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Interactive comment on "Disaggregating surface change mechanisms of a rock glacier using terrestrial laser scanning point clouds acquired at different time scales" *by* Veit Ulrich et al.

Anonymous Referee #2

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General comments: The overall focus of this study is to discriminate the multidirectional topographic change of an active rock glacier system in normal and flow direction and to investigate the benefits of interpreting surface change using short-term (3 weeks in July 2018) and long-term (July 2017 - July 2018) TLS time series. Interestingly, the contribution of the 3-week data to annual movement is variable. Whereas the 3-week surface change normal to the rock glacier (assessed by the M3C2 algorithm) overbalances the yearly average, creep rates of the rock glacier (assessed through boulder tracking) is in accordance with the average, long-term signal.

The topic is highly relevant for the scientific community and stimulates progress in

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topographic change analysis approaches. The manuscript is written by experienced authors and largely well structured and formulated (as far as I can judge as a non-native speaker). Thanks for reading!

However, the paper needs clarification regarding several points. After careful reading and compiling a list of keywords that should be revised, improved and/or supplemented, I read the (thankfully very detailed and comprehensive!) comments of reviewer 1 as well as the authors' response. Since the vast majority of my concerns are already being questioned/discussed here, I will keep my review rather short, add some additional specific comments (see below, please ignore potential redundancies) and enter directly into the discussion.

In accordance with reviewer 1, my major concerns relate to 1) the lack of discussion on the drivers of topographic change and 2) on inconsistencies and missing methodological details about the calculation of displacement rates in rock glacier flow direction using boulder tracking. In addition, some information is missing and some inconsistencies exist in the manuscript (see specific comments).

To 1.) As stated by reviewer 1, drivers of the observed (multi-temporal and multidirectional) topographic change are not sufficiently discussed, although they are formulated as a major objective of the study (line 61). To this request, the authors replied that the focus of the paper is strictly to develop/explore a method for multidirectional 3D change analysis over different (overlapping) periods and agreed to clarify this in the full revision of the paper. This is OK for me, although I would like to see a more detailed discussion on drivers and controls of the observed topographic change (also due to the fact that - as also already noted by Reviewer 1 - the data basis, which finally consists of two temporarily overlapping data sets, is not that extensive for a systematic methodological study). If I am right, there is many complementary (e.g. geophysical, meteorological, topoclimatic) data available for this well studied rock glacier, which might help to interpret drivers and patterns of geomorphic change in greater detail.

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To 2.) As also stated by reviewer 1, the assessment of single boulder displacements remains unclear and corresponding methodological details are missing (In which areas were which boulders analysed and how?). In their reply, the authors again agreed that "the distinction between different types of boulder movement in different areas and the way how boulders are used as indicators for rock glacier flow is not clear, and that related parts of the manuscript will be revised." This is necessary and welcome.

I am looking forward to receive the revised manuscript.

Specific comments:

Chapter 1 (Introduction):

- Please provide more information on rock glaciers in general.

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

Fig. 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".

Chapter 2 (Study Site and Data):

- 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.

- 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”.

- Delete “therefore” (Line 90).

Fig. 2:

- 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).

Chapter 3 (Methods):

- I recommend shifting information on data acquisition from chapter 2 to a first paragraph here.

- Please provide more details on data acquisition and processing (e.g. scan ranges/ footprint size, potential difficulties due to perspective/ shadowing effects, and most importantly, on registration procedure and errors (between the scan positions and between the campaigns).

Fig. 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).

Chapter 4 (Results):

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

- 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).

Fig. 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.

Fig. 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).

- I do not understand Lines 202/203 “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.” Why are blue areas “relatively stable”? In my eyes, this contradicts the statement in line 236-238: "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." Please clarify.

- 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.

Figs. 4, 5, 6:

- Please add north arrows to all maps (better orientation in Fig. 2).

Chapter 5 (Discussion): Part 1 - Level of detection and implications for monitoring:

- Line 212: Correct “more numerous”.

- 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?

Chapter 5 (Discussion): Part 2- Implications for rock glacier understanding:

- 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.

Chapter 5 (Discussion): Part 1 and 2:

- If the above suggestions related to the discussion are followed, I also recommend exchanging the order of the two subchapters in the discussion: Firstly implications for

rock glacier understanding and secondly (further) implications for monitoring of geomorphic systems with respect to different monitoring intervals and the LoD.

Chapter 6 (Conclusions):

- According to the points related to the discussion, I also recommend to widen the conclusions.

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