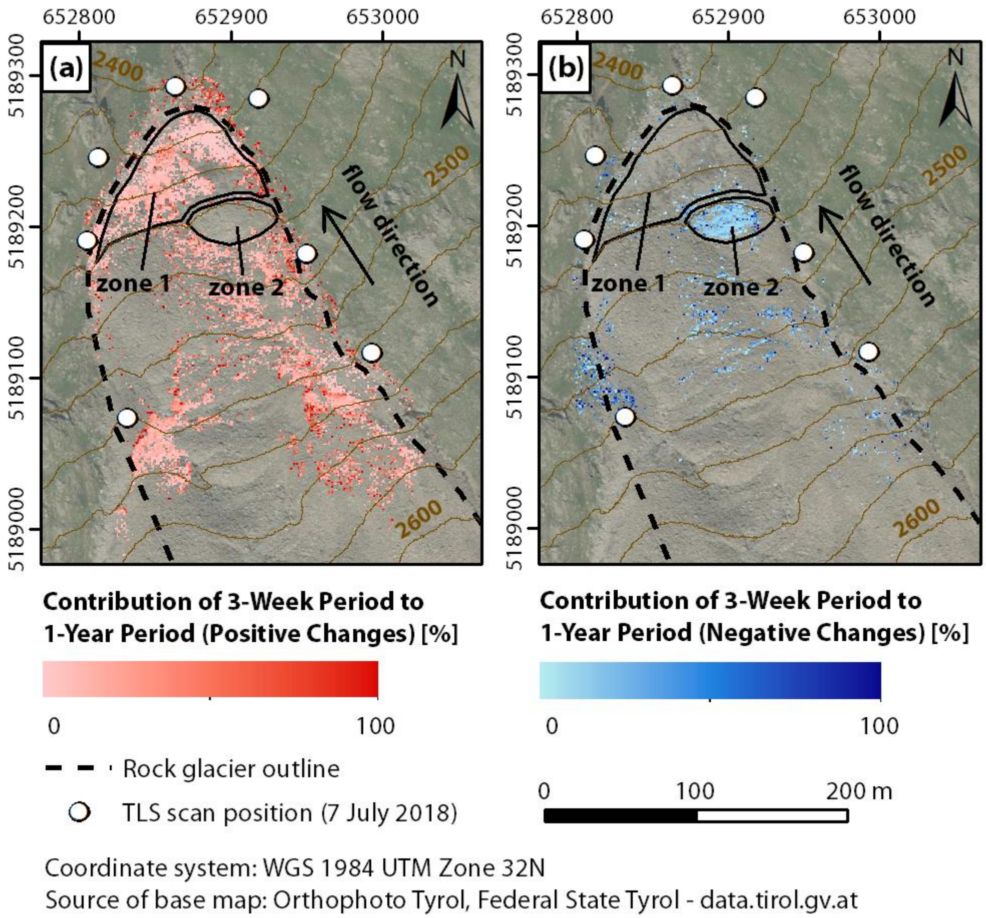
The ratio of distances travelled by individual boulders at the rock glacier front (active zone 1) sheds light on how independently they move relative to creep of the rock glacier. In the three-week period, only few single boulder movements (eight were detected) exceed the level of detection, with the magnitudes of their movement differing considerably. The movement of boulders no. 1 ~~to~~ -6 in the three-week period is < 1 m (Fig. 5a), which, combined with the direction of this movement, indicates that their movement is induced by creep~~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~~5a), indicating that these boulders have moved gravity-induced, i.e. under their own weight, ~~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 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.~~



Figure~~.~~ 5. Movement of single boulders in two different sub-areas of the rock glacier front during the three-week period (a) and the 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.

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 all ~~more homogeneous than in the three-week period and that are~~ well below 5 m (Fig. 5b). ~~We cannot assume that no b~~Boulders in the one-year period ~~are~~ moving independently from the rock glacier advance~~,~~ ~~but such movements over larger distance~~ (presumably over distances > 5 m) could not be identified visually, because they likely could not be re-identified between successive point clouds due to the many occurrences and large distances of boulder movement.

In comparing different change directions, the M3C2 distances illustrate that in active zone 2 (Fig. ~~-~~4), the three-week period contributes -0.1~~0~~ m,~~–~~ or 20 %, of the annual surface change (-0.5 m) in the normal direction (Fig. 6). However, the measurements of boulder ~~displacement~~ movement indicate that the three-week period contributes 0.08 m, or 6 %, of the annual surface change of 1.4 m 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~~ movement measurements implies that quantified movement was in-line with the annual average during this three-week period.



Fig~~.~~ure 6. Percentage contribution of the three-week period to the annual surface change. 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. ~~regarding~~(a) positive changes, ande (ba) ~~and~~ negative changes~~ (b)~~. 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..

5 Discussion

5.1 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~~ a larger number of ~~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 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 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 gravitative boulder movements at the rock glacier front, by monitoring at timescales of three weeks as compared to one year may therefore lead to the 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 gravitative 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.

Other applications involving the disaggregation of discrete changes at multiple temporal resolutions can benefit from our approach. Quantifying the contribution of a shorter time period to the changes of a longer time period and differentiating change in various directions can help to increase the understanding of the spatial and temporal distribution of coastal erosion (Westoby et al., 2018; Benjamin et al., 2020) or the development of glacial calving events (Petlicki & Kinnard 2016). Landslide analyses (e.g. Crepaldi et al., 2015) can also gain information about the local velocity of movement in different time periods by combining calculations of elevation difference with object tracking in flow direction. When applying our method, the temporal distribution must be adapted to the specific use case.

5.2 Implications for rock glacier understanding

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 (Hartl et al., 2016) have shown that warm summers with high precipitation ~~generally lead to an increase in surface velocity. At the lower end of the tongue, however, the same atmospheric conditions~~ can lead to a decrease in surface velocity at the lower end of the tongue, 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 (based on annual monitoring). This indicates seasonal variation in~~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 (Kääb, 1997). 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 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 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 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 (Delaloye et al., 2010; Kenner et al., 2017)~~(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~~ concept 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, methods assessing change in multiple directions at each location of the rock glacier are required.

6 Conclusion

The aim of this study was to develop a method for multidirectional 3D change analysis drawing on terrestrial lidar monitoring at a sub-monthly interval.~~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 b~~By considering change as the ratio of movement during a three-week period compared to the annual deformation, ~~of a rock glacier~~different surface change types related to the deformation of the lower tongue area of an active rock glacier can be disaggregated. 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 and can be disaggregated and estimated separately by our approach. ~~, 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 change in the direction of~~-~~ rock glacier flow as indicated by boulder movements. These findings highlight that multidirectional analyses at an increased temporal resolution (e.g. bi-weekly to monthly) will play an important role in the setup of future observation networks, because they can help to ~~, in order to~~ disaggregate different surface change ~~mechanisms~~ types 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 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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Tables

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