Response to Reviewer #3's comment on "The mechanical origin of snow avalanche dynamics and flow regime transitions"

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July 15th, 2020

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 paper presents a systematic approach to evaluate the potential of the Material Point Method (MPM) for snow avalanches. The MPM method provides the possibility to account for different flow regimes of the avalanche flow in rather a novel approach.

In a first step the paper concerns avalanche on a selection of very simple geometries (At this point one could have considered a variety of parabolic track as this might be closer to Nature). The authors present a nice comparison of the influence of various parameters which would determine the flow regime.

Reply: We thank this reviewer for the suggestion on the parabolic track, which could be interesting and more realistic for future studies on snow avalanches with MPM modelling. This has been added to the discussion.

I do have slight problems with section 3.3.2. First of all, the main idea behind so-called alpha-beta model (Lied and Bakkehoi, 1980) is that the runout angle alpha is proportional the beta angle, which is a measure of the mean slope angle. Hence there is no dependency on a length scale in the runout. Furthermore, solely considering the alpha angle involves little information without the corresponding beta angle. Having said that, Fig. 8 and Fig. 9 are not that easy to understand. For example, even though the velocities Fig. 9 seem to correspond somehow with the measurements, their origin (frictional behavior) might be rather different. E.g. the velocity of 70 m/s in the simulations correspond to nearly free fall velocity (2gH)ˆ.5 whereas as the measured one is close to (gH/2)ˆ.5. Hence there is a mix up in the comparison.

Reply: The following offers our point-to-point response to the comments on section 3.3.2.

1) Dependency of α on length scale: We agree that the runout angle α highly depends on the mean slope angle β. According to Lied and Bakkehøi (1980), the following correlation between α and β was obtained based on 111 avalanches

$$\alpha = 0.97\beta - 1.4°$$

with a standard deviation of 3.5° and R = 0.88. However, a more accurate prediction of α was reported as follows in Lied and Bakkehøi (1980)

$$\alpha = (6.2 \times 10^{-1} - 2.8 \times 10^{-1} Hy'')\beta + (1.9 \times 10^{1} Hy'' - 2.3)^{\circ} + 1.2 \times 10^{-1}\theta$$

which has a standard deviation of 2.3° and R = 0.95. H is the total vertical displacement. y'' is the terrain profile of the avalanche path described by the second derivative. θ is the inclination of the starting zone (Note the θ in Lied and Bakkehøi (1980) has a different definition with the slope angle θ in our study). Thus, the runout angle also depends on the length scale of the avalanche path in addition to the mean slope. As stated in Lied and Bakkehøi (1980), "*The most important parameter is the β. Hy'' is also an important parameter*".

2) Discussion of α without mentioning β: As reviewed above, the average slope angle β is a very important factor controlling the runout angle α. The origin/reason for proposing β is to describe the mean slope angle of a complicated and irregular flow path which is normally the case in reality. In our study, ideal slopes are used for the sensitivity study, whose mean slope angle β is very close to their actual slope angle (θ in our manuscript). We initially discussed the effect of θ without mentioning β to avoid the repetition. The relation between β and θ has been clarified in the revised manuscript. In addition, it is found that the positive correlation between the maximum runout angle and the slope angle from MPM in Fig. 8 agrees with the α-β model, which has been mentioned in the revised manuscript.

3) Comparison of flow velocities from MPM and real measurements: As mentioned in Lines 269-270 in the manuscript, the real avalanche with a velocity of 70 m/s was a powder snow avalanche, whose dense core can be captured by the current MPM model while the powder cloud is beyond the scope of this study. We agree that the high velocities (close to 70 m/s) from the real avalanche and the simulated avalanche come from different physical processes. The high velocity of the real avalanche is resulted from the large drop height (1940 m from McClung and Gauer (2018)). In contrast, the high velocity of the simulated avalanche is mainly controlled by the properties (low friction and low cohesion) of the flow. While we observe a generally fair agreement of the MPM and field data in Fig. 9, a quantitative comparison would require full consistency of the model setup (e.g. drop height, flow properties), as we did in Section 4 of the paper. Our main motivation here is to show the influence of mechanical (M and β) and geometrical (θ and L_0) properties on the v_{max}-α relationship and give a new insight to the negative correlation observed from the data in McClung and Gauer (2018) (Lines 273-277).

   According to the relation between the flow velocity and the drop height reported for real snow avalanches (Gauer, 2014), the high flow velocity close to 70 m/s obtained with a drop height of 211.2 m from the MPM simulation might not be realistic for snow avalanches. It has been clarified in the revision that the adopted material parameters are designed to study a wide range of different material properties, while the cases with very low friction M and cohesion β leading to the very high velocity might not be realistic for snow avalanches. The material parameters need to be carefully calibrated for investigation of real snow avalanches.

References:

- Gauer, P. (2014). Comparison of avalanche front velocity measurements and implications for avalanche models. *Cold Regions Science and Technology*, 97:132-150.
- Lied, K., and Bakkehøi, K. (1980). Empirical calculations of snow–avalanche run–out distance based on topographic parameters. *Journal of Glaciology*, 26(94):165-177.
- McClung, D. M., and Gauer, P. (2018). Maximum frontal speeds, alpha angles and deposit volumes of flowing snow avalanches. *Cold Regions Science and Technology*, 153:78-85.

Finally, the authors present a promising comparison between simulations and real avalanche measurements.

It would be interesting to see how the model would behave when erosion and entertainment is also considered.

Some minor remarks can be found in the attachments.

Reply: We appreciate the reviewer's interest in the performance of the model with consideration of erosion and entrainment. We also consider entrainment as an interesting and very important process in snow avalanches, and will be the topic of our next study using MPM (Lines 371-375).

Specific comments:

1. Line 9: "Each of the flow regimes shows" should be "Each of the flow regimes show"?

Reply: Since "each" is our subject, "shows" is used.

2. Line 13: "scaled α angle", an angle can hardly be scaled.

Reply: The scaled α angle refers to the dimensionless α*. This notation has been clarified in the revision.

3. Line 14: "It is found …" to "It is found that …".

Reply: Revised.

4. Line 29: "classified" to "considered".

Reply: Revised.

5. Line 30: Delete "including".

Reply: “including” has been replaced by “namely,”.

6. Line 30: “Recent study” to “A recent study”.

Reply: Revised.

7. Line 36: “tools”, model (I think is the better word here).

Reply: Thanks for the rewording. Revised.

8. Fig. 2 caption: Add “(Tab. 1, Group II)”.

Reply: Added.

9. Line 146: “front position” to “the front position”.

Reply: Revised.

10. Fig. 3 caption: Add “(Tab. 1, Group II)”.

Reply: Added.

11. Fig. 3: Which mu value is used in the calculation of v_{max}^{b}*?*

Reply: Thanks for the question. The value of mu is 0.5, which has been added to the text and to Table 1.

12. Fig. 4 caption: Add “(Tab. 1, Group II)”.

Reply: Added.

13. Fig. 5 caption: Add “and lengths L”.

Reply: The data with different lengths L (L_0 in the revised manuscript) are not included in Fig. 5. They are plotted in Fig. 6.

14. Fig. 6 caption: Add “slope angles”.

Reply: The data with different slope angles are not included in Fig. 6. They are plotted in Fig. 5.

15. Line 226: “which hints an analogous physical rule behind the trend”, what is the physical rule you are thinking of?

Reply: As described in Lines 225-246, the data from the different groups of simulations give a similar trend, which drives us to normalize the results and find the analogous physical rule behind the similarity. Based on the normalized results in Fig. 7, there are different physical processes governing the data in the different regions. The maximum velocity of the cases close to the zero line in Fig. 7 is controlled by the friction between the flow and the bed (Lines 238-239). On the other hand, the velocity of the cases with small M and β in Fig. 7 is governed by the snow properties (Lines 239-244). Furthermore, the velocity of the cases far below the zero line in Fig. 7 is due to an acceleration smaller than the theoretical one obtained from a block sliding over a frictional bed (Lines 244-246). All the cases from the different groups follow and share these three physical processes.

*16. Figs 8&9: I'm wondering how the graphs would look like for H = L*tan(slope) combined.*

Reply: We tried to plot all the data in one figure for the varying H (H_0 in the revised manuscript and hereafter) as shown in Fig. 1 below. The increase of drop height does not necessarily give an increasing maximum velocity if we compare the data with H_0 = 73.5 m and the data with H_0 = 132.0 m. This is because these two groups do not have the same slope angle in this study. Thus, it is necessary to separately discuss the groups with a fixed slope angle and the groups with a fixed horizontal length, as we did in Figs 8&9. It is mentioned in the revised manuscript that, instead of fixing the horizontal length L (L_0 in the revised manuscript) when the slope angle is changed (Groups I, II, III in Table I), one could fix the vertical drop height H_0 and change the horizontal length.

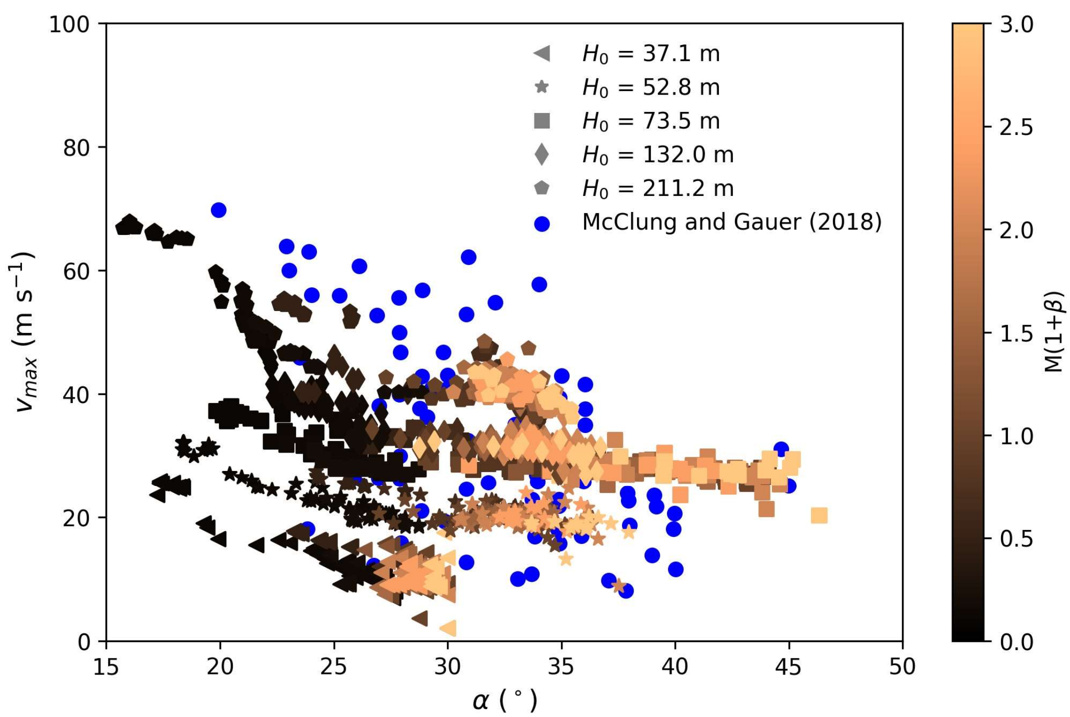

Figure 1. Evolution of the maximum velocity with α for varying drop height H_0.

*17. Line 355: "Both slope angle and path length have a positive correlation with the maximum front velocity on the slope", this is not that surprise as total Drop height H = L*tan(slope). and Umax \prop f(H).*

Reply: We agree that the total drop height should have a similar effect as the horizontal length L and the slope angle θ. The reason that we separately discuss the slope angle and the path length is that we have both the slope angle and the path length in the calculation of the theoretical maximum velocities v_{max}^{b} and v_{max}^{f} (Lines 152-156).