Response to Anonymous Referee #1

We thank Anonymous Referee #1 for his or her time and effort in reviewing our manuscript. We sincerely appreciate the constructive feedback and helpful comments that will improve the quality of the manuscript. Below we have addressed all the points by stating the referee comments (RC) and outlining the corresponding author's response (AR) in *italics*.

RC: The manuscript investigates a cascade of processes in the Radurschl Valley in the Austrian Alps. The outburst of a (supra-) glacial lake initiated the event, which continued with the failure of a rock glacier front with subsequent debris flow initiation. The deposit of the latter caused the blocking of the valley and the formation of a lake, which was drained to manage the risk related to its possible outburst. The series of events and their description are very interesting and, in my opinion, would enrich the scientific literature. However, I have some concerns regarding the manuscript, which in my opinion could profit from some revisions.

The methods are described at a level of detail that is not sufficient for understanding the analysis and reproduce the study. In this sense, they need to be revised and improved. The results and the discussion are mixed at several points in the text, with several repetitions and omissions. The logic structure is at times difficult to follow.

As a general suggestion, I would welcome a major revision of the text. Firstly, the authors could more effectively highlight the original analysis and results of the study, avoid substantial repetitions, and increase the logic structure of the manuscript. Secondly, the use of technical language should be always preferred to common-language expressions (e.g. "temporal changes" vs "dynamics", see detailed comments later) in all cases where this is possible and the methods should be described in more detail. Some minor analysis and addition to the data presented might improve the manuscript and its relevance in the community.

In the following, I provide some more specific comments, that I believe could improve the manuscript. I hope that the authors can receive the feedback in the in the same spirit in which it was written and for what it is: constructive suggestion to improve the paper.

AR: *We welcome the constructive feedback provided by Anonymous Referee #1 and thank him or her for regarding our contribution as relevant to the scientific literature. We agree that the manuscript would benefit from revisions based on the comments provided by Anonymous Referee #1. Below we address the outlined issues point by point, including major revisions of the text, the figures and the provided Supplementary Material.*

Specifically, we will streamline the description of methods, eliminate repetitions and omissions, and highlight the largely open-source based nature of our study. We will provide the corresponding public access options directly in the text, extend the 'Data availability' section, and include data collected by the authors in the Supplementary Material, ensuring full reproducibility of our analysis.

In line with the referee's comments, we suggest revising the manuscript in order to highlight the original analysis and results of the study. In this sense, recapitulation of previous literature will be reduced and generic statements underpinning the chosen methods will be replaced by more specific descriptions. Regarding the use of technical language, we will revise the entire manuscript accordingly, aiming at more precise descriptions and avoidance of redundant adjectives. We added additional data and analysis based on the valuable suggestions of Anonymous Referee #1 and Catherine Bertrand (Referee #2), improving the lines of evidence according to the aims of our study.

RC: Page 1, Line 1: Is the front of the rock glacier failing or are the debris accumulated in the gully (below the rock glacier) that are triggered and flow downhill? I write the comment here, but it applies to several other sections in the manuscript. I think that there is a distinction between rock glacier failure, active layer detachment, and debris flow initiation at a rock glacier front. Neglecting the differences between all these processes is in my opinion a first-order approach, which might well be justified in certain contexts, but should not be used in this manuscript, where the focus is on this specific topic."

AR: *We recognize that precise terminology is essential. The paper addresses debris flow initiation at a rock glacier front, as indicated by distinct features of the debris flow initiation zone (figure 4a, 4b). The appearance of cut-off ice lenses (figure 4b) as well as the depth/width ratio (figure 4a) preclude an active layer detachment. The rock glacier is not undergoing a phase of destabilization as entire landform, but local failure in a specific part of the* *rock glacier front, where a newly formed meltwater channel connects it to a temporary thermokarst lake (please see also RC and AR addressing page 2, line 55; RC and AR addressing page 8, figure 4; RC and AR regarding page 6, line 111 and following; as well as RC and AC addressing page 14, line 308). Observations supporting this specification are presented below (revised text and Supplementary Figure 2; new Supplementary Figures 3, 4, and 5). We will update the entire manuscript accordingly, ensuring consistent and precise language.*

RC: Page 1, Line 3: What does "multivariate permafrost degradation" mean? What is "retrogressive debris flow"?

***AR:** We suggest replacing "multivariate permafrost degradation" by "permafrost degradation" as well as the term "retrogressive debris flow" by "debris flow", as these are the essential features we would like to highlight in the abstract.*

RC: Page 1, Line 5: What do you mean by "environmental forces" and what are the "ambiguous conditions"?

***AR:** We suggest replacing the sentence in line 5–7 by "Potentially destabilizing factors were analyzed systematically to deduce the failure mechanism." We acknowledge that the terms "environmental forces" and "ambiguous conditions" lack the desired precision and are not strictly necessary.*

RC: Page 1, Line 6: The paper is an application of the methodology presented in Glade and Crozier, 2005. If I understood this correctly, the authors do not establish a basis for multi-hazard assessment but apply an existing method. If contrarily the authors argue that they implemented the methods for hazard assessment, I would welcome a clearer explanation of the original methodology, particularly with regards to the concept of hazard.

***AR:** As correctly indicated by Anonymous Referee #1, the paper applies the methodology presented by Glade and Crozier (2005). We agree that our original description was misleading and suggest deleting the phrase "and establish a basis for multi hazard assessment in similar settings".*

RC: Page 2, Line 55: I would argue that destabilizing rock glaciers are defined by the combination of abnormal velocities and the presence of surface features such as cracks and scarps. Several recent papers in the literature provide a more accurate description of rock glacier destabilization.

***AR:** We follow the referee's argument and suggest replacing the sentence in line 55–57 by "Destabilizing rock glaciers are defined by a sudden acceleration of the landform, exhibiting displacement rates up to several meters per year, and the presence of surface features such as cracks and scarps (e. g. Marcer et al., 2021)."*

Lit.: Marcer, M.; Cicoira, A.; Cusicanqui, D.; Bodin, X.; Echelard, T.; Obregon, R.; Schoeneich, P. (2021): Rock glaciers throughout the French Alps accelerated and destabilised since 1990 as air temperatures increased. Commun Earth Environ 2 (1), 383. DOI: 10.1038/s43247-021-00150-6.

RC: Page 3, Line 63: reading this line, the expectations to this paper sky-rocketed. Unfortunately, I must say that they were not satisfied by the manuscript, especially with regards to hydrogeological and mechanical aspects (some comments later). With this I don't want to suggest major revisions, but simply to be more precise in the description of the goals of the paper.

***AR:** We thank Anonymous Referee #1 for communicating concerns about sky-rocketed expectations. We suggest deleting the sentence in line 62–64.*

To be more precise in the description of the goals of the paper, we suggest revising the last paragraph of the introduction (line 65–69) as follows: "The aim of this paper is to explore the destabilizing factors leading to local failure of an active rock glacier front in the high-mountain cirque Hüttekar in the Austrian Alps. We analyze the cascading processes involving thermokarst lake outburst, debris flow, and river blockage. We evaluate a set of potentially contributing factors, assess critical combinations, and develop a consistent conception explaining debris flow initiation at the rock glacier front. Similarities and differences with respect to documented debris flows at other rock glacier fronts are analyzed, and conclusions drawn regarding hazard potential."

RC: Page 4, Line 96: This sentence is in my opinion very controversial. Are the authors stating that the rock glacier originated 170 years ago as a result of the LIA glacier advance? The next sentence quickly describes the surface morphology of the terrain influenced by recent glacier advances. Why not considering the simplest and mostsupported hypothesis that the rock glacier pre-existed and was simply overridden by a glacier during the LIA? Anyway, I would simply avoid this argument, which is irrelevant for the discussion of the results and the topic presented in the paper. If the authors want to keep the statement, I would welcome more extensive explanations of their theory.

AR: *We agree and follow the suggestion of Anonymous Referee #1 to avoid this argument. Thus, we suggest deleting the two sentences in line 96–99 and revising the associated paragraph as outlined in our response to the referee comment addressing page 5, line 105 (please see below). Accordingly, we suggest deleting Supplementary Figure 1.*

RC: Page 5, Line 105: how do the authors know that the channels are eroded into the ice core? Are the authors referring to water flowing on top of the permafrost table or to water infiltrating into the ice-core? This is a very interesting topic and if observations are available, they could be presented and discussed in more detail. If no more details are available, I would still welcome a clearer description of the observations (if considered relevant).

AR: *We follow the suggestion of extending the description of our observations, including more relevant details and presentation of the available material. Regarding the observed channels along the rock glacier permafrost table, we suggest deleting the term 'eroded' to avoid hypotheses about the generating process at this point. We revised our description to include all available details, given the difficulties in precisely identifying flow paths in active rock glaciers. The updated description is presented below, along with a new figure including a photograph of an observed water current along the permafrost table (please see below). As a preliminary suggestion, the new figure could be included in the Supplementary Material and is provisionally termed „Supplementary Figure 3". While it is possible that some water is infiltrating into the rock glacier ice-core as well, we cannot prove this by direct observations and thus avoid speculations regarding this issue. In the context of the present study, we consider it sufficient to demonstrate the establishment of a thermokarst channel connecting the thermokarst lake to the debris flow initiation zone, irrespective of its exact vertical position. Evidence for this connection is described in our response to the referee comment addressing page 7, line 123 (please see below) and documented through photographs in Fig. 4 of the original manuscript, the revised Supplementary Figure 2 presented below, as well as the new Supplementary Figure 3 presented below. Accordingly, we suggest revising the last paragraph of section 2 'Study site' by replacing line 96–107 by:*

"The largest rock glacier in Hüttekar-cirque is 1408 m long and up to 493 m wide, covering an area of 0.5 km² in the lowermost parts of the cirque. Its gently sloping surface is characterized by distinct furrows and ridges, while the steep front rests on top of a slope above Radurschl Valley. Rock glacier debris is composed of orthogneiss derived from the Glockturm massif. In the southeast, the lower, debris covered parts of Glockturmferner transition into the rock glacier rooting zone. The exact boundary between debris covered glacier and rock glacier is not known. Massive ice is frequently visible beneath a ~1–2 m thick debris layer in a shallow depression at the southeastern edge of the rock glacier, close to the suspected transition zone. The debris layer consists of poorly sorted boulders with individual blocks measuring up to 4 m, arranged in a loose, clast-supported structure. The blocky surface layer covers a finer-grained layer dominated by well-graded gravel and sand that is exposed along the rock glacier front. The unfrozen domain of this heterogeneous debris layer increases irregularly in thickness towards the rock glacier front, reaching a maximal thickness of ~5–10 m.

A small meltwater current from Glockturmferner infiltrates into the rock glacier rooting zone (Fig. 3). Water flowing along the permafrost table is visible and audible between boulders at several places in the southern part of the rock glacier. These water currents follow distinct channels that can be traced below the boulders along the rock glacier surface. Where visible between the boulders, the channels are up to 1 m wide and 20 cm deep (Supplementary Figure 3). Surface water bodies in Hüttekar-cirque are restricted to small meltwater lakes and currents in immediate vicinity of the two glaciers. The absence of surface creeks in the lower parts of Hüttekar-cirque indicates that it is drained exclusively by subsurface flow, emerging as a group of small springs at the toe of the slope descending to Radurschl Valley (Fig. 3, Supplementary Figure 3). The exact number and position of these springs varies during the year but is always constrained to the sedimentary cone covering the toe of the slope, as evident from 23 field surveys between 2019 and 2022 covering all months. Spring discharge of individual outlets is < 1 l/s and electrical conductivity ranges from 60 to 75 µS/cm, as indicated by repeated measurements during these surveys."

To visualize these observations and allow for direct assessment of these features by the interested reader, we suggest including a new figure in the Supplementary Material ("Supplementary Figure 3") showing photographs of key observations:

Supplementary Figure 3.

In addition, we updated Fig. 3 to include the position of the springs and highlighted the observed meltwater channel:

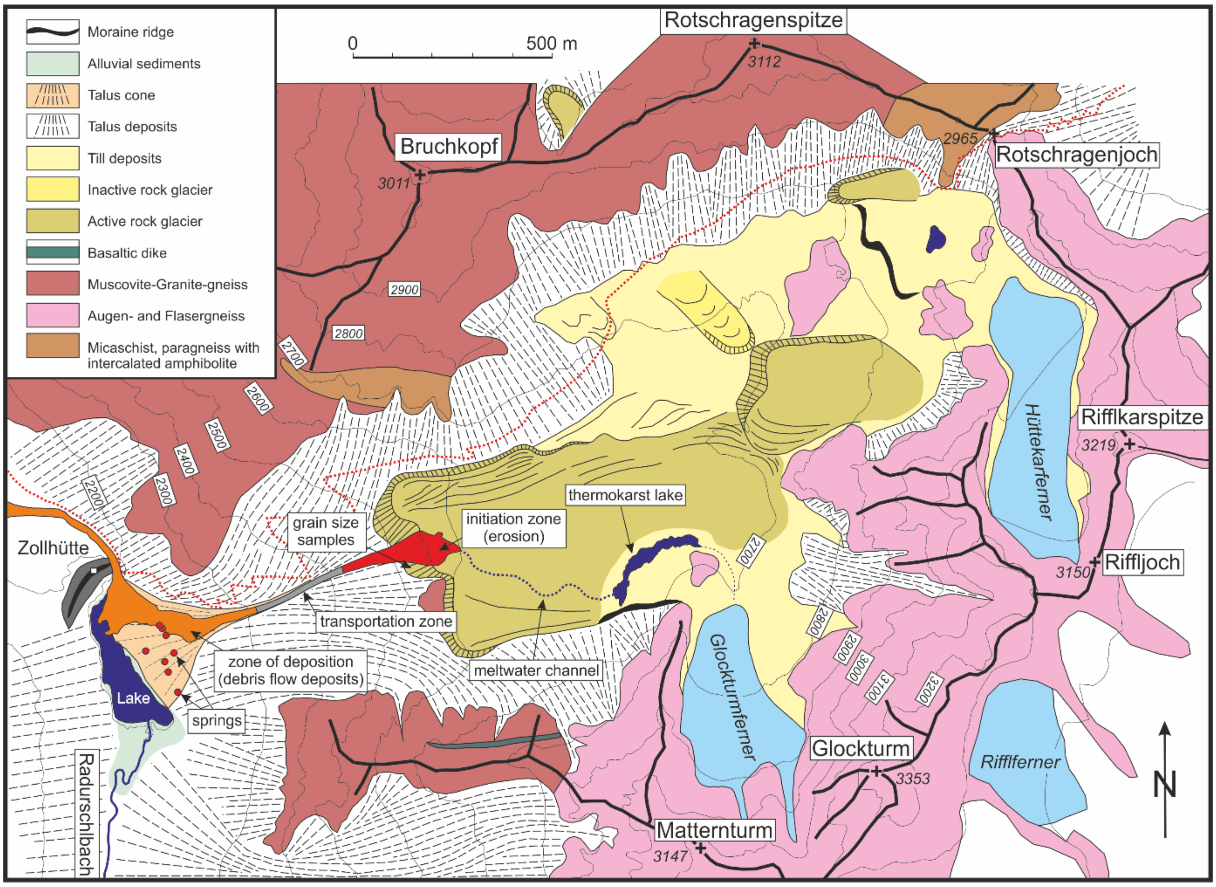


Figure 3. *Geological-geomorphological map, compiled using the most recent geological map provided by the Geological Survey of Austria (Moser, 2012). It is complemented by ortho-images and a high-resolution digital terrain model (DTM) derived from airborne laser scanning data (Government of the Province of Tyrol, 2021a). The map is based on comprehensive field mapping (2019–2021).*

RC: Page 6, Line 106: what is a "retrogressive debris flow"? I see here some confusion between "retrogressive erosion" and "debris flow".

AR: *We suggest replacing the term by "debris flow".*

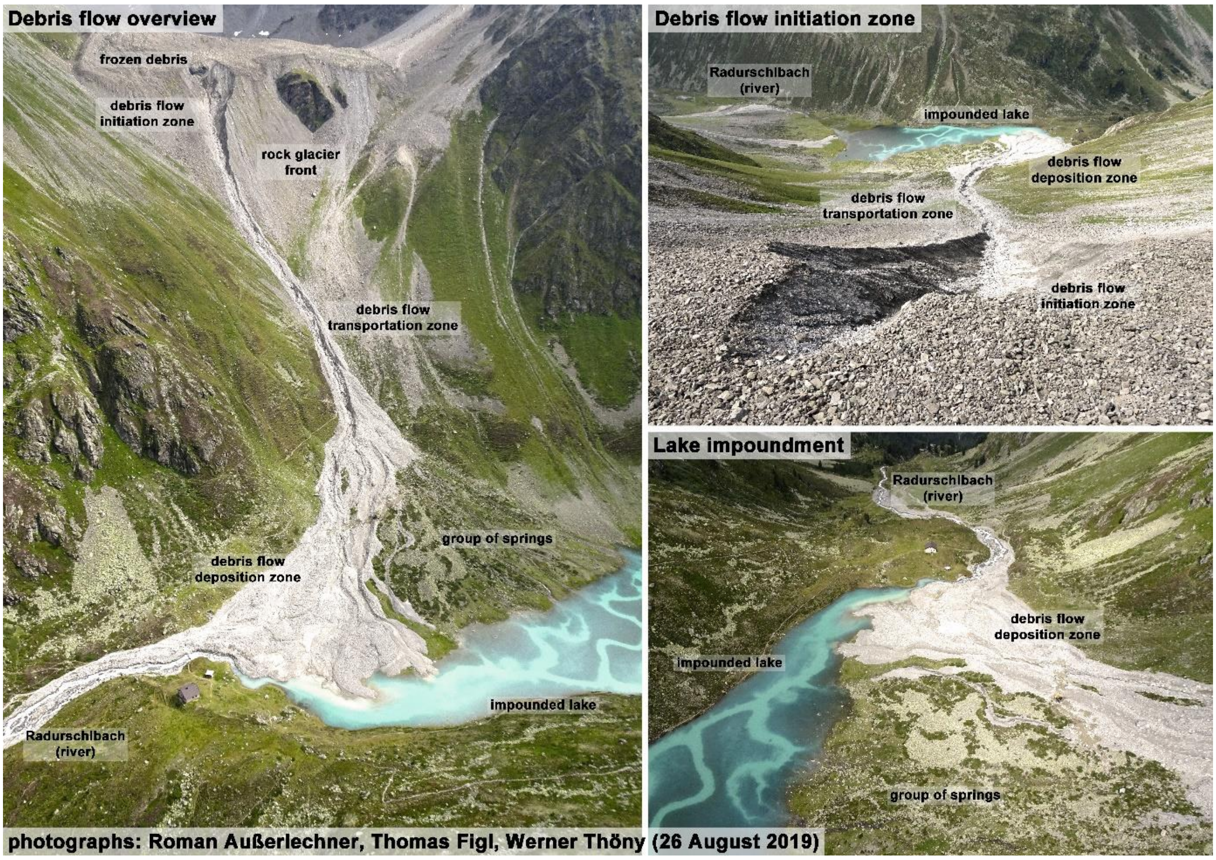
RC: Page 6, Line 111 and following: This paragraph is extremely interesting, and I suggest to extend the description (here) and discussion (later) of the observations, the numbers presented, the methodology used to derive them, and their uncertainties. These points might be extended in several locations in the manuscript, maybe replacing some of the repetitions and digressions that are currently present.

AR: *We thank Anonymous Referee #1 for expressing his or her interest and suggestions to extend the descriptions. Please note that the presented numbers merely serve as an indication of the scales involved and are not used for any calculations. We revised the paragraph (line 109–122) accordingly, focusing on the issues addressed by Anonymous Referee #1:*

„A debris flow erodes the steep slope bordering Hüttekar-cirque to the west (Fig. 2; classification according to Hungr et al., 2014). Following a moderate precipitation event, destabilization initiated on 13 August 2019, mobilizing a volume of several thousand m^3 from the steep rock glacier front (Fig. 4a). The debris flow started at 03:00 AM (Central European Summer Time, UTC+2), the main event lasted until about 12:00 PM, followed by reduced debris flow activity that persisted until the next day. The debris flow was observed by Josef Waldner (staff of the nearby hut Hohenzollernhaus) and Gerhard Schaffenrath (local shepherd). On 14 and 26 August 2019, respectively, the debris flow was documented during helicopter flights by Roman Außerlechner, Thomas Figl and Werner Thöny (Geological Survey of Tyrol). Slope failure initiated along an irregularly shaped rupture in ice-

cemented debris, exposed at the main scarp (Fig. 4b). Accelerating and disintegrating, the transported mass evolved into a debris flow following a narrow channel down the steep slope below the rock glacier front (Fig. 2, Fig. 3; Supplementary Figures 3 and 4, respectively). About 200 m below the initiation zone, the debris flow spread out and formed a fan of 33,000 m^2, thereby damming the river Radurschlbach at an elevation of 2,200 m a. s. l. (Fig. 4c, Fig. 4d; Supplementary Figures 3 and 4, respectively). Based on in situ observations, aerial photographs, and several surveys conducted before as well as after the debris flow event, a total volume of 40,000 – 50,000 m^3 of mobilized sediment is estimated, providing a rough indication of the event magnitude. Consequently, a lake covering an area of ~60,000 m^2 developed in Radurschl Valley, causing the downstream riverbed to fall dry temporarily (Fig. 4c; Supplementary Figures 3 and 4, respectively). Excavation of a drainage channel lowered the mean water depth from 2 m to 1 m during the following days to prevent a potentially catastrophic outburst. The corresponding water depths are reconstructed from in situ observations and reviewed by mapping the maximum lake extent as well as the lake extent following excavation, and corresponding volume calculations employing a high-resolution digital terrain model described in section 4.1. Subsequently, a dam was constructed on the debris fan to restrain future debris flows from damming Radurschlbach again."

We suggest supporting this description with a new figure, showing the entire debris flow including initiation zone, transportation zone, and deposition zone, as well as details including frozen material, levees, and river blockage. As a preliminary suggestion, the new figure is provisionally termed „Supplementary Figure 4" and presented below:



Supplementary Figure 4

RC: Page 7, Line 123: Concurrently means at the same time. The question of the timing is essential for the process described. Please explain in more detail what is known (and how, see previous comment) and what are your hypothesis. Later in the manuscript, they should be tested and discussed.

AR: *To clearly distinguish observations from hypotheses, we suggest revising the entire paragraph (line 123–134), addressing the issues outlined by Anonymous Referee #1 as precisely as possible. Please note that due to the remoteness of the study site and the absence of instrumentation at the time of the event, the timing of individual processes can only be roughly reconstructed (temporal resolution on the order of several hours). In accordance* *with these constraints, our study presents rough estimates of the involved time scales (thermokarst lake development ∼2 months, thermokarst lake drainage ∼1 day, debris flow event ∼1.5 days) that can reliably be deduced. Throughout the manuscript, we will highlight the fact that the discussed implications and drawn conclusions are consistently reconciled with the accuracy of these estimates. The revised event description (line 123–134) addresses the issues outlined by Anonymous Referee #1:*

"During the same night as the debris flow initiation, a thermokarst lake on top of Hüttekar Rock Glacier, ∼350 m behind the debris flow initiation zone, started draining and emptied almost completely during the following day, as indicated by local observations (Fig. 3, Fig. 4e, Fig. 4f). The thermokarst lake had started to develop coincidently with the onset of snowmelt in early June 2019 within a shallow depression where massive ice within the rock glacier prevented drainage (Fig. 4g). During the last decades, a comparable feature had never been observed before in Hüttekar-cirque, despite frequent visits by hikers, hunters, shepherds, and staff of Hohenzollernhaus (Josef Waldner, pers. comm.). In line with these observations, publicly available remote sensing data and historical maps of Hüttekar do not exhibit any indications of thermokarst lake development on Hüttekar Rock Glacier before June 2019 (evident from Sentinel-2 satellite imagery provided by Copernicus and processed by Sentinel Hub (https://www.sentinel-hub.com/), historical ortho-images and laserscans provided by the Government of the Province of Tyrol, (https://www.data.gv.at/; https://lba.tirol.gv.at/), historical maps provided by the Government of the Province of Tyrol (https://hik.tirol.gv.at)). In the stage of its largest extent, the thermokarst lake was approximately 300 m long, up to about 150 m wide and 4–5 m deep, comprising an estimated water volume of ∼150,000 m^3.

Effective drainage occurred through a large crevasse (width ∼1.5 m, height ∼2 m) that formed in association with the debris flow initiation (Fig. 4h). The crevasse is part of a newly formed channel system connecting the thermokarst lake to that part of the rock glacier front that failed, constituting the debris flow initiation zone. While the exact vertical position of this channel system is not known, clearly discernible and precisely confined collapse structures within the debris layer indicate the trace of this channel network along the rock glacier surface (Fig. 4e, Fig. 4f; Supplementary Figures 2 and 3, respectively). Large amounts of water were rapidly transferred to the debris flow initiation zone and torrent beneath. Retrogressive linear erosion visible in the initiation zone indicates that concentrated water flow emerged at the main scarp (Fig. 4b), in good agreement with earlier observations of rock glacier front failures (Kummert et al., 2018; Marcer et al., 2020; Kofler et al., 2021). Erosion of unfrozen sediment in the vicinity of the debris flow initiation zone persistently modifies its shape and continues to widen it until today. Since then, the depression storing the former thermokarst lake never filled again but still shows distinct morphology (Supplementary Figures 2 and 3)."

RC: Page 7, Line 126: it is interesting that local knowledge is taken into account. Still, I suggest to perform a systematic analysis with modern remote sensing data (Sentinel 2 for example) to quantify the evolution of the lake in recent times.

***AR:** We agree with this valuable suggestion and performed a systematic analysis with modern remote sensing data, carefully scanning available archives for indications of thermokarst lakes appearing on Hüttekar Rock Glacier before June 2019. In addition, we included historical and modern maps in our analysis. We suggest communicating our results as outlined in the completely revised section 3 (please see our response to the referee comment addressing page 7, line 123).*

RC: Page 7, Line 139: Are the authors talking about dynamic forces here? Impact from external mass movements? Earthquakes?

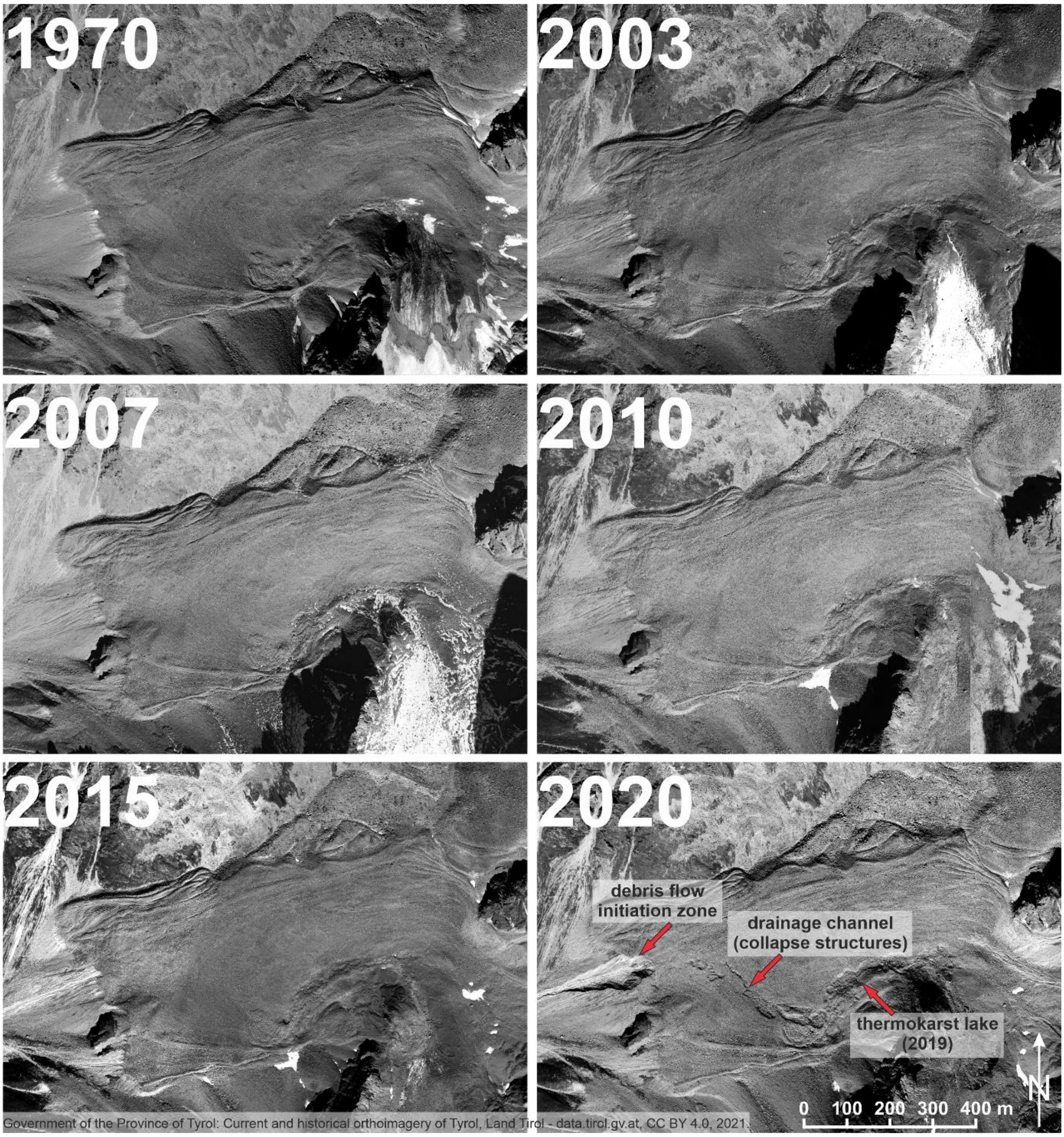
***AR:** We acknowledge that the term "dynamic forces" as used in our original manuscript is misleading. Throughout the manuscript, we suggest replacing the term "dynamic forces" by "dynamic factors", strictly following the nomenclature suggested by Glade and Crozier (2005). In this way, we highlight the consistent application of the factor mapping methodology for landslide susceptibility assessment provided by these authors, in accordance with our responses to the referee comments addressing page 1, line 6 (please see above) and page 9, section 4.1 (please see below), respectively.*

RC: Page 8, from Figure 4: Very interesting observations of the rock glacier front. What's the height of the shear horizon depth here? I would be very happy to see in the published version of the manuscript a detailed description of this area (possibly before and after the event?), which is highly relevant to the debris flow initiation. A figure showing a simple comparison before-after the event (maybe in appendix?) would be very useful. What is the thickness of the debris around the lake? And around the front? Panel g and h seem to indicate a debris covered glacier. Would It be possible to provide a more detailed geomorphological assessment of the landform and a map of it?

AR: *We thank Anonymous Referee #1 for appreciating the observations of the rock glacier front and his or her suggestions to present them in more detail. To communicate these observations as objectively as possible, we followed these suggestions by preparing a new figure that shows a comparison before-after the event. The new figure could be included in the appendix or in the Supplementary Material, where further photographs are already available. As a preliminary suggestion, the new figure is provisionally termed „Supplementary Figure 5" and presented below:*

Supplementary Figure 5.

In addition, we extended Supplementary Figure 2 showing ortho-images of Hüttekar Rock Glacier before the 2019 debris flow event (1970, 2003, 2007, 2010, and 2015) as well as after the event (2020):



The depth of the shear horizon is highly variable, as the debris flow initiation zone is characterized by an irregularly shaped rupture in ice-cemented debris, adjusting its shape and widening by erosion of unfrozen debris in its vicinity. These issues are now highlighted in the revised description of the debris flow event in section 3 (please see above). The unfrozen debris around the front is up to 5-10 m thick. The thickness of the debris around the lake is ∼1-2 m (now included in the revised description of the study site in section 2, please see above). As the glacier (Glockturmferner) transitions into the rock glacier (Hüttekar Rock Glacier), a clear boundary between the two landforms cannot be drawn. We summarized what is known as precisely and objectively as possible in the revised description of the study site (please see above).

Accordingly, we suggest complementing line 271 and the following with a detailed description of the debris flow initiation zone before and after the debris flow event:

"Prior to landslide initiation, the prospective initiation zone was characterized by steep slope angle and convex downslope curvature (Table 2). It formed a part of the 400 m wide and 100 m high rock glacier front, bounded to the top by a distinct erosional edge separating it from the flat rock glacier surface. The steep rock glacier front (35° on average) exhibited roughly homogeneous appearance, except for two bedrock outcrops in its southern part (Supplementary Figures 3 and 5, respectively). Since the debris flow initiated on 13 August 2019, the 80 m

wide and 200 m long debris flow initiation zone eroded into the rock glacier front exposes its internal structure. It forms an irregular, concave niche characterized by steep flanks that are up to 30 m high and composed of loose, poorly-sorted sediment (Fig. 4a, b; Supplementary Figures 2–5). Its top is connected to collapse structures connecting it to the former position of the thermokarst lake as described in Section 3, with linear erosion features indicating emergence of concentrated water. After the debris flow initiation, frozen material was exposed immediately below the top (Fig. 4a,b; Supplementary Figures 3 and 4, respectively)."

We hope that the revised geomorphological description given above, the revised Fig. 3 shown above, the revised description of the area before and after the event, the revised Supplementary Figure 2 shown above, and the new Supplementary Figures 3, 4, and 5 presented above clarify the issues outlined by Anonymous Referee #1.

RC: Page 9, Section 4.1: some of the text presented here might be more suited for the introduction. Also, the analysis of the presented factors on slope stability is not clear to me. I don't see any stability assessment, or somehow I missed it. Maybe a clearer description of the methods might help.

AR: *As correctly stated by Anonymous Referee #1, our study does not provide a full stability assessment of the slope, but rather an analysis of landslide susceptibility employing factor mapping as outlined by Crozier and Glade (2005). We suggest revising Section 4.1 (line 145–172), removing general statements that are misplaced in this section and providing a more precise method description. The revised text will also highlight the public availability of the analyzed data sets by specifying corresponding weblinks and providing the grain size analysis data in the Supplementary Material.*

RC: Page 9, Line 165 and following: This is in my opinion an interesting approach, but cannot be introduced so lightly. Please provide more details, assumptions, rationale, and potential limitations. As known, the internal structure of rock glacier is very different from the active layer (also not homogeneous in the active layer!). Assuming the the latter is representative of the first is not valid in my opinion, especially given the photographs presented in figure 4. Were the boulders only collected at the surface? Only evaluating the boulders at the surface creates a bias towards boulders. How were the samples collected at the front? Who went there? Where exactly were they collected? How representative should this be of the internal part of the rock glacier, especially the shear horizon if you suggest that water was flowing there (erosion/deposition at the surface)?

AR: *We agree with Anonymous Referee #1 that the internal structure of rock glaciers is highly heterogeneous and that the differentiation between active layer, rock glacier core, and rock glacier front is essential. To clarify this point and to restrict the analysis to the most essential features of the studied rock glacier, we suggest cancelling the discussion of the coarse-grained surface layer and focus on the composition of the rock glacier front, which is where the debris flow initiated. We revised Fig. 3 (please see above) accordingly, and restricted Fig. 6 to the grain size distribution of the rock glacier front (please see below). We suggest deleting line 284–290 and revising 165–172, addressing the issues outlined by Anonymous Referee #1:*

"The structural characteristics of the material involved in the debris flow are inspected by analyzing the grain size distribution of the rock glacier front. In August 2009, four samples were taken 50 m southwest of the later debris flow initiation zone and analyzed by wet sieving (position indicated in Fig. 3). Due to the heterogeneous structure of the rock glacier, these samples are not representative for the grain size composition of the entire rock glacier. In contrast, the material at the rock glacier front appears comparatively homogenous. Considering the proximity of the sampling locations to the subsequent debris flow initiation zone, and the dangerous sampling conditions at active rock glacier fronts in general, we consider the samples reasonable approximations to the grain size composition of the material that was mobilized during the debris flow event on 13 August 2019."

In addition, we suggest including the grain size analysis data in the 'Supplementary Material'. The revised Fig. 6 is presented below:

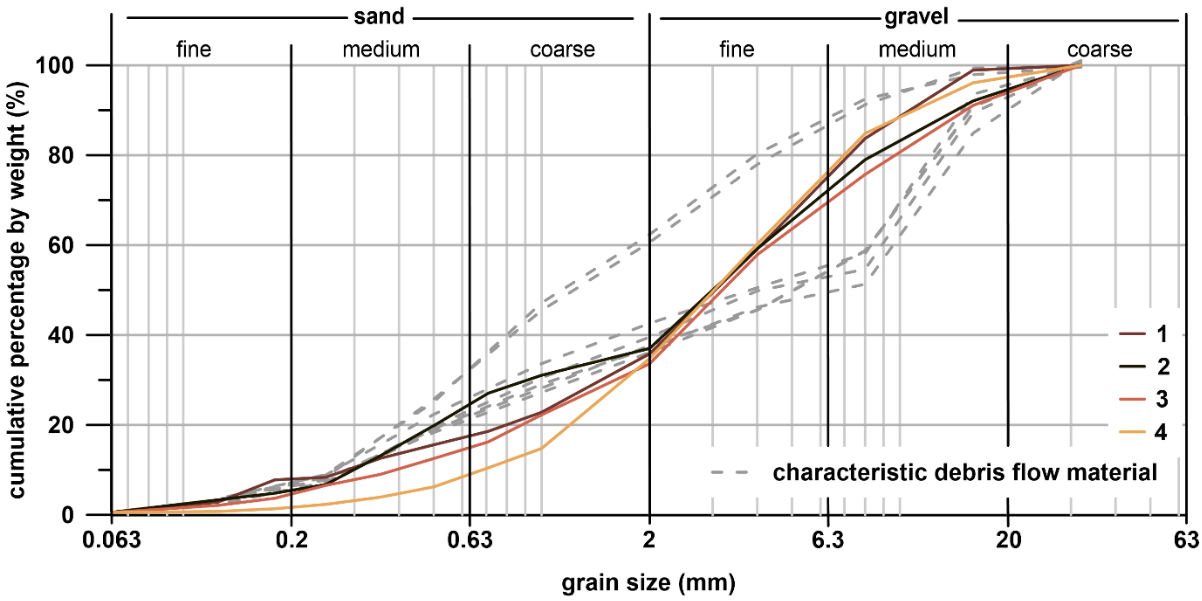


Figure 6. *Grain-size distributions of material composing the rock glacier front. The corresponding sampling locations are 50 m southwest of the debris flow initiation zone, as indicated in Fig. 3. Dashed grey lines represent source compositions of a set of experimentally investigated debris flows showing contractive shear response and undrained failure (USGS debris flow flume; Major (1996); Iverson (1997); Iverson et al. (1997)). Classification according to ISO 14688-1 (International Organization for Standardization, 2017).*

RC: Page 9, line 177: this is not a sufficient description for the data used.

AR: *We suggest complementing the description by expanding line 178–182 as follows: "In the observation period 1970–2020, a simple but effective approach was used to assess the surface displacement rates within single periods (1970-2003-2007-2010-2015-2020). In doing so, 200 prominent blocks, geometrically well distributed on the rock glacier surface, were visually identified at each ortho-image epoch to approximate the horizontal surface displacement rates at the respective location. Visual detectability within optical imagery is approximately half of a pixel size (in this case 10 cm). In this study assessed surface displacement rates cover at least 3 years, so with a given spatial resolution of 20 cm of the ortho-images, minimum rates of 3–4 cm are theoretically detectable on Hüttekar Rock Glacier. Additionally, the position of the rock glacier front line (top of the erosional slope) is mapped at every epoch. Both analyses provide the basis for assessing the kinetic patterns on the rock glacier surface (Avian et al., 2009; Kummert and Delaloye, 2018)."*

RC: Page 10, line 183 and following: is the use of climate relevant here? Are the authors not limiting the analysis to meteorological forcing? Also, what is meant by "progressive change of climatic factors"? In general, the description of the method is not sufficient for reproduction, and in this sense, it should be improved and extended.

AR: *We will address these issues carefully by revising and extending the method description to ensure reproducibility and demonstrate the relevance of climate in the context of the study. We consider the long-term influence of climate relevant for two reasons: (1) The limiting factor governing the rate and extent of thermokarst evolution at Hüttekar Rock Glacier is the available energy input, which is outstandingly high in summer 2019 compared to earlier years (as indicated in Table 3; please see also line 188–190 on page 10 and line 315–316 on page 16). In this sense, the analysis of climate allows putting the conditions during summer 2019 in a long-term context. (2) The strong increase in air temperature and positive degree day sum, outpacing corresponding trends at the global and European Alps scale (please see line 317–320 on page 16), suggests that permafrost degradation and upward shifting of the lower permafrost boundary affected Hüttekar-cirque strongly during the years preceding 2019. We agree with Catherine Bertrand (Referee #2), who outlined that the discussion of our study results "poses the problem in the long term, especially the effect of climate change which accelerates the degradation of permafrost and favors the creation of a thermokarst and the possible consequences." (please see comment on egusphere 2022-567 by Catherine Bertrand, https://doi.org/10.5194/egusphere-2022-567-RC2).*

Accordingly, we believe that the results are relevant in the context of our study and suggest revising the manuscript to explain and highlight this relevance.

We recognize that the open-source based nature of the entire study was not adequately highlighted in the original manuscript. The dataset analyzed here is almost completely publicly available, implying that the analysis is reproducible. Currently, the only exception is the employed snow model (SNOWGRID). However, full access to this dataset will be provided in the future via the Central Institute for Meteorology and Geodynamics (Austria). Similarly, the methods of analysis rely on open-source software that is publicly available. To address the issues outlined by Anonymous Referee #1, we suggest revising the main text of the manuscript accordingly, highlighting public access options to the analyzed data, extending the 'Data availability' section, and including processed data in the Supplementary Material.

RC: Page 10, Line 210: are the calculations about snow cover validated in any way?

AR: *We recognize that the original manuscript is lacking information regarding the validation of the snow model. The analyzed dataset is a subset of a nationwide dataset that is continuously updated through the distributed SNOWGRID model (Olefs et al., 2013). The resulting snow cover data are routinely evaluated and validated by the Central Institute for Meteorology and Geodynamics using more than 50 station measurements of snow depth, additional measurements regarding snow depth and snow water equivalent (5 stations along with more than 200 individual measurements), snow depth measurements employing laser sensors, winter mass balance measurements of glaciers within the model domain, spatial validation of snow cover extent using satellite-based fractional snow cover area provided by MODIS, as well as cumulative runoff data (Olefs et al., 2020). Additional verification stems from feedback provided by a large range of SNOWGRID applications including research projects as well as commercial applications (for an overview, please see https://www.zamg.ac.at/cms/de/forschung/klima/klimatografien/snowgrid). We suggest revising and extending the snow model description in line 207–214 of the manuscript, including an explanation of the model validation procedure.*

Lit.: Olefs M., Koch R., Schöner W. and Marke T. (2020): Changes in Snow Depth, Snow Cover Duration, and Potential Snowmaking Conditions in Austria, 1961–2020—A Model Based Approach. Atmosphere 11(12):1330. DOI: 10.3390/atmos11121330.

RC: Page 11, Line 218: The statements about the hydrology seems to be results. What observations are available? Please expand the description of the data and methods here. E.g. why until the 13th of August?

AR: *We agree with Anonymous Referee #1 that these observations are misplaced here. As outlined in our response to the referee comment addressing page 5, line 105, we suggest reporting the role of glacial meltwater in the last paragraph of section 2 (Study site), summarizing the hydrology and hydrogeology of Hüttekar (please see above). The employed methods aim at maximizing comparability with a similar study performed by Kofler et al. (2021), who analyzed the initiation of debris flows from two rock glacier fronts in nearby mountain ranges. To estimate the total water input received by Hüttekar-cirque in 2019 prior to the debris flow initiation, we calculated the cumulative rainfall, snow melt and ice melt from 1 January 2019 to 13 August 2019 (failure date) and compared it to the respective water volumes in previous years (consistently totalized from 1 January to 13 August). We will revise the description of data and methods accordingly, addressing the issues outlined by Anonymous Referee #1.*

RC: Page 14, line 308: Data of surface velocities would be very interesting. Is it possible to present them? Especially relevant if the authors speak about destabilization. Possibly you could also see some signal in ice melt (vertical component – once subtracted subsidence due to dynamics).

AR: *We thank Anonymous Referee #1 for this valuable suggestion and will prepare a new figure illustrating our results. In addition, we suggest providing the feature tracking data showing the rock glacier surface kinematics as Supplementary Material. Please note, however, that the study addresses local failure in a specific part of the rock glacier front, not destabilization of the entire landform. We believe that several of the comments answered above will help clarifying this important distinction in a revised version of the manuscript. Therefore, in our opinion calculating the subsidence due to rock glacier dynamics and extracting some signal in ice melt is beyond the scope of the current study.*

RC: Page 17, Figure 8: great figure. I suggest to add the equations to the lines and expand the discussion with regards to failure processes (Lou and Similaun different from this case, no?)

AR: *We thank Anonymous Referee #1 for appreciating the figure and for providing valuable suggestions that will improve the figure as well as the main text of the manuscript. We agree with these suggestions and prepared an updated figure including the equations (please see below). As correctly noted by Anonymous Referee #1, the documented debris flows at Murfreit Rock Glacier, Lou Rock Glacier, Similaungrube Rock Glacier, Hintergrat Rock Glacier, and Ritigraben Rock Glacier occurred in response to heavy rainfall, in contrast to the debris flow at Hüttekar Rock Glacier. To highlight this key difference, we suggest modifying line 336–340 of the manuscript as follows:*

"These characteristics distinctly contrast with the rainfall events preceding well documented debris flows from rock glacier fronts in the European Alps. Those occurred most often in response to heavy rainfall (Fig. 8): the Ritigraben event on 24 September 1993 (Lugon and Stoffel, 2010), the Murfreit event on 02 July 2003 (Krainer et al., 2012), the Hintergrat and Similaungrube events, both on 13 August 2014 (Kofler et al., 2021), as well as the Lou event on 14 August 2015 (Marcer et al., 2020). In contrast, the rainfall event preceding the debris flow at Hüttekar Rock Glacier was neither especially intense, nor especially persistent (Fig. 8)."

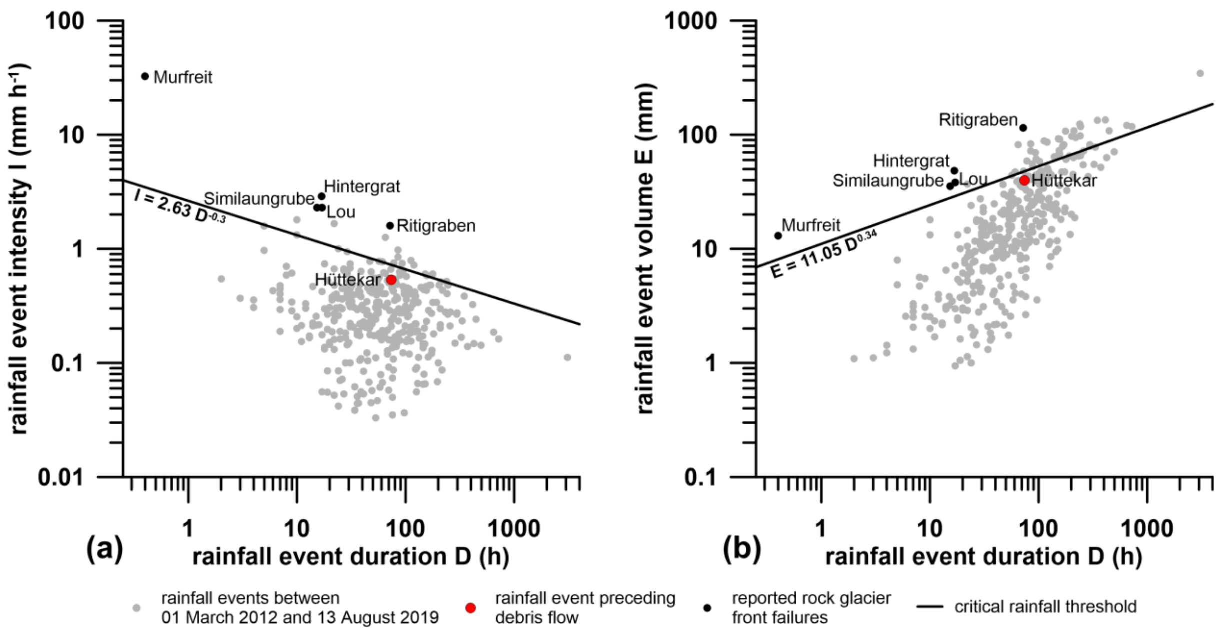


Figure 8. *Rainfall event frequency analysis with respect to (a) rainfall event intensity I vs. rainfall event duration D and (b) rainfall event volume E vs. rainfall event duration D based on INCA (note logarithmic scale). Regional thresholds describing minimum conditions for rainfall-induced debris flows are based on Nikolopoulos et al. (2015b) and Marra et al. (2016), with equations given below the corresponding lines (thresholds are representative for the summer season). Characteristics of triggering rainfall events are based on Lugon and Stoffel (2010), Krainer et al. (2012), Kofler et al. (2021), and Marcer et al. (2020).*

RC: Discussion and Conclusions: I would welcome a more detailed discussion of the original results of the manuscript, limiting long review of previous literature. Same for the conclusions. Maybe some of the comments above can help in the process.

AR: *We thank Anonymous Referee #1 for his or her valuable comments and suggestions and agree that the comments above will help in the process of revising the 'Discussion' and 'Conclusion' section, respectively. Specifically, we will restrict the review of previous literature and instead focus on the original results of the manuscript, including (1) the unfavorable predisposition of the front of Hüttekar Rock Glacier, (2) the rapid development and sudden drainage of the thermokarst lake on Hüttekar Rock Glacier, driven by extraordinarily high atmospheric energy input during summer 2019 following a long-lasting general warming trend promoting permafrost degradation, (3) the quantification of the energy available for thermokarst evolution at Hüttekar Rock Glacier, critically linked to the development of the thermokarst lake and channel considering the considerable* *distance (about 350 m) between thermokarst lake and rock glacier front, and (4) implications for future considerations regarding debris flow initiation in permafrost-affected terrain.*