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# *Interactive comment on* "Enhanced rockwall retreat and modified rockfall magnitudes/frequencies in deglaciating cirques from a 6-year LiDAR monitoring" *by* Ingo Hartmeyer et al.

**Ingo Hartmeyer et al.**

ingo.hartmeyer@georesearch.ac.at

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Dear Arjun Heimsath,

thank you for your constructive and insightful comments which we feel helped to improve the manuscript.

We (i) uploaded a revised version of the manuscript (changes highlighted), (ii) posted a new author's comment to inform on minor general amendments in the manuscript, and (iii) below provide a point-by-point response to all your comments. Our response

is structured as follows: (1) referee comment, (2) author's response and (3) changes in manuscript text.

(1) Firstly, this is a study compiling 6 years' worth of repeat LIDAR scans of the same glacial features. This needs to be explicitly addressed and acknowledged in the discussion of results as well as in the introduction. (2) Has now been made more explicit in (i) introduction, (ii) results, and (iii) discussion sections.

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(1) In the introduction, I suggest including a section distinguishing between long term average studies (e.g. ones that use cosmogenic nuclides in one way or another like Greg Stock's extensive work in Yosemite or the approach of Heimsath and McGlynn (Geomorphology, 2008)) and the shorter time scale ones that are reporting results from monitoring studies such as this one (note that the Alaska paper of O'Farrell, Heimsath et al. (ESPL 07) had a short section of converting scree deposit to rock retreat rates as an example of short term studies). (2) We included a section distinguishing between short- and long-term studies to the introduction and integrated both suggested references (O'Farrell et al., 2009; Heimsath and McGlynn, 2008). We also included a table to the discussion (Table 1) that provides the time scale of the listed investigations. (3) The text now reads: Cirque wall retreat rates have been quantified using a variety of different approaches including long-term averages based on sediment deposits (e.g. Larsen and Mangerud, 1981), cosmogenic dating (e.g. Heimsath and McGlynn, 2008), and cirque allometry (e.g. Evans et al., 2006) as well as short-term monitoring studies based on lacustrine deposits (e.g. Hicks et al., 1990), supraglacial scree (e.g. O'Farrell et al. 2009), and terrestrial LiDAR (e.g. Kenner et al., 2011).

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(1) In the discussion section, it would be helpful to have a more thorough examination of the inferred frequency magnitude curves given limits in the data. Extensive examples from the hydrological sciences address the time scale issue and perhaps some can be

used as template for framing this discussion (apologies, while I remember reading such papers I don't remember who they were by – I was better versed in this literature years ago). (2) We added a new paragraph to the discussion (Sect. 5.2) that addresses time scale issues and limits of the frequency-magnitude concept. Utilizing a bootstrapping simulation we further constrained the robustness of the sensitivity analysis inferred from the magnitude-frequency distribution. (3) The text now reads: Large rockfalls are rare in the observational record, yet they are of significant relevance for the shaping of alpine landscapes (Guthrie and Evans, 2007). How observations made over a few months or years relate to landscape evolution over millennia or longer (Paine, 1985) still remains elusive. The straight mathematical extrapolation (Sect. 4.4) indicates that rockfalls $\geq$ 10,000 m$^3$ ($\geq$ 100,000 m$^3$) recur on multi-decadal (centennial) time scales. Data from short observation periods however, can only provide a partial explanation of episodic process dynamics (Crozier, 1999). Furthermore, event frequency estimates based on short records assume long-term stationary systems (e.g. Klemeš, 1993) – an assumption that is particularly unrealistic given the severity of recent climate change. Similar to hydrological systems, estimating the event probability for rare, large events outside the observed frequency-magnitude spectrum introduces significant time scale issues (Blöschl and Sivapalan, 1995) and should be considered with caution also in slope systems. Due to the episodic dynamics of rockfall processes, sensitivity estimations of observed magnitude-frequency distributions such as performed in the present study (Sect. 4.4) are of high relevance. Repeated random removal of one fifth of the events (bootstrapping simulation) as well as the targeted removal of large events (> 100 m$^3$) did not significantly alter the resulting power law exponents and thus confirms the validity of the differences observed between proximal and distal areas.

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(1) Second, I think a conceptual sketch/model to accompany Figure 2 would help a lot for visualizing how the authors tackle this problem. I found Figure 2 almost incomprehensible and if it had a sketch accompanying it that showed how measurements

made in this study resulted in the inference of a retreat rate that would be great. (2) We adapted Figure 2 and hope that in combination with the additional section (Sect. 3.3) on the calculation of rockwall retreat rates the reader now gets a better understanding of the geological structure and rockwall retreat rates inferred.

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(1) To this end, there really needs to be a better explanation of how these data are used to infer headwall retreat rates. Which areas were used and how exactly were the calculations done? What's the uncertainty on those calculations and what are the assumptions and simplifications? All of these questions could be illustrated in some way in a good conceptual model. (2) We added a new subchapter (Sect. 3.3) to describe the calculation of rockwall retreat rates (and modified Fig. 2). We also added the uncertainty of the retreat rates to the text and the figure in Sect. 4.2 (Figure 5 now contains error bars). (3) The text now reads: 3.3 Rockwall Retreat Rate Calculation First, the total rockfall volume registered was divided by the number of observation years to obtain mean annual volume (m$^3$). Second, the volume was divided by the surface area of the investigated rockwall (m$^2$) to derive the (slope-perpendicular) rockwall retreat rate. Rockwall surface area calculations were carried out in CloudCompare: point clouds of rockwalls were first subsampled (thinned) to a homogenous point density of 0.5 m-1 in order to prevent a potential bias due to variable resolution within point clouds. The subsampled point cloud was then used to generate a mesh based on a Delaunay triangulation (maximum edge length 4 m), which served as basis for the surface area calculation.

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(1) Similarly, I think there needs to be better justification for the log binning approach. Given the short methods sentence addressing this I have no way to evaluate how good it is and whether it is justified. Does it introduce some bias? Convince me better that it does not with more analyses. The key question is whether it would make the report-

ing of results based on percentage of total rockfall volume quite different depending on how the sizes were binned? (2) We added a paragraph to justify the log binning approach. (3) The text now reads: Magnitude-frequency distributions of rockfalls often follow a power law function (as is also the case here, see Sect. 4.4). To classify rockfall volumes, the recorded events were grouped into bins of logarithmically increasing size to balance against strongly uneven event volumes (Fig. 3). This follows the volumetric classification introduced by Whalley (1974, 1984) (debris falls < 10 $m^3$; boulder falls 10-102 m3; block falls 102-104 m3), which is commonly used in science and engineering (e.g. Brunetti et al., 2009; Krautblatter et al., 2012; Sellmeier, 2015).

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(1) Finally, the distinctions between this paper and its companion paper could be made more clearly. (2) To highlight the distinctions of the companion papers we (i) expanded the abstract, (ii) summarized the key findings of the companion paper in the introduction (Sect. 1), and (iii) modified the conclusions (Sect. 6). (3) The summary given in the introduction reads as follows: This paper is closely linked to a companion paper (Hartmeyer et al., 2020) which identified significant glacial thinning (0.5 m a-1) adjacent to the monitored rockwalls and found elevated rockfall activity in the freshly deglaciated terrain. 60 % of the rockfall volume detached from less than ten vertical meters above the glacier surface. High rates 10-20 m above the glacier indicate enhanced rockfall activity over tens of years following deglaciation. Rockfall preconditioning could start inside the Randkluft (gap between cirque wall and glacier) where sustained freezing and ample supply of liquid water likely cause enhanced physical weathering and high plucking stresses. As the glacier is wasting down strong temperature variations are assumed to induce pronounced thermal stress, cause rock fatigue and lead to the first-time formation of a deep active layer, which is expected to exert a significant destabilizing effect on glacier-proximal areas.

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