Response to Reviewer #3's comment on "Detrainment and braking of snow avalanches interacting with forests"

Louis Védrine, Xingyue Li*, and Johan Gaume
*Correspondence: xingyueli@tongji.edu.cn
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We thank Referee #3 for his or her detailed comments and valuable suggestions, which helped us to improve the quality of the paper. Our point-to-point replies to the comments of the reviewer are summarized below.

The manuscript "Detrainment and braking of snow avalanches interacting with forests" by Vedrine et. Al. is a computational study on how detailed numerical modelling approaches can contribute to investigate how gravitational mass flows interact with obstacles. The forest (obstacles) can offer a protective effect which reduces the size or frequency of avalanches by stopping the formation of avalanches or reducing the magnitude of an event. This work focuses on quantifying the mass and energy reduction capabilities of forest (detrainment and braking) in the transit zone of a small or medium sized avalanches by detrainment, which reduces the kinetic energy of the avalanche by removing mass.

The work highlights the possibility of using purely numerical methods (MPM) to quantify the potential effect of forests and parameterize the forest snow interaction within simple relationships of terrain (slope), flow (velocity) and forest parameters (density). The simulation experiments were carried out on a generic slope with a constant slope angle, examining the influence of mainly avalanche type/velocity and different forest formations/density with respect to mass/energy reduction. The parameters of the MPM avalanche model are defined by prior experiments to resemble the behavior of colder to warmer flow regimes and calibrated with regards to snow forest interactions based on a single documented field observation. The single event validation could be considered as weakness of the study. However it is known that corresponding data is sparse – but it would be interesting to comment on other the possibility of other parameter combinations that might lead to similar results, or how they would change for another observation example. Another clarification would be desirable for the definition (and numerical implementation) of detrained mass (see specific comments below) in the MPM model and how changing boundary conditions (slope angle) would influence the results.

Reply:

i) Indeed, as underlined by Stritih (2021), there are scarce empirical data on the braking effect on avalanche, especially at local scale. However, as suggested by reviewer 1, the revised manuscript have further considered the study of the stand density index (Reineke, 1933) which is a widely used parameter by practitioners. This parameter reflects a combined effect of tree diameter and forest density, the law (Eq.11 in the manuscript) can be used by substituting one of these two parameters with the stand index density.

ii) A clarification of the definition of the detrainment mass has been made in the revision.

iii) The effect of the slope angle is indeed important. The first order effect of the slope angle is on the front velocity, as shown by Li et al. (2020). In fact, the slope angle between the release zone and the forest has a direct effect on the front velocity which is quantified in equations 7 &11.

The second order effect is on the geometry of the snow wedges formed behind the trees. To study the effect of the slope angle, the one tree configuration (Fig. 1a in the manuscript) is used with the release zone very close to the tree to reduce the effect of the front velocity. In addition, to exclude the effect of the velocity on the mass stopped, the mass has been normalized with a front speed of 10m/s (Eq.7 in the manuscript). As expected, the mass stopped decreases with an increasing slope angle (Fig. R1) as with the model proposed by Feistl et al. (2014). (Eq. 8 in the manuscript). However, our results in Fig. 7 suggest that the bed friction is a key parameter on the evolution of the detrainment mass, and that the dynamic of the avalanche needs to be considered. Nevertheless, as the effect of slope angle is closely related to other factors like avalanche velocity and bed friction, it is very difficult to quantify its individual effect, and we did not propose a law with slope angle in our study.

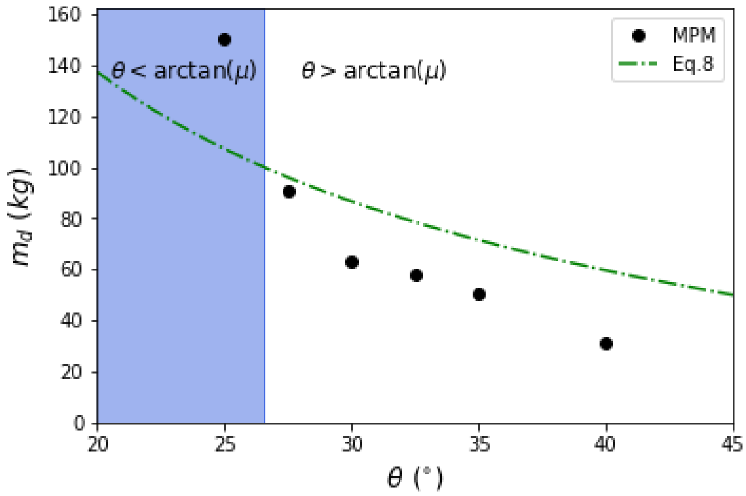

Figure R1. Evolution of the stopped mass with the slope angle for a bed friction of 0.5.

For future studies, we propose to calibrate the model for a given pair of parameters (bed friction and slope angle). Indeed, we have shown that it is possible to find a constant α, that enables us to use the law Eq.11 for different slope angles such as $M_d(\theta = 35°) = \alpha\, M_d(\theta = 30°)$. This parameter α accounts for the geometry change of the wedges. As illustrated in Fig. R2, the evolution trend of the detrainment mass with the different slope angles does not change, showing the validity of the proposed Eq. 11. For this specific case, the value of α is 1/1.7.

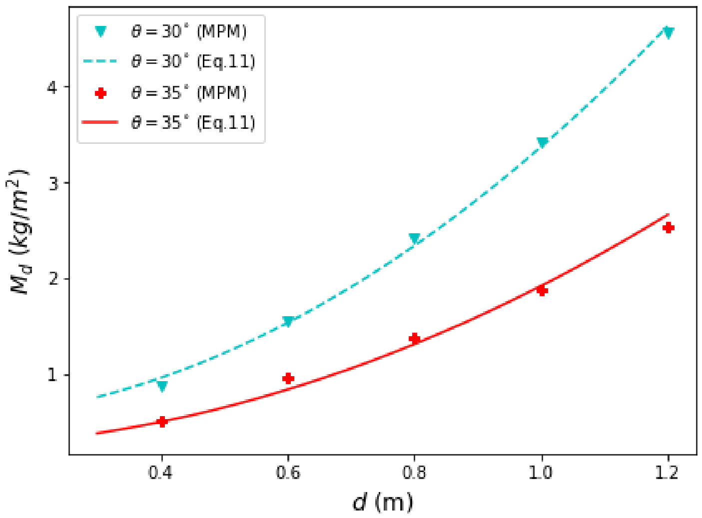

Figure R2. Evolution of the detrainment mass with the tree diameter for 2 different slope angles. For the model used in the case of a slope at 35 °, we use a geometric correction factor of $\alpha = 1/1.17$.

Generally, the manuscript is well written and well organized, providing suitable figures and supplementary material. Some possible enhancements include the figures in the energy analysis and the consistency between equations and figures (e.g. fig 5, “velocity” = “v_f” in eq. 7, more examples in the specific comments (e. g. Fig 10)).

Reply: We thank the reviewer for the helpful comments, according to which we have revised the manuscript.

Specific comments :

- l 11: “wet compared to dry snow”: Since this is a numerical study i would suggest to rephrase (or is there evidence in field observations?): “for the parametrizations of cold to warm snow”

Reply: We have rephrased the description as suggested, since there is indeed no direct field data or experimental data of all the snow properties used in this study. The snow properties in Case 2 are calibrated with the data reported by Feistl et al. (2014). Based on Case 2 and our parametric study (Li et al., 2020), we have further modified the snow friction and cohesion to get a relatively colder snow in Case 1 and warmer snow in Case 3.

In addition, we have further clarified the physical meaning of the snow properties adopted in this study as detailed in the reply to reviewer 2.

- l 36: What about the study of “Brožová, N., Fischer, J. T., Bühler, Y., Bartelt, P., & Bebi, P. (2020). Determining forest parameters for avalanche simulation using remote sensing data. Cold Regions Science and Technology, 172, 102976 (11 pp.). https://doi.org/10.1016/j.coldregions.2019.102976”. Does it relate or include relevant data to evaluate the results of this study?

Reply: This study is based on and complementary to the work of Feistl (2015) where a value of the detrainment coefficient K for different types of forest is proposed. The study by Brožová et al. (2020) assesses the quality of forest structural parameters obtained from remote sensing data using two different methods and using the value of K given by Feistl (2015). They compare the effect of the forest parameter on the avalanche flow.

This study essentially aims to make the method proposed by Feistl et al. (2014) operational by facilitating the determination of forest parameters and no new comparison with Feistl (2015) is provided in terms of the braking of forest on avalanches.

We have added discussion on the study by Brožová et al. (2020) in the revision, because the method proposed by Brožová et al. (2020) is an essential step in the process of risk prevention, for example within the framework of bayessian networks (Stritih, 2021). Indeed, remote sensing can help to identify the forest parameters used in this study, which allows a simple application, and gives access to information which was not considered in the study but would be interesting to be considered in the future such as surface roughness.

- Table 2 “Case 1..3”: I think it could be beneficial to name the cases “cold/intermediate/warm” here and throughout the paper to make it easier for the reader (and please check consistency of warm/wet and cold/dry throughout the paper).

Reply: As discussed above, since the snow parameters are not directly linked to the field observations and rather represent the mechanical properties which can correspond to a cold, intermediate or warm snow, we keep the name cases 1-2-3. This has been clarified in the revised manuscript.

- l 143, “some arches appear in case 3”: Can you comment on how “arches” (surges?) are defined in this context?

Reply: In this context, an arch is formed by stopped snow between two trees due to the jamming effect (Feislt et al., 2014). This phenomenon occurs when the size of the wedges behind the trees is so large that two wedges intersect. This phenomenon is more obvious when the snow is highly cohesive and frictional and when the spacing between the trees is small. This arch phenomenon is similar to the jamming of a granular flow in a two-dimensional hopper (Lai et al., 2001). Further clarification has been made in the revised manuscript.

- l 165 “detainment mass”: Does this mean snow is considered detrained if its velocity<0.5m/s and adds to “M_stopped” – how does it relate to (frictional) stopping – are these numerical of flow model quantities? A clarification on the definition of “M_stopped” seems to be crucial for the paper and could be included at this point, particularly the difference between “stopped” (Fig 5), “maximum” and “final” (Figs 5,6) or “stored” (Fig 7). Please also check the corresponding units [kg] or [kg/m^2] used for “M_stopped”.

Reply: We thank the reviewer for pointing out the ambiguous notations. We define the detrainment mass as the total mass of the snow particles which have a velocity smaller than 0.5 m/s during the flowing process. To be in line with the notation used by Feistl et al. (2014) we use the notation M_d for the detrainment mass in (kg/m^2) (per unit of area).

When the stopped mass of a single tree (e.g. Fig. 6) is of interest, we use the mass stopped m_d (kg) in the revision. In this case, we do not normalize the stopped mass with the area around the tree as the area is difficult to define. Please note that in Fig. 7, although there are multiple trees, it is the stopped mass by individual trees that we compare to Fig. 6, therefore, m_d (kg) is also used in Fig. 7 in the manuscript.

The mass stopped behind the trees evolves with time due to the changing shape of the wedges over time. Therefore, we study two critical quantities (Fig. 6), the maximal mass stopped which refers to the maximum mass stopped behind the tree over time, and the final mass stopped which refers to the mass stopped at the end of the simulation. We choose to plot these two quantities because the maximum mass stopped is related to the global detrainment mass over the entire forest and the final mass stopped corresponds to the mass of snow which is observed in the field measurement.

- l 192: Does maximum detrained mass refer to the maximum over time (detrained snow = v> 05m/s?, see comment above)?

Reply: Yes, please see the detailed reply above.

- l 214: Should this not be p_3 and p_4?

Reply: Revised.

- l 243: This sentence is confusing, please clarify: decreases linearly, as function of ..?

Reply: The sentence has been revised as follows.

In addition, in terms of potential energy, whereas the potential energy without forest decreases linearly as a function of time, with forest, due to the mass which stays on the slope, the potential energy decreases more slowly with time. Consequently, at the end of the simulation, the potential energy does not vanish due to the detrainment mass.

- l 281: Is the statement that the random distribution has a higher protective effect valid after checking one specific distribution?

Reply: Thanks for the comment. To validate the result obtained on the small slope (Fig. 13 in the manuscript), we carried out the energy study on a larger scale with another random forest as shown in Fig. R3, with a forest length of 160 m instead of the original 40 m. We observe a stopped mass of 7735 kg and 20540 kg for respectively the staggered and the random arrangement, a similar dissipation for the two cases and a slightly higher detrainment energy for the regular arrangement (Table R1). These conclusions are in agreement with those obtained from the original study at a smaller scale, the detrainment energy is similar between the two arrangements, but the mass stopped, and the runout-distance (Fig. R3) suggest that the random arrangement has a higher protective effect.

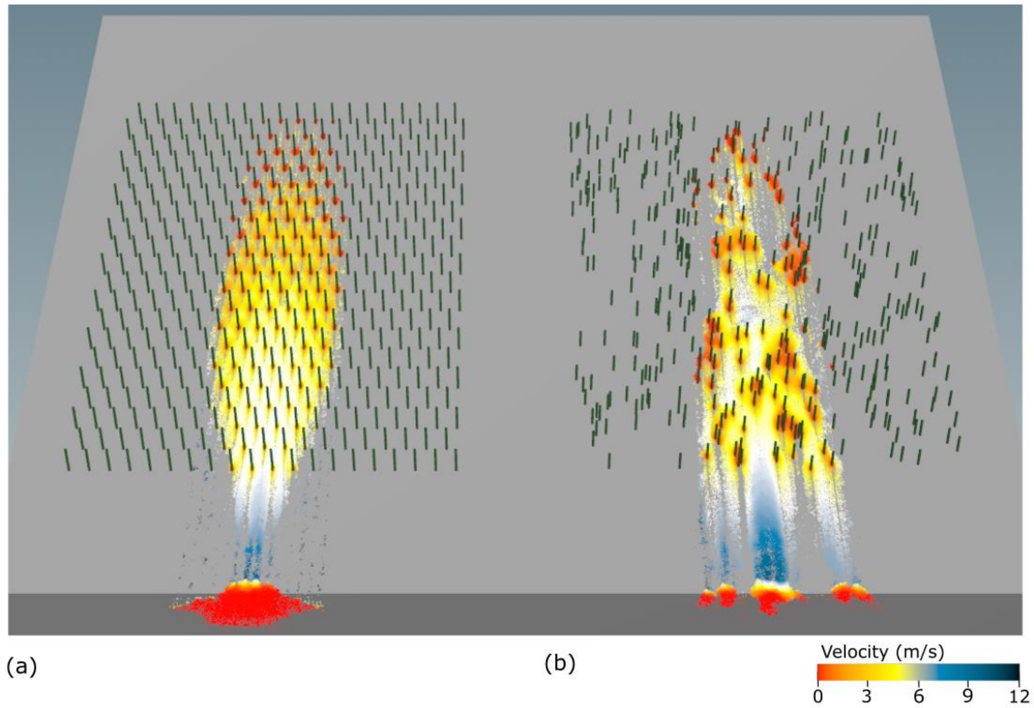

Figure R3. Flow profile for 2 different forest arrangements: (a) regular staggered, (b) random, at t = 33 s, snow type: Case 2.

Forest arrangement	m_d(kg)	E_{pd}(MJ)	$\tilde{E}_f$ (MJ)
Regular staggered	7735	96.3	6.0
Random	20540	88.6	6.1

Table R1. Mass stopped, detrainment and dissipation energy for two types of forest arrangement.

- l 301: Please double check the argument with low/high velocities.

Reply: It has been double checked that the argument is true, but the description of the velocities is unclear. Therefore, we have revised the sentence as follows: When the avalanche velocity is high, the plateau stage of the detrainment mass obtained from our study is higher than the decreasing stage by Feistl et al. (2014). Consequently, an implementation of our proposed velocity-based model would lead to higher detrainment mass, which results in lower runout distance and smaller velocity.

Equations:

- Why is "." Sometimes used as mathematical symbol for multiplication in the manuscript (e.g. eq. 7-11)?

Reply: The symbol has been removed to avoid the confusion.

Figures:

- Fig 2: "d" and "e" are used twice once for tree diameter and spacing and once for the forest arrangements. "snow profile" should rather be "vertical velocity profile"?

Reply: The tree diameter "*d*" and spacing "*e*" have been written in italic. The snow profile has been changed to "cross-sectional view at the center of the middle tree of the snow stopped" to be clear.

- Fig 6: legend wrong? 3.5 and 3.4 are the ones in Feistl et al. And eq. 3.4 is the same as eq.8?

Reply: Corrected.

- Fig 7: is this for case 2?

Reply: Yes, this has been clarified in the revised manuscript.

- Fig 10: is "M_d" from MPM the same as "M_stopped" in the previous figures (same, "M_d" from eq. 11 = "m_d"). What kind of r^2 is used? Is it possible to comment on how the different cases (1-2) are distributed in this figure?

Reply:

i) We have further revised and clarified the adopted notation in the manuscript. Please see detailed the reply to the previous comment on the notation.

ii) We use r^2 as the coefficient of determination which is equal to the square of the Pearson correlation coefficient.

iii) It is possible to differentiate cases 1-3 by using different markers as shown in Fig. R4. We notice that case 1 gives the lowest detrainment mass, and case 3 has the highest detrainment mass as expected. The original Fig. 10 has been replaced with this new figure in the revision.

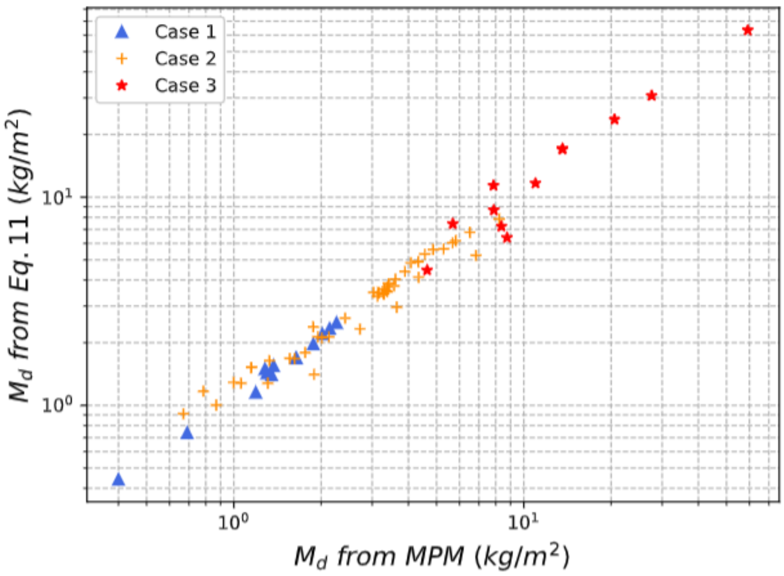

Figure R4. Evolution of the detrainment mass predicted with the model (Eq. 11) and with the observation.

- Fig 11: Do both avalanches reach the bottom after 9 s (effect of forest on front velocity)?

Reply: Yes, with and without forest, the front of the avalanche reaches the bottom of the slope at the same time because there is always a part of the front that is not deviated and that crosses the forest without any collision (please see supplementary movie 5 or Fig. R5).

We define the time when the avalanche reaches the bottom of the slope when the first 1% of the front reaches the bottom of the slope. We have chosen a criterion based on a small percentage of the avalanche front because in some cases a large part of the avalanche is stopped in the forest and will never reach the bottom of the slope, and in this case, we can assume that with and without forest the front of the avalanche reaches the bottom of the slope at the same time. But in fact, the decrease of the front velocity depends on the percentage of the avalanche that is considered as the front, and this decrease will be observed if we consider more particles as the avalanche front. This has been clarified in the revised manuscript.

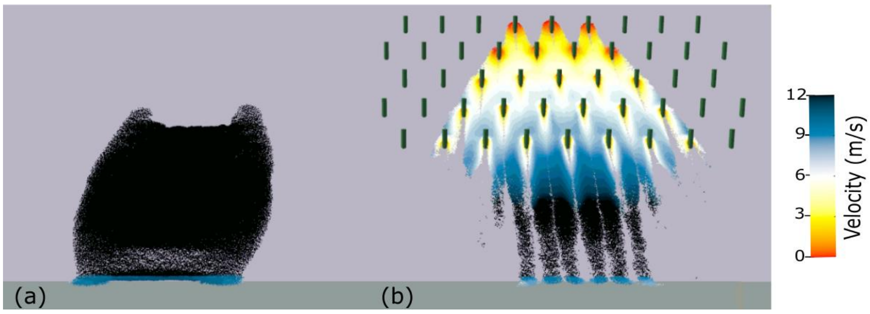

Figure R5. Flow profile: (a) without forest and (b) with a regular staggered forest (Case 2, v_0=6 m/s, t=8.75 s).

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