Response to Catherine Bertrand

We thank Catherine Bertrand for 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: This study analyses the possibility of a gravitational event occurring as a result of a cascade of rapid events, namely the rupture of a thermokarst lake, the rupture of a rock glacier front, the development of a debris flow and the blockage of a river impacting the Radurschl valley (Ötztal Alps, Tyrol) on 13 August 2019. The analysis of the overflow risk of an artificial lake created during such events is a topical issue with important societal challenges.

This article proposes an interesting methodology based on multi-criteria analysis that is of interest to the scientific community. It is an interesting article well-argued and can be published in your journal.

The bibliographical references are numerous. These citations support the scientific demonstration but sometimes make the reading more difficult. For example, is it necessary to cite references from 1984 to 2010 (see line 231) or between 1990 and 2010 in line 235. It is not a question of ignoring previous work but of finding the right balance between citations.

Also, there are many examples where authors are quoted twice in two consecutive sentences (line 137 and 138 for Glade and Crozier et al., lines 183 and 185 for Patton et al. to name just two examples). Is this necessary? Why not choose the most striking points of the work without wanting to refer to everything that is said in the article. I think the readability would be improved by reworking the citations. But this is a side remark that does not detract from the quality of the work.

The article is well constructed, and the argument is well presented.

AR: *We welcome the constructive feedback provided by Catherine Bertrand and thank her for regarding our contribution as relevant to the scientific community, for highlighting the associated societal challenges, and for appreciating the article construction and our presented line of argument. We recognize that the numerous bibliographical references make our submitted manuscript difficult to read and will follow her recommendations regarding the right balance between citations. Accordingly, we suggest revising the entire manuscript, reworking the citations focusing on the most striking points, avoiding quotes in consecutive sentences as well as excessive quotations, and restricting recapitulation of previous literature to highlight the original analysis and results of our study.*

RC: In the introduction why not mention the study site in the last paragraph?

AR: *We agree with Catherine Bertrand and suggest revising the last paragraph of the introduction (line 65–69) to describe the goals of the paper more precisely 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: Line 63 the authors underline the fact that the assessment of the hazard potential of rock glaciers requires an integrated approach combining hydrogeological, meteorological, thermal, geomorphological, and mechanical aspects in a coherent framework. As these aspects are well identified in the introduction, why not go into more detail later?

AR: *We agree with Catherine Bertrand and suggest deleting the sentence in line 62–64. The applied methodology will be described in more detail in Section 4 (Methods) that will be revised accordingly.*

RC: The hydrogeological descriptions are described succinctly from line 104 onwards. What arguments do you have to say that the cirque is drained only by subsurface water? Do you have any idea of the mineralization of the water from your various sources? Is it possible to indicate them on your figure 2 or 3. What arguments do you have for saying that the water flows along distinct channels eroded into the ice core?

AR: *We recognize that the site description provided in the original manuscript should be extended, including more relevant details and presentation of the available material. The slope downstream from Hüttekar-cirque, representing its orographic catchment outlet and connecting it to Radurschl Valley, does not show any indications of surface water. A group of springs emerging at the toe of the slope is the only observable outflow from Hüttekar-cirque. We mapped these springs and measured the electrical conductivity of spring water during several field surveys between 2019 and 2022. We suggest revising the original description as outlined below, including the results of these measurements. We followed the suggestion of Catherine Bertrand and included the position of these springs in the geological-geomorphological map (revised Fig. 3 presented below). In addition, we present a new figure below that could be included in the Supplementary Material and is provisionally termed „Supplementary Figure 3". The photographs document the absence of surface water bodies in Hüttekar-cirque as well as along the downstream slope connecting it to Radurschl Valley. Some of the springs at the toe of the slope are visible in two of the photographs and are outlined accordingly.*

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 photograph of an observed water current following one of these channels along the permafrost table that is included in Supplementary Figure 3.

Accordingly, we suggest revising the last paragraph of section 2 'Study site' by replacing line 96–107 as follows:

"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:

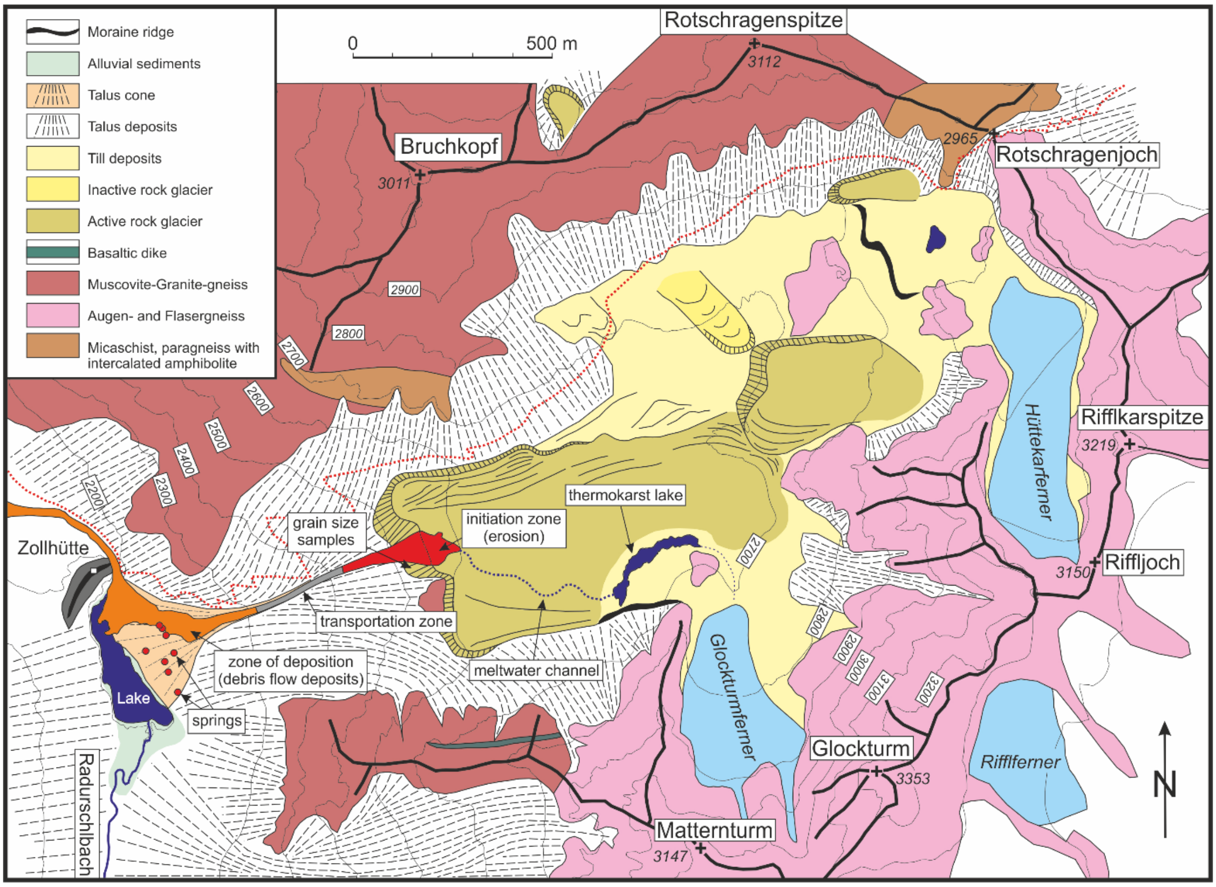

Figure 3. *Geological-geomorphological map, compiled using the most recent geological map provided by the Geological Survey of Austria (Moser, 2012). It is complemented by ortho-images and a high-resolution digital terrain model (DTM) derived from airborne laser scanning data (Government of the Province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

RC: Line 105 you refer to a considerable catchment area when the only indication given of the size of the catchment area is 2.8km^2. Can you provide additional information to clarify this point?

AR: *We suggest revising the entire paragraph (line 96–107) as outlined above (please see response to the referee comment addressing line 104 of the manuscript). With the revised paragraph, we now suggest avoiding the term "considerable" as it could be misleading here. While Hüttekar-cirque is the most prominent cirque in Upper Radurschl Valley, we acknowledge that it cannot be regarded "considerable" in a general sense.*

RC: Line 88 can you clarify what you mean by "moderate annual precipitation"?

AR: *We suggest clarifying this issue by replacing the sentence in line 88–89 as follows:*

"With respect to long-term averages across Austria, annual precipitation is moderate (1042 mm compared to 1077 mm areal average across Austria) and mean annual air temperature is low (-2.5°C compared to 6.6°C areal average across Austria), reflecting the high altitude of Hüttekar-cirque and its central position close to the main chain of the Alps."

RC: Table 1 the legend of your table shows a chronicle of data from 1976 to 2019 which is based on references from 2016 and 2018, there is a problem in your dates.

AR: *We acknowledge that our original table caption was misleading and suggest revising it as follows:*

"Long-term (1976–2019) mean monthly air temperature and precipitation in Hüttekar-cirque. Numbers are calculated based on the continuously updated SPARTACUS dataset (Spatiotemporal Reanalysis Dataset for Climate in Austria), as described in Hiebl and Frei (2016, 2018)".

RC: 2019 does seem to be a special year from a meteorological point of view, with more snow and precipitation than the previous 4 years. Since 1976, have there been similar rain and snow conditions as those that caused the disaster, i.e. have you analysed all your weather data by year with the same finesse to see if there were similar weather conditions without necessarily reaching the 2019 disaster?

AR: *We agree with Catherine Bertrand that 2019 was a special year from a meteorological point of view. Specifically, air temperature, available melting energy as well as the timing and rate of snowmelt distinguished it from the previous years, suggesting that these are the most promising weather factors for further analysis. In contrast, rainfall and ice melt volume were relatively low in 2019 compared to the previous years.*

The winter season preceding the debris flow was characterized by a prominent snow cover, almost monotonically gaining volume until 29 May 2019. Accordingly, snowmelt was restricted to June, starting at a high SWE stored in the snowpack (Fig. 7). The late onset of snowmelt is responsible for the unusually high peak on 29 May 2019 (while during the preceding years, phases of ablation and accumulation throughout spring precluded a comparable peak). Due to the exceptionally high temperatures in June, the snowmelt process proceeded under a high-energy environment, leading to very high rates of meltwater production that caused widespread flooding in Tyrol (despite the fact that June 2019 was a particularly dry month).

In contrast to the high intensity of the snowmelt process, comparing total volumes of snowmelt, ice melt and rainfall between 1 January 2019 and 13 August 2019 (failure date) to earlier years (consistently totalized from 1 January to 13 August) indicates inconspicuous overall conditions in 2019 (Fig. 7c), acknowledging that the relatively short record precludes statistically substantiated conclusions. Compared to the four years before 2019 (for which continuous SNOWGRID data are available), the total snow melt volume exceeded the 5-year-average by 19 %, while the total ice melt volume and rainfall volume were slightly below this average (-3 % and -2 %, respectively). The rapid snowmelt efficiently eliminated the snow cover in Hüttekar, so that snowmelt ceased on 22 July 2019, i.e. 22 days before the debris flow initiated. Accordingly, we infer that there is no indication for particularly high antecedent moisture conditions at the rock glacier front at the timing of the debris flow, except for the water stored in the thermokarst lake. We suggest including the results of this analysis in a new table that could be included in the Supplementary Material.

The critical issue here is the combination of (1) large amounts of snow available for melting at the beginning of June 2019 and (2) abnormally warm and dry weather conditions during June 2019, implying an extraordinary high-energy environment. The rapid meltdown of large amounts of water under high-energy conditions favored the development of a small meltwater lake on the surface of Hüttekar rock glacier. The high atmospheric energy input during June 2019 likely speeded up the development of thermal convection in this lake, bridging the thermal insulation provided by a 'dry' debris layer (air filling the pore space). Accordingly, we suppose that the convective transport of thermal energy within the lake started melting the massive ice constituting the bed of the thermokarst lake, incising the depression and promoting further accumulation of water. Once initiated, this processes allowed for the development of the large thermokarst lake that developed on Hüttekar Rock Glacier from 3 June 2019 – 13 August 2019. Thus, we propose that the crucial factors distinguishing 2019 from earlier years are the rapid and late snowmelt, the high energy environment during the summer months, and the storage of water in the lake.

We thank Catherine Bertrand for her valuable feedback and suggest addressing these issues by revising the method description (line 183–228) as well as the presentation of results (line 313–330). In addition, we suggest extending the discussion of implications in the revised 'Discussion' section, following the lines of evidence outlined above.

RC: The particle size analysis was done on 8 samples. Is this enough to cover the whole surface?

AR: *We agree with Catherine Bertrand that this is a critical issue. Since the internal structure of rock glaciers is highly heterogeneous, the 8 samples cannot be regarded representative for the entire rock glacier. To clarify this point and to restrict the analysis to the most essential features of the studied rock glacier with respect to aims of our study, we suggest cancelling the discussion of the coarse-grained surface layer and focusing on the composition of the rock glacier front, which is where the debris flow initiated. This is in line with comments provided by Anonymous Referee #1. 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 replacing line 165–172 as follows:*

"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:

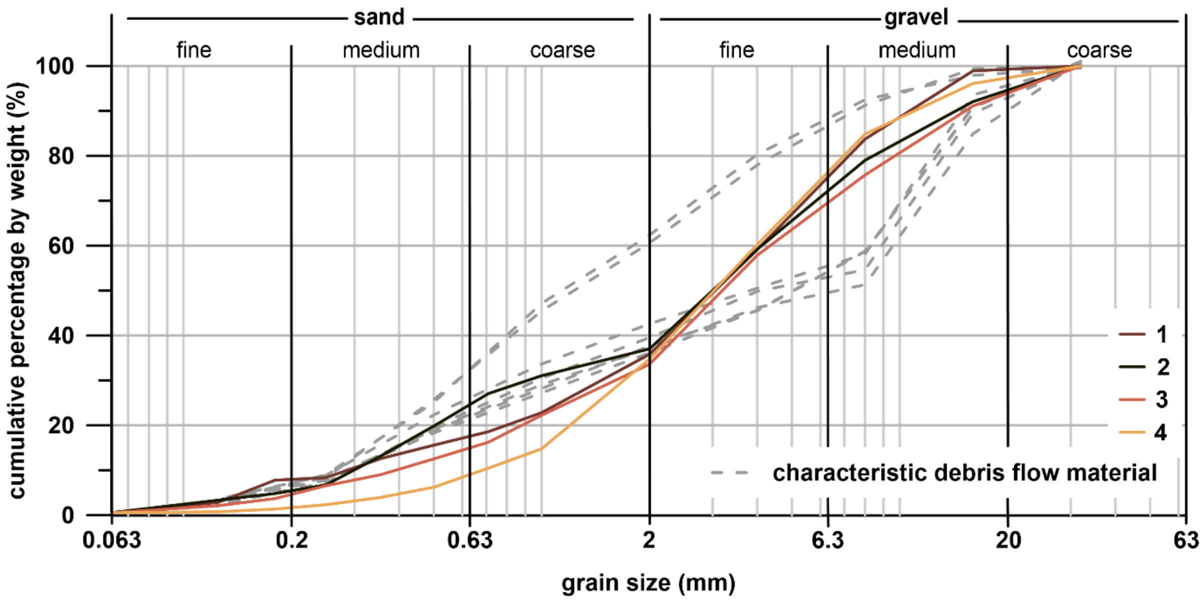

Figure 6. *Grain-size distributions of material composing the rock glacier front. The corresponding sampling locations are 50 m southwest of the debris flow initiation zone, as indicated in Fig. 3. Dashed grey lines represent source compositions of a set of experimentally investigated debris flows showing 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: The discussion is really interesting and poses the problem in the long term, especially the effect of climate change which accelerates the degradation of permafrost and favours the creation of a thermokarst and the possible consequences.

AR: *We thank Catherine Bertrand for her appreciation and her precise summary of the implications of permafrost degradation and thermokarst development in a changing mountain environment. To highlight this key result of our study more clearly, we suggest putting more emphasis on this topic in the 'Discussion' section, in turn shortening the literature review provided in the original manuscript.*

RC: Finally, the authors point out that debris flows are initiated by the destabilisation of rocky glacier fronts and most often occur in response to heavy rainfall. They also state that intense snowmelt or rain-on-snow events and exceptionally warm periods have also been identified as triggering factors. My question is, does climate change mean less snow and less rain? If so, what is the real impact of climate change on the risk? Can the authors elaborate on how they pro climate change: more snowmelt because more heat with less rain? less snow so a lower snowline and fewer glaciers? What is their scenario?

AR: *We thank Catherine Bertrand for this valuable suggestion and will include an additional paragraph in a revised version of the 'Discussion' section addressing these issues. With respect to thermokarst evolution, the key* *issue is the expected increase in available melting energy that is closely linked to rising air temperatures. Since the development of thermokarst features, such as channel networks, depends critically on the energy input, we expect the establishment of these features in areas currently characterized by continuous permafrost that generally acts as an aquitard. Our study has shown that such channel systems might develop within weeks, and subsequently are able to rapidly transfer large amounts of water. It is this rapid and hardly predictable development of thermokarst features that challenges the evaluation of slope stability under a warming mountain climate. Once established, the channel system might concentrate water at points of converging channels regardless of the details of the triggering mechanism.*

RC: In conclusion, this article sheds important light on the risks involved weather conditions. The proposed retrospective analysis is interesting and deserves to be published in your journal.

AR: *We thank Catherine Bertrand for her valuable and constructive feedback and would welcome the opportunity to address the issues outlined above in a revised version of the manuscript.*