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Reply on RC2

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Community comment on "Multi-method monitoring of rockfall activity along the classic route up Mont Blanc (4809 m a.s.l.) to encourage adaptation by mountaineers" by Jacques Mourey et al., Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2021-128-CC2, 2021

First of all, thank you for the two thorough reviews. They made us really think about what were the main objectives and novelties of our study.

There are on average 35 fatal accidents per year in summer mountaineering in France (Soulé et al. 2014). On average, 3.7 of those fatal accidents have occurred every summer in the Grand couloir du Goûter since 1990 (Mourey et al. 2018), hence its reputation in the media as the "couloir of death". Rockfalls directly explain at least 29% of the accidents and are partly involved in the accidents due to a fall, which account for 50% of the accidents (Mourey et al. 2018). Rockfalls are therefore one of the main factors that explain this high accident rate and contribute in making it one of the most accident-prone area in the Alps for mountaineers.

It is this particular context that motivated our study with the objective of **acquiring knowledge on rockfalls and their triggering factors in the Grand couloir du Goûter that would be of interest to mountaineers and help them adapt to the local risk of rockfalls.** This would potentially reduce the number of accidents in this sector.

Regarding this motivation, we provided one of the few continuous databases on rockfall activity in permafrost conditions with day and night and weather independent conditions thanks to the deployment of a seismic array. To our knowledge, only Guillemot et al., 2020, GJI, provided such database (which is not analyzed in terms of triggers), and other previous rockfall databases were either continuous but focusing on local unglaciated mountain areas (Helmstetter and Garambois, 2010; Dietze et al. 2017a, 2017b, 2020; Hibert et al. 2011, 2017, Durand et al. 2018; DeRoin, N., and McNutt, S. R., 2012) or at regional scales (Dussauge et al. 2003; Dammeier et al. 2011; Manconi et al. 2016; Hibert et al. 2019), or on discontinuous monitoring of rockfalls at high elevation thanks to sensors other than seismic (TLS for example). This database allowed us to investigate the daily and sub-daily scale of rockfall triggering, thanks also to the complementary monitoring of other parameters (precipitations, ground and air temperatures, frequentation, snow cover). This new data provides complementary observations to seasonal, annual, or decadal observations usually investigated (Gruber and Haeberli, 2007; Krautblatter and Moser, 2009; Ravanel and Deline, 2010; Allen and Huggel, 2013; Draebing et al. 2014). We therefore show the effect of temperature and snow melt at this time-scale, as well as anomalous peaks of rockfall activity, that correlate with high human frequentation. Although the effect of temperature at the hourly scales are well known by mountaineers, the phenomenon has never been quantified.

Also, our data on the mountaineers traffic on Mont Blanc route show that climbers are not aware of the variations in rockfall frequency and/or that they cannot/won't adapt their behavior to this hazard. Therefore, the cross-comparison of data on rockfalls and climbers traffic in the couloir provide a second novel findings regarding the behaviour of mountaineers facing rockfall danger. This justifies all the more the importance of acquiring knowledge on rockfalls and their triggering factors in the local context of the Grand couloir du Goûter and to disseminate it to the mountaineers to encourage their adaptation. This comparison also allowed us to identify the type of knowledge needed by climbers to adapt in the most efficient way. This interdisciplinary analysis between rockfall hazard and mountaineers behaviour is also quite new.

The two reviewers point out that our work is a case-study, and wonder how it can be generalized. We fully agree with this case-study comment. We however oppose to this argument the exceptional site studied here with a very high accidents rate which, to our point of view, justify by itself focusing on this specific case-study with a strong operational objective. Furthermore, in a context where several international scientific entities (IPCC, MRI, WMO) clearly identify a profound lack of knowledge on the vulnerability to climate change of socio-economic activities in mountains and a lack of medium- and long-term efficiency of adaptation strategies in glaciated mountain areas (McDowell et al. 2019), our study is a relevant example of operational research that promotes adaptation measures. We agree with the referees that this motivation was not sufficiently put forward. In a new version of the article we propose to emphasize this point by completely reformulating the introduction, discussion and conclusion (see specific comments below).

In particular, we also propose to limit the parts where our results confirm previous studies on the effects of snowmelt and permafrost degradation at the seasonal scale but to emphasize the value of our data in identifying hourly triggering factors and discussing the effects of thermal processes as triggering factors.

Finally as raised out by the two reviewers, we will clarify all the method sections, for instance by adding figures to explain the classification of the seismic data.

Specific answer to referee 2:

(1) In accordance with all the modifications planned in this revised manuscript, and in order to focus more on the research objective we propose the following title : Multimethods monitoring of rockfall activity on the classic route up Mont Blanc to promote the adaptation of mountaineers.

Concerning the interdisciplinarity of this work, Darbelley F. 2014. Rethinking inter-and transdisciplinarity:undisciplined knowledge and the emergence of a new thought style. Futures 65, 163-174. DOI:10.1016/j.futures.2014.10.009, define interdisciplinarity as follows: "Interdisciplinarity: this brings into play two or more established disciplines so that they interact dynamically to allow the complexity of a given object of study to be described, analyzed and understood". As we use measurement methods, concepts and analysis methods from several disciplines (human geography, seismology, remote sensing, geomorphology) and we cross the results from each method to answer the same research question, we consider our work as interdisciplinary.

(2) In reaction to the second comment, we will completely rework the introduction and the discussion of the article to show the interest and the new findings of our study. We conducted this study because the Goûter couloir sector is very popular for mountaineers and has a particularly high accident rate. We have shown in a previous study (Mourey*et*

al. 2018) that rockfall appears to be one of the main factors explaining accidents (see comment below for more details on how we established the link between rockfall and accidents). Our prime objective was therefore not to gain new knowledge about the factors triggering rockfalls in high alpine mountains. Our objective was to document rockfalls and their triggering factors specifically in the Goûter couloir, in order to help mountaineers adapt to rockfall hazard in this particularly accident-prone sector. Despite this site-specific study, we also show that the observations we provided follow classical patterns of rockfall triggering at the seasonal scale in permafrost areas. This shows that the results obtained on our site of study - in particular the novel hourly and daily time scales of triggering - can be representative of other areas. We will therefore completely revise the organization of the article to justify this objective and show how we have achieved it. We will integrate section 2 (Rockfall Triggering Factors) into the introduction and better connect it to our objectives and the method used. In the discussion, we will reduce the section in which we explain that our work confirms the results of previous studies at the seasonal scale (although this is an interesting result in itself). Instead, we will emphasize our results at the daily scale. Databases on rock destabilization in high alpine mountains at such a fine scale are rare and our results bring interesting elements on the factors of rock fall triggering at the daily scale. Indeed, if the triggering of rockfalls in high mountains is often associated with permafrost degradation (multiannual scale) and freeze-thaw cycles (daily and seasonal scale), our results suggest that temperature variations and thermal stress is an important triggering factors at the hourly scale in the grand couloir du Goûter.

In order to meet the main objective of this study, which is to promote the adaptation of mountaineers to the risk of rockfall, specifically for the Goûter couloir, we will also add two sections in the discussion on the "Interest of the acquired knowledge for mountaineers" and "Dissemination of the acquired knowledge to the mountain community and implementation of management measures of the route".

(3) We will significantly shorten section 2 and integrate it to the introduction in order to justify the methods we used. We will be more precise in the description of preparing and preconditioning factors in the description of the site. We will among other things precise that the topographical and geological characteristics of the Grand Couloir du Goûter are particularly favourable to the triggering of rockfalls and due to the fracturing of the rock in the area and previous rockfalls in the couloir, many rocks/blocks are mobilizable as secondary rockfalls. We will also note that the couloir is in the altitudinal range where permafrost is degrading, which has been identified as the one where rock collapses related to permafrost degradation occur the most (Ravanel et al. 2017).

(4) We will remove the section 3.1 and keep only one section in which we describe the study site and better describe the site, how mountaineers are organising their ascent and when they have to cross the Grand couloir du Goûter.

(5) We explained in the introduction, based on a previous study (Mourey et al., 2018), that 29% of the accidents are due to a rockfall, and that rockfalls are also involved in parts of the 50% of accidents due to a climber fall. Rockfalls are therefore one of the main factors that explain this high accident rate. The identification of the cause of the accidents was based on the analysis of the reports that rescuers drafted after each accident one by one. This method is well described in the mentioned study: Mourey et al. 2018. We will make a specific attention to clarify this point in the future introduction and site-study sections.

(6) We will follow this later proposition to better justify our study in the new introduction. We engaged with this new case study because it is an area with a high accident rate and rockfalls are one of the main factors of this accidentology. Despite this accidentology, almost no studies have been undertaken to document this hazard.

(7) Thanks for these comments also pointed out by reviewer 1. This shows that our methods section lacks sufficient explanations that we will provide in our revised manuscript (See also our answer to the referee 1 to the similar question). We will add the clarifications required including a new figure to better explain the classification. In addition we will provide the keys to understand the rockfall localization methods, which is well described in Lacroix and Helmstetter (2011), but some parameters were indeed slightly adapted to this case-study.

(8) The seismic energy is defined by integrating the seismic envelope over the signal duration. We will define it in the text. Therefore it is not a rockfall energy but the seismic energy recorded by the array. This can then be transformed onto a volume, as LeRoy or Hibert do, but requires calibration that we don't have. It would also require to better take into account the effect of the snow cover on the impact attenuation, which is not possible without calibration data in hard/soft snow conditions and bare rock conditions. So this step is a study by itself. Therefore we are not dealing with volumes and just keep the analysis of the seismic energy recorded. As we explained, this seismic energy reflects on the first order the variation of the rockfall volumes in similar snow conditions, as all the sources are coming from the same area. We will pay attention in the revised manuscript to clarify this aspect.

We will also remove the CRYOGRID model. Following the restructuring of the manuscript it is not needed. We only used the CRYOGRID model to show that the active layer is the deepest at the end of the summer season, which has already been shown by other studies (Magnin et al. 2017 ; Pogliottio et al. 2015). Moreover, it limits the number of time series and clarifies the manuscript.

(9) The three periods in the discussion were defined according to the variations in rockfall frequencies at the seasonal scale. Designating groups from continuous data allows us to clarify the discussion and easily designate a period of the season. We feel it makes the flow of the discussion easier. In the revised manuscript, we will better explain how and why we designed our 3 seasonal periods.

(10) We propose to shorten the discussion on the triggering factors related to snowmelt and permafrost degradation for which we effectively confirm previous studies. The fact that our results are in agreement with these studies is, however, a result in itself and gives even more credibility to our results. On the other hand, we propose to add details on the interest of our results to better evaluate the effects of daily temperature variations and thermal stress on the triggering of rock falls. It seems to us that this is a point in which our data provide interesting and innovative results on the triggering of rockfalls in high alpine mountains.

Finally, as we have already stated, in order to make the link with the first objective of our study (the acquisition of knowledge to favour the adaptation of mountaineers to the local risk of rock falls) we will add two sections on the "Interest of the acquired knowledge for mountaineers" and "Dissemination of the acquired knowledge to the mountain community and implementation of management measures of the route". The conclusion will also be rewritten.

We do not claim that our data "allow to claim that climbers trigger rockfalls". We explain that according to our fields observations some rockfalls are triggered by the climbers themselves and it is possible that 2 anomalies in the daily distribution of rockfalls may be due to anthropogenic triggers. On days when rockfalls are least frequent we can estimate that the "natural" triggers are the least effective and the rockfalls triggered by mountaineers can be highlighted. Therefore we can support the assumption that mountaineers are triggering rockfalls with the example of a day when rockfalls activity is very limited but strictly coincides with the frequentation.

The section "Climate change and future projections" is indeed not directly linked to the acquired data. However, it seems important to us to specify that the situation in the future will probably not improve, which justifies all the more a better consideration of the rockfall hazard by mountaineers. We will clarify this point and move the section "Climate change and future projections" after the section on "implementation of management measure of the route".

(11) In order to improve the quality of the writing we will have the manuscript corrected by a native english speaker. Referee 1 also sended a document with several suggestions to improve the texte that we will take into account.