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## Reply on RC1

Fumitoshi Imaizumi et al.

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Author comment on "Temporal changes in the debris flow threshold under the effects of ground freezing and sediment storage on Mt. Fuji" by Fumitoshi Imaizumi et al., Earth Surf. Dynam. Discuss., <https://doi.org/10.5194/esurf-2021-41-AC1>, 2021

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We sincerely thank you for the efforts you have made to review our manuscript. Comments from the reviewer are very helpful for us to improve our manuscript. We have responded to all review comments in the following paragraphs.

[Comment] The manuscript (MS) deals with the role of (a) ground freezing and (b) sediment storage in debris-flow triggering and how rainfall thresholds are affected. Relatively long records (~50 years) of debris-flow observations in a Japanese gully are combined with ground-freezing periods estimated from a model, and sediment storage volumes estimated from LiDAR measurements or aerial photographs. While the role of sediment storage was less revealing, the authors found ground freezing to alter rainfall thresholds significantly and explain it with different infiltration rates depending on if the ground is frozen or unfrozen. The MS discusses an important topic with possible impacts both on the development of early warning systems and climate change impact assessments in cold debris-flow prone regions.

[Reply] It is our great pleasure that the reviewer is interested in our study.

[Comment] The MS is generally well written and structured. The data sets provide a good basis for the research on the influence of climate on debris-flow activity. The author's approach in estimating ground-freezing periods and connecting it to debris-flow triggering is original and promising. However, the analysis and discussion on other potential reasons for differences in rainfall thresholds are missing and therefore I had difficulties in believing the findings. The main reasons concern the following:

Seasonality in rainfall. I assume that the frozen periods mainly fall in spring and autumn. Are rainfall event characteristics also different in these seasons compared to summer? You could either estimate rainfall thresholds for your data split into seasons. They may look similar as the ones you already obtained and then you could argue that you obtain the same thresholds when splitting into frozen and unfrozen. Another way would be to show histograms of rainfall characteristics (e.g. mean intensity) for frozen and unfrozen periods. If they look similar, you know that the shift in rainfall threshold is not

introduced by seasonal characteristics.

[Reply] As the reviewer points out, rainfall characteristics are different between frozen and unfrozen seasons. As shown in Fig. 7e and 7f, total rainfall and rainfall intensity in frozen periods are higher than those in unfrozen periods. However, in unfrozen periods, there are so many rainfall events exceeding rainfall thresholds in frozen periods without occurrence of debris flows (Fig. 7, 8). Therefore, rainfall threshold is clearly different between frozen and unfrozen periods (Figs. 7, 8). Based on the suggestion by the reviewer, we will add a figure which shows seasonal characteristics of rainfall events.

[Comment] Antecedent rain/wetness and snowmelt. Another reason for lower ID thresholds could be the antecedent conditions. Antecedent rainfall and snowmelt are probably the most important control. Analysing antecedent rainfall can be done from your data. Are there snow depth measurements to constrain the melting season?

[Reply] Unfortunately, there is no snow depth measurement around the initiation zone of debris flow. However, diurnal changes in the ground surface temperature (Fig. 4) indicates that snow is not deep even in the mid-winter. Although we have mentioned it in the discussion (line 352), we will add statements about snow in the result section. We also add an analysis on the antecedent rainfall.

[Comment] Uncertainties. They can be quite large, especially if based on only a few points. With CSI you have an objective measure to estimate ID-thresholds, which is good. However, when you calculate ID-thresholds with different data (frozen & unfrozen), the significance of these differences is unclear. Because some of these thresholds were estimated based on few triggering events, the thresholds can be very sensitive to individual data points. Ideally, you would assess uncertainties e.g. with bootstrapping. However, I realize that such an analysis is not useful for e.g. Fig 9c, where you have quite a few points. Hence, it would be useful to show uncertainties at least where there are e.g. >10 triggering events.

[Reply] We agree that uncertainties can be large, especially in the analysis with few debris flow events. We will try to evaluate uncertainties using statistical methods such as the bootstrapping. As the reviewer points out, it may be difficult to evaluate uncertainties of analysis with a few debris flow events by statistical methods (e.g., bootstrapping).

[Comment] These points would need to be clarified in order to convincingly show the relevance of ground freezing on debris-flow triggering. Then I see it as a very valuable contribution to Esurf. Furthermore, there were some unclarities in the methods and the data sets used. Further comments related to this and other minor issues are listed below.

#### Specific comments

41: I think you mention wildfires as an example for the sensitivity of hydrological parameters (e.g. infiltration rate) but the connection is not clear when reading. If wildfires are not relevant for cold regions, which you focus on, I would focus on the hydrological properties of cold regions.

[Reply] Wildfire itself is not important in cold regions. However, relationship between infiltration rate and occurrence of debris flows has been discussed mainly in wildfire studies. We will revise the sentence to emphasize relationship between infiltration rate and occurrence of debris flows. We also add citations on the hydrological processes in cold regions.

[Comment] 40-48: Is the hydraulic conductivity the main difference from frozen to unfrozen periods? What is the role of water storage capacity?

[Reply] As the reviewer points out, changes in the maximum water capacity, which decreases by the formation of ice in sediment matrix, is a potential factor affecting occurrence of debris flow. If water capacity affects the rainfall threshold, rainfall threshold in winter, when frozen depth is shallow (e.g., <1.0 m), would be higher than that in spring, when frozen ground is thick (e.g., >1.0 m, Fig. 5). We hope effect of water capacity can be discussed by analyzing seasonal changes in the rainfall threshold.

[Comment] 58: What process drives sediment production?

[Reply] Rockfall, failure of basaltic lava, rockfall, dry ravel, soil creep are important sediment supply processes. We will note types of sediment supply process.

[Comment] 86: 2737 mm y-1

[Reply] We will revise based on the suggestion.

[Comment] 132: please specify, within 1 calendar day or within 24 hours?

[Reply] One calendar day. We will specify.

[Comment] 137: Could you add a marker in the figure to show JMA station?

[Reply] It is hard to mark JMA summit station, because it is just at the summit of the Mt. Fuji (triangle in Fig. 1a). We will specify location of JMA station in the text.

[Comment] 141: TM (Fig. 1d)

[Reply] We will add "Fig. 1d" after TM.

[Comment] 143: It is not ideal to match air with ground surface temperature. Could you please state how this affects your extrapolated temperature?

[Reply] Amplitude of diurnal changes in the ground surface temperature is generally

higher than that of air temperature. Although we use daily average temperature in the estimation of downward progress of freezing and thawing fronts, difference between air temperature and ground surface temperature potentially affects our results. We will add explanation on that.

[Comment] 143: Please explicitly state which model you are using and add some description regarding the main assumptions, required input, output, why was it developed or for what is it usually used? For which spatial and temporal scales is it usually used?

[Reply] We used linear ordinary least squares regression. Assumption in the model is that the errors in the regression should have conditional mean zero. Input and output are the daily average temperature at JMA summit station and the daily average ground surface temperature at TM, respectively. The daily average ground surface temperature was used to estimate downward progress of the freezing and thawing fronts. Spatial scale would highly depend on spatial non-uniformity of the ground surface temperature affected by local topography. We will add explanations related to this comment.

[Comment] 149: Eq 1 & 2, please add the independent variable to the equation (e.g.  $T(t)$ ) and units. Now it is difficult to distinguish between variables and parameters. Do  $c_f$  and  $c_m$  vary with time? Although you cite the equations, it would be helpful if you would state the assumptions behind it. Is this the degree-day method you mention before? The meaning of  $c_f$  and  $c_m$  are not clear to me.

[Reply] Eqs. 1 and 2 are the degree-day method. This is coming from an approximate solution of unsteady heat conduction equation.  $c_f$  and  $c_m$ , which are derived from thermal conduction, moisture content ratio, heat of fusion and other parameters, are constant. This method assumes that sediment characteristics and moisture content ratio are spatially and temporally constant. We will explain these assumptions. We also add the independent variable as suggested by the reviewer.

[Comment] 177: Caine (1980) was the first to use ID thresholds to my knowledge, so I would add the reference. You should also have "rainfall" somewhere in this sentence.

[Reply] We will cite Caine(1980) in the sentence. We also add the term "rainfall" in the sentence.

[Comment] 183: How do you know if there was snow or not?

[Reply] We do not have data on the absence and presence of snow cover. This sentence explains general determination of slush avalanche and debris flow. We will clarify what we mean.

[Comment] 187: I don't understand the reasoning for choosing 24 hours. First, I don't think the gully is much larger than other debris-flow prone gullies, or if so, please provide a comparison. Second, is it clear that water has to be concentrated from a large area from the headwaters, are debris flows triggered by runoff in this site? The chosen time period is

not irrelevant because it affects the number of non-triggering rainfall events, thus also the CSI and thus the rainfall threshold.

[Reply] Drainage area of the Osawa creek at the apex of alluvial fan is 11 km<sup>2</sup>, larger than Chalk cliff (USA), Gatria (Italy), Kamikamihori, Ohya (Japan), Rebaixader (Spain) and other torrents. Although drainage area of Illgraben is similar to Osawa-creek as a whole, initiation zones of debris flow in Illgraben, which are dispersed in multiple sub-basins, are smaller than that is Osawa failure (about 1 km<sup>2</sup>). Therefore, scale of hydrological processes in Osawa creek is likely larger than other debris-flow prone torrents. However, we do not have data which support adequacy of the 24 hours. We will try some other time period separating different rainfall events (e.g., 6 h ,12 h).

[Comment] 194: 5 x 10 m or 5 x 5 m?

[Reply] As we described, 10 × 10 m or 5 × 10 m is correct.

[Comment] 202: Looking at Figure 1 I have some troubles imagining the channel deposit dropping to zero. How is the justified? Is it really zero and the bedrock with outcropping bedrock or is it just the lowest value?

[Reply] Geology in Osawa failure is alternation of basaltic lava and scoria. In the section with basaltic lava, we can find exposure of bedrock in channel. However, it is sometimes difficult to distinguish channel deposit from scoria layer. Our analysis is based on the lowest elevation value. We will clarify that.

[Comment]209: What are the expected consequences of these inherent errors?

[Reply] This may affect misclassification of channel deposits in the period with aerial photograph survey, especially in the period from 1993 to 1997 when volume of the channel deposits was just around the threshold of volume classes. We will note potential effects by these inherent errors.

[Comment] 210: Please explain why you decided to determine two thresholds. Are there indications for that with <350'000 m<sup>3</sup> supply is the limiting factor?

[Reply] The boundary of the two classes was set to 350,000 m<sup>3</sup> to ensure that a statistically sufficient number of debris flow events could be allocated to both volume classes. Hence, this value does not have any physical meaning relevant to occurrence of debris flow. There is a possibility that rainfall threshold does not change exponentially at a specific volume of channel deposits. Therefore, it would be better to classify into many volume classes. However, it was not possible to conduct such analysis because insufficient number of debris-flow events, especially in unfrozen periods. This is limitation in our study. We will add explanation on this point in the text.

[Comment] 215: Table 1, could you add the dates of the aerial photographs here? It is not easy to follow in the text when which data was obtained. I think the text does not refer to the table.

[Reply] As suggested by the reviewer, we will add information of the aerial photograph in the table.

[Comment] 230: Figure 3. Could you add markers to dates with photograph/Lidar observations?

[Reply] We will add markers of the date with measurements.

[Comment] 249: Could you please add markers for debris flows/slush avalanches?

[Reply] Just two debris flows were occurred in this period (March 5, 2018 and May 21, 2019). We will add markers.

[Comment] 258: How did you calibrate? What measure did you optimize? I can't judge your model performance from this section, only visually from Fig. 5.

[Reply] We selected  $c_f$  that minimizes errors in estimation of downward progress of freezing line in the depths between 0.25 to 1.25 m.  $c_{\square}$  was calibrated based on the melting timing at a depth of 1.25 m. We will clarify calibration methods.

[Comment] 264: If it is a physical parameter, I guess it should have some unit, right?

[Reply] Unit of  $c_f$  and  $c_{\square}$  are  $\text{m } ^{\circ}\text{C}^{-1/2} \text{ d}^{-1/2}$ . We will add unit.

[Comment] 268 – L. 280: Unfortunately, I don't see how this section fits into the story. Why do you only show one example of channel change? What happened to the other Lidars? How can you generalize from this figure that all debris flows sourced from channel deposits?

[Reply] Total 68 debris flow initiation points were detected by the analysis of airborne LiDAR data in the period from 2008 to 2017. Hence, a large space for topographical and statistical analyses is needed to generalize findings in this section. Although it is worthwhile to deepen topographic analysis, we are afraid that aim of this paper will be obscured by adding such analyses. Furthermore, as the reviewer comments, this section is not closely related to the main topic of the paper. Therefore, we will remove this section from revised manuscript.

[Comment] 283-387: These two result sections are very clear (with reservations mentioned in the general comments).

[Reply] Thank you so much for your comment.

[Comment] 349: If you say what was not considered, please also mention what your model considers.

[Reply] Our model considers ground surface temperature. We will revise the sentence.

[Comment] 354: This is true for the ridge, but aren't wind and incoming solar radiation conditions different in the creek? Can you say something about the distribution of snow within the creek?

[Reply] As the reviewer points out, snow depth at the bottom of gully is deeper than that at ridge and side slopes of the gully. Unfortunately, we do not have data showing spatial distribution of snow in the creek. We think ground freezing and snow condition on the side slopes of gully is more important than in the bottom of gully because of their large areas. We will add a discussion on the distribution of snow depth.

[Comment] 356: What is your definition of "significantly different"?

[Reply] We will revise the sentence based on the uncertainty of the threshold, which will be evaluated based on the previous comment from the reviewer.

[Comment] 377: Figure 10. In the light blue frozen layer, are the pores filled with ice? Nice schematic!

[Reply] Light blue layer indicates frozen ground. However, we cannot make sure if the pores are completely filled with ice or not.

[Comment] 394: why is this ratio controlling the movement?

[Reply] It is because the ratio controls balance between shear stress and shear strength of cohesionless sediment (Imaizumi et al., 2016; 2017). We will clarify.

[Comment] 431: I think a detailed explanation is required for why the underlying data is not publicly available

[Reply] We will add explanation in "Data availability". Because this is a study commissioned by Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan, the ground temperature data are available from the corresponding author, Fumitoshi Imaizumi, upon reasonable request and agreement by MLIT. Rainfall and topographic data are available upon agreement by MLIT, which has copyright of the data.

[Comment] Figures 1 & 6 are missing coordinates

[Reply] We will add coordinates.

Thank you again for reviewing our manuscript.