General comments

We thank referee 1 for the detailed and constructive suggestions for improving our manuscript. We agree with the comments and suggestions and will address the individual suggestions in more detail below. Please find our answers in blue in the text.

This is a very interesting study investigating the long-term evolution of a relatively large sample of individual rock glaciers. Despite the increasing number of studies on rock glacier dynamics and evolution, there is still a lack of knowledge on the past velocities of rock glacier. This study aims at filling this gap and gives very interesting results. The analyses are thorough, very detailed and original. The errors are systematically considered and their analyses are carried out in depth.

I have however a major concern regarding the length and the structure of the manuscript. First, the text is very long and it should be reduced by about 20%. Second, and most important, the manuscript is not well structured. The results and discussion are merged into a single very long chapter, which does not allow the reader to have a clear view on the most important results of the study. The results must definitely be separated from the discussion, which is the classical way for a research paper. The references to the literature must be systematically moved to the Discussion chapter, allowing the keep the Result section more strictly factual (typical examples P16L424-428). There is also a countless number of subtitles. As a consequence of all of this, we get progressively lost. In the end we lose the main information, which is a pity because the quality of the analyses is very good and the results very interesting. Therefore, a strong effort must be made to improve the structure of the manuscript and to make it clearer.

Examples of modifications to the structure to be made :

- Move chapter 4.1 after 4.2
- Chap 4.4 (and 4.3.3., which should be merged with 4.4) should be moved in the Discussion and condensed.

The difficulty for such a study relies on its intrinsic interest : whereas similar studies generally consider one or two landforms, here a large amount of data is available for 9 rock glaciers. Thus, the authors must find a way between presenting sufficient data without losing the reader in two many details. A way to do it would be to focus more on the general trends and to reduce a bit the analyses of the exceptions and of the special cases.

We agree with the comments on the length and structure of the manuscript. As we have generated a lot of data on the different rock glaciers, it was very difficult to highlight the really important results and discussion points. However, your comments have led to more clarity about what the important statements and results are. We will more clearly provide the important points and elaborate them better. In addition to the proposed changes to the introduction, we will separate, restructure and condense the results and discussion sections for better structure and clarity. In the results section, we will present the strictly factual results of the rock glacier inventory, the changes in the meterological forcing, the flow velocity analysis and the surface elevation change analysis, particularly the last two points in a more general way. In the discussion section, we will discuss the flow velocities and volumetric changes in the regional context and work out the similarities and differences in the reaction. As a further point, we will relate the flow velocities and volumetric changes to the

changes in the forcing parameters (temperature, snow cover and precipitation) and discuss them more systematically on the basis of the existing literature.

The introduction is a bit lengthy and not well structured. Up to line 55 it's a long summary on the general characteristics of a rock glacier. Not everything is useful, thus I suggest to shorten this part and to keep only what is necessary. Another issue is that we must wait the end of the introduction to know the goal of the study. Ok, the precise objective must be presented after the state of the art, but the general objective, or at least the topic of the paper must be stated much earlier. Thus, I recommend to reorganize the introduction and to better structure it (see specific comments).

We will significantly revise and shorten the passage on general rock glacier characteristics. In addition, we will state the aim of the study in a sentence at the beginning of the introduction.

The state of the art is generally good, but additional references on the current state/velocities of rock glaciers, including destabilizing ones, could be added. For example Kummert et al. 2018, Vivero & Lambiel 2019, Marcer et al. 2021,…

Although we have attempted to present information on the current status, destabilisation and velocities of rock glaciers on different temporal scales and their influencing factors in the introduction (P2&3, L55-72), we understand the suggestion to to support these statements with more recent literature. We will incorporate the recommended literature at the appropriate passages.

In such a study it would really help to have a Google Earth link to visualize the rock glaciers, or/and pictures of each rock glacier.

We agree. In complement to figure 1 we will include a .kmz file with the locations of the rock glaciers in the suppementary part of the paper.

The results of the rock glacier inventory are presented in the Study area section, whereas the method for achieving it is presented after, in the Material and Methods section. This is not coherent. Since this rock glacier inventory is part of this study, the results must be moved in the corresponding section and removed from the Study area section.

We agree. We will only mention the previous studies on rock glaciers in the Kaunertal in the study area section and present the results of the inventory in the results section.

The calculated 3D displacements are changes normal to the surface. As explained by the authors, they are an alternative to the traditional DoD, and even a better quantification of the thinning/thickening processes on an ice-sursaturated permafrost body (see Vivero & Lambiel 2019 for a similar study). But this is not 3D displacement. The latter is rather a displacement that considers the 3 components x, y and z. As such this defines the displacement parallel to the slope angle, and thus the real displacement, contrary to the horizontal 2D displacement. The titles and text related to this must then be reformulated.

We agree that 3D displacement is a misleading term. As Referee 2 has pointed out, our methodology for calculating volumes by gridded '3D displacements' is invalid as this leads to small but systematic errors in volumes. Therefore, for the calculation of the volumes we have to apply the classical 2.5 D method via DoDs and will determine the uncertainties according

to Anderson (2019). Since a test has shown that there are hardly any differences in the representation of surface changes between the previous approach and the DoD method, we will also present these as DoDs in order to avoid confusion. Although there are now some studies that directly compare point clouds, as mentioned in your comment, we have come to the conclusion that using DoDs throughout the paper increases comparability to other studies and enhances comprehensibility.

If I understand well the chart on Snow cover onset, snow arrived roughly early September around the years 2010. This means that what you consider as the snow cover onset in fact corresponds to the first snow, meaning that snow can then melt completely until new snow falls. Hence, this parameter cannot have any influence on the rock glacier kinematics. Much more important is the date when a substantial snow cover is established (~50 cm), allowing ground insolation. In addition, I suggest to add as a parameter the date of complete snow melt in spring. This has a strong influence on the MAGST and thus on rock glacier kinematics. See PERMOS 2019. Permafrost in Switzerland 2014/2015 to 2017/2018. Noetzli, J., Pellet, C. and Staub, B. (eds.), Glaciological Report Permafrost No. 16–19 of the Cryospheric Commission of the Swiss Academy of Sciences, 104 pp.

For the analysis of snow cover onset and duration, we followed the criteria described in Peng et al., 2013. They describe the snow cover onset as the first day of the first five consecutive days with snow in fall (considered September to January) and the end of the snow cover as the last day of the last 5 consecutive days with snow in the melt season (February to July). The duration is calculated by counting the number of days between the snow onset and snow end.

We agree that this is probably not the decisive factor for the morphodynamic development of rock glaciers with regard to snow. We have made a further analysis, for the onset of a substantial snow cover (50cm) and the date of complete snow melt and will integrated this into the study.

The interpretations of the velocities and surface changes regarding the external parameters are sometimes rather hypothetical and should more systematically rely on existing literature. This would be much easily achieved by moving these interpretations in the Discussion chapter.

We agree with this. As mentioned before, we will separate results and discussion, and in the discussion of morphometric changes in relation to external paremeters, we will refer more systematically to existing literature.

Specific comments

P1L12. Two times “change” in the same sentence.

We will replace change with shift.

P1L20. In the rest of the manuscript you don’t talk about vertical 3D, but only 3D. Be consistent. But take also in consideration my comment above about 3D.

For a detailed answer, see comment above. Since we will change the methodology completely to a DoD analysis, we will call it surface elevation change.

P2L31. **are** responsible

We will correct this.

P2L32. **generally** coarse debris layer (the coarseness depends on the lithology).

We will add generally.

P2L33. landforms

We will correct this.

P2L38. Remove “also”. If the origin is periglacial, then the ice forms by freezing of water.

We will remove also.

P3L77-80. Here you present the results of a specific study on velocity variations for selected rock glaciers. But it must be moved around L60, where you talk about rock glacier velocities. In addition, it appears weird to give details for a specific region only for one study. Thus, either you stay more general, or you keep these details but, in the meantime, you must give similar details for the other referenced studies.

We have decided to describe the details of the study by Groh & Blöthe (2019) in more detail, as they cover the same research area but with a different temporal and thematic focus.

We will move the more detailed description of the study to chapter 2, study area, as it fits better here.

P3L85. **of** rock glaciers

We will correct this.

Figure 1: add the location of the study area in Austria; add the location of the highest summit.

We will add the national borders to the overview map for better orientation and included the location of the highest peak.

P4L103. Why “pseudo” ? It sounds weird.

The authors of the permafrost map (https://doi.org/10.1594/PANGAEA.917719) refer to it as a pseudo probability of permafrost being present but do not specify the term. In the corresponding publication (Schrott et al. 2012), pseudo probability does not appear either. However, as this is not relevant for our study and the permafrost map is only shown for illustration purposes, we will remove peudo.

P4L106-108. Obviously the road was built for the ski activities. You could make it clearer and say a bit more on the anthropogenic influence.

We will further elaborate very briefely on the anthropogenic influences, as except for the glacier road there is no influence on rock glaciers and their kinematics.

P6L127. To avoid repetition replace the second “Berger et al. (2004) by “The latter”.

We will replace this.

P6L150-154. This refers to the state of knowledge on factors controlling rock glacier kinematics. Therefore, it should be moved into the introduction.

As this information is already included in the introduction, we will delete it from the methods and material section.

Table 1: Mi**n**istry

We will correct this.

P7L170. This is an open reproach towards the company that can be critical. I suggest to moderate your sentence.

This was not intended as a reproach to the company, but we understand that it can be understood as such and will chang the sentence.

Table 2: Uniformize the font

We will correct this.

P8L200-201. How many GCPs did you use ?

We used 101 GCPs, which we picked very carefully directly from the point cloud in stable areas and as evenly as possible over the entire study area.

We will specify the numer of GCPs.

P10L240. ha**d**. In general, check the tenses. Sometimes the present is used, sometimes the past (L245: better were than are).

We will correct this and and check tenses used throughout the text.

P11L274. Figure number ?

It should read figure 4. We will add the figure number.

P12, chap. 3.6. See my general comment on the 3D displacements.

See your answer in the general comments.

P12L300. **a LoD**

We will correct this.

P13L320-322. Syntax problem with this sentence.

We see the problem and will rephrase the sentence.

P15L366-367. The end of the sentence is strange.

We wanted to express the reduced positive temperature trend of winter and autumn temperatures compared to summer and spring temperatures. We will rephras the sentence to express this more clearly.

P15L367. El**e**vation.

We will correct this.

P15L375. You could complete with additional references.

In an earlier version of the manuscript, we had included additional references at this point, such as Gruber et al. (2004). Unfortunately, The Cryosphere limits the number of references for research papers to 80, so we had to remove some references.

P15L389-390. I don't understand this sentence. You mean that P increased from 931 mm/yr to 957 mm/yr at Weißsee ? Please reformulate. And in the following lines it is not clear of which station you are talking about. And why not showing the data for Weißsee station ?

We wanted to express that in the period under investigation (1953-2017) the mean annual precipitation of the station Plangeroß was 931 mm/yr and in the case of the station Weißsee in the period since the recording (2007-2017) the mean annual precipitation was 957 mm/yr. In the following passage we describe the data of the station Plangeroß. We will completely rewrite this passage.

We have not plotted the station data, as we have only used them to check whether the stations with longer time series, which are not located directly in the area, measure valid data. We can include a graph in the appendix with the measured data (temperature, precipitation and snow depth) of the Weißsee station.

P16L408. Honestly the tiny decrease in the snow duration cannot be considered as a trend. it only takes one year with a positive anomaly for the trend to reverse. And how do you calculate the snow cover onset ? From which snow depth do you consider that the snow cover is permanent ?

We agree that this cannot be seen as a trend. For the analysis of snow cover onset and duration, we followed the criteria described in Peng et al., 2013. They describe the snow cover onset as the first day of the first five consecutive days with snow in fall (considered September to January) and the end of the snow cover as the last day of the last 5 consecutive days with snow in the melt season (February to July). The duration is calculated by counting the number of days between the snow onset and snow end.

We agree that this is probably not the decisive factor for the morphodynamic development of rock glaciers with regard to snow. We will make a further analysis, as suggested in the general comments, for the onset of a substantial snow cover (>50cm) and the date of complete snow melt and integrat this into the study.

P16L422. How much were the velocities for this period ? According to Fig. 8 they should not have been much higher than 0,5 m/yr. Such displacements should not have provoked decorrelation.

In the period 1953 - 1971, the maximum flow velocity for RG 8 occurred in the area of the front and could only be determined by manual mapping of a few individual blocks. The maximum flow rate was 1.66 m/yr, which corresponds to a total movement of 29.85 m during this period. Therefore, the rate of movement could no longer be determined by image correlation. One should not confuse the maximum flow velocity with the average flow velocity. The maximum flow velocity for RG 08 is still over 1 m/yr in the following epoch (this is somewhat difficult to see in Figure 4, as the maximum flow velocities in the boxplot are outliers and are therefore only shown as dots). Based on the topography, movement pattern, and elevation of the rock glacier front, we suspect the "end" of a rock glacier destabilisation, as is often observed today, as a reaction to the positive temperature anomalies in the 1940s. However, this is only a speculation, as no data are available before 1953.

We will rephrase this passage to make this clearer.

P17L433. You could also reference to the PERMOS reports.

As we have shown before, the references at The Cryosphere are limited to 80. Since we have already used the six references with which we substantiate the statement, we have opted for these. Nevertheless, we find the PERMOS reports exciting and will include them if possible.

Figure 4: What do the red dots and bars indicate ?

The red dots indicate the mean value, the red bars indicate the insignificant measurements.

We will add this description to the legend of figure 4.

P18L454. Space before "Roer"

We will correct this.

P18L458. Could it be differently ? At the scale of the study area the changes in external forcing are the same for all the rock glaciers.

We agree and will reformulated the sentence.

P19L482. Fig **5**. To compare the size of the different rock glaciers the scale should be the same, and obviously it is not (in any case it is too small to verify it).

No, the scale of the rock glacier maps is not the same, but it is indicated in the maps, admittedly a little small. We will separate the graphs and maps to create 2 figures for better readability and we will adjust the scale.

P19L483-484. … which is so normal ! I don't know any rock glacier showing uniform velocities on its entire surface.

We are aware of that. We just wanted to describe the patterns we see in the flow velocity maps. We will modify the sentence.

P19L491-492. This is highly speculative. With such a low sample it is not possible to conclude anything about the link between rock glacier acceleration and altitude. And there is no objective explanation why higher rock glaciers would react more than lower ones.

The reasoning behind this was hat the higher-elevated rock glacier RG05 only reacted so strongly in the last epoch, as a delayed reaction to the temperature increase due to the higher elevation. However, we understand the concern that the sample is far too small for such a statement and will delete this sentence.

P20-21, Figure 5. Figure a bit complicated. Everything is too small and thus difficult to read. I suggest to make 2 figures with 1) the charts and 2) the maps.

We will do that. If this separation takes up too much space, we will move the charts to the appendix. In addition, we will mark the areas with measurements below the error value and place a desity plot or violin plot of the velocities next to the maps in order to have a better representation of the development of the different kinematic areas as requested by referee 3.

P22L523. What do you mean by "system state" ?

By system state we mean the change of the rock glacier or permafrost body to increased temperatures, for example the formation of drainage systems.

P22L225. "summer" instead of "autumn".

We will correct this.

P22L530. But the velocities are not only controlled by air temperature but also, and in a large portion, by the historic development of the snow cover, including the date of complete snow melt.

We are aware of this, and will address it in the reformulated chapter of the discussion that deals with the influence of external factors on rock glacier velocities. For this we will do the additional analysis of the complete snowmelt.

Figure 6: Indicate the period of comparison regarding the anomalies in T and P. I guess 1961-1990 ?

You are correct, the reference period for anomalies is 1961-1990. We will indicate this in the caption of figure 6 and in the method section.

P25L570. But generally a long duration of the snow cover is related to a thick snow cover, and thus leads to increasing liquid water, considering also that the latter is available all along the snow melt period.

We agree. Since we will change the analysis of the snow cover, as mentioned before, all related paragraphs will change as well and we will take this comment into account when we revise the corresponding paragraph.

P25L582. Looking at Fig 7 the value for RG 05 seems to be lower than 0.031

Since figure 7 is a box plot, the mean value is not shown, but the mean value is actually 0.031 m/yr. The boxplots can be misleading here as outliers are not plotted, we will clarify this in the caption.

P25L591. What is this other rock glacier pushed forward ?

This is to describe the changes observed in the "3d displacement" maps and associated boxplots. These are made up of positive and negative changes. We wanted to use the term "pushing forward" to describe the frequently observed advance of rock glacier front due to flow. We will reformulate this paragraph to make it clearer.

P26L598-606. Please refer to the corresponding Figure. This is an example of too long paragraph regarding the data that have to be presented. The same could be said in 3 lines. Not necessary to give all these details for RG 02.

We will take this comment into account when we revise the results and discussion sections of the paper. We have already given the structure of the revision of the results and discussion section in the general comments section.

P26L615. …different sizes. We already know this.

We agree and will deleted the sentence.

P27L618-621. Despite the fact that the maps are tiny (please increase the size, for instance by making 2 figures), I rather see patterns of positive or negative changes instead of scattering. Or you mean scattering at a larger scale ? But anyway the figures are too small to be analyzed by the reader.

We agree. We have tried to integrate all the information about the flow velocity and "3d displacements" into one figure each, so that everything can be seen and compared at a glance, but we see that this has been done at the expense of recognisability and will separate the figures. You are right it should be patterns of positive and negative changes instead of scattering. We will change this accordingly in the text.

P27L621-622. I don't understand the sentence. And avoid references in the middle of a sentence.

We wanted to express that the evolution of the characteristic flow bulges on the rock glaciers can be seen here. We will formulate the passage in the text in a more comprehensible way.

P29, chap. 4.6.1. I don't see any particular evolution for this rock glacier, since most of the landforms studied show an increase in velocities from 1997. This section is highly speculative and I suggest to delete it.

Since on this rock glacier, unlike most others, not only the flow velocities increase, but also the pattern of lower and higher flow velocities changes, we have linked this to the construction of the glacier road. Since the construction of the glacier road, the high flow velocities occur below this road. However, you are right a direct connection is rather speculative. Since we are deleting the special cases chapter, we will only briefly refer to the anrtopogenic influence of this rock glacier due the the construction of the glacier road.

P29L671. RG04 is obviously a push moraine (i.e. frozen sediments – probably a rock glacier – deformed by the LIA glacier advance). This is highlighted by the back-creeping movement towards the former glacier position and the strong subsidence, indicating high ice content. This must be considered in the analysis.

We will take this into account in the analysis, although we have decided to delete the chapter on special cases and include it very briefly in the discussion.

P29L681-687. Ok for the possible reactivation, but it would be interesting to propose some hypothesis to explain such a reactivation process.

Perhaps we should reconsider the term reactivation. Here we have followed Michelleti et al. (2015), who described similar behaviour for a similarly small rock glacier in the Hérens Valley (Switzerland). As described in the text, the flow bulges indicate that the rock glacier must have already moved before 1997, but the flow velocities in the epochs 1953-1997 are barely above the error value that can be achieved with our method. Therefore, the rock glacier is transitioning from a transitional state with presumably very low flow rates to an active state with measurable, higher flow rates.

In the text we give a very general explanation: "The sudden and sharp change might indicate a change in the internal structure of the rock glacier system and mechanism of flow" (P30L686-68). Hereby we wanted to express the assumption in very general terms that changes in external factors could lead to the formation of new drainage systems in the rock glacier and/or a formation of new or reactivation of older shear zones, which could strongly influence the kinematic behavour of the rock glacier.

P30L702. Permafrost is a thermal phenomenon. It can thus not melt.

We agree. We have decided to delete the chapter on special cases, but will take the comment into account in the revised discussion.

P30L708. "… in the area of shear surfaces…" : what do you mean exactly ?

Here we wanted to express that the horizontal movement of the rock glacier (either in the area of the shear zone or by internal plastic deformation) can result in positive and negative values in the surface elevation changes, but a net volume change can only result from material input, output, compaction or melting of the ice body. We see that the formulation is not well comprehensible and will express this differently in the revised version.

P30L709. "change" without s

We will correct this.

P31L720. "similar magnitude". Do you mean similar values ? Because it is evident that horizontal velocities are expected to be much higher than "3D" changes.

We see that this is an incorrect formulation. In this sentence we wanted to express that in the previous analyses a good spatial and temporal view of the individual rock glaciers was possible, but the comparison with each other and the relationship between flow velocity and surface elevation change is facilitated by figure 10.