Response to Reviewer #2's comment on "The mechanical origin of snow avalanche dynamics and flow regime transitions"

Xingyue Li, Betty Sovilla, Chenfanfu Jiang, and Johan Gaume*
*Correspondence: johan.gaume@epfl.ch
July 15th, 2020

We thank Referee #2 for his or her insightful comments and helpful advice, which increase the quality of our paper. The following provides our point-to-point responses to the general comments, specific comments, and technical corrections from the reviewer.

General comments:

The paper presents a novel application of the authors recently developed approaches, successfully combining experimental findings on the flow regime evolution in snow avalanches and respective modelling approaches. The authors reach the goal of showing the models ability to replicate different flow regimes (and the associated flow characteristics, such as velocity, ...) by tuning the corresponding material parameters.

One point that could be enhanced in my eyes is the discussion of the role and connection between the numerical method/solver and the applied flow/material model. As the title states, the paper aims at the identification of the mechanical rather than the numerical origin of flow regimes in snow avalanches. However, the numerical method/solver (MPM) is often highlighted and associated with the success of the modeling results rather than the corresponding material model (see comments below).

Overall the paper is very well written and includes helpful figures with corresponding supplementary material (with some small exceptions mentioned below). This valuable contribution is of high quality, enjoyable to read and fits to the scope of TC.

Reply: We thank this reviewer for the encouraging comments. Regarding the numerical framework and the material model, this study indeed focuses on the material model, as we mainly investigate the effect of material property in addition to slope geometry. The relation between the numerical framework and the material model has been clarified in the revised manuscript as detailed in the reply of specific comment 2 below.

Specific comments:

1. p2 l 41-51 and section 2.1: could you include a comment what the main differences (e.g. 2d/3d, depth resolved/averaged, ...) are to the classical, numerical approaches that are used in common simulation software that you also cite throughout your paper (such as Christen et al. (2010)). In particular the similarities and/or differences are to other particle based methods such as SPH (which are also used for classical shallow water

2d avalanche modelling Sampl and Zwinger (2004)) would probably be interesting for the reader to also interpret the future potential of the MPM methods (see conclusions).

References:

Christen, M., Kowalski, J., and Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. Cold Regions Science and Technology, 63:1–14.

Sampl, P. and Zwinger, T. (2004). Avalanche simulation with SAMOS. Annals of Glaciology, 38(1):393–398.

Reply: We have provided further introduction of existing numerical approaches for snow avalanche modelling in the revised manuscript, including 2D, 3D, and particle-based continuum methods, as follows.

Popular classical numerical tools for modelling snow avalanches primarily apply two-dimensional (2D) depth-averaged methods based on shallow water theory (Naaim et al., 2013; Rauter et al., 2018), which fail to capture important flow characteristics along the surface-normal direction such as velocity distribution (Eglit et al., 2020). Nevertheless, 2D models are computationally efficient and provide acceptable accuracy, which serve as a powerful tool in many applications like hazard mapping. In comparison, three-dimensional (3D) simulations can fully resolve flow variations in all dimensions, which consequently require longer computation time. In recent years, particle-based continuum methods, including Smooth Particle Hydrodynamics (SPH), Particle Finite Element Method (PFEM), and Material Point Method (MPM), have gained increasingly popularity in avalanche modelling, as they are able to easily handle large deformations and discontinuities (Abdelrazek et al., 2014; Salazar et al., 2016; Gaume et al., 2018). In particular, MPM has proven to be an effective and efficient tool in investigating snow (Stomakhin et al., 2013; Gaume et al., 2018). Compared with SPH where boundary conditions are challenging to generalize, MPM can readily address complex boundaries (Raymond et al., 2018). Moreover, MPM does not suffer from the time consuming neighbor searching that is inevitable in many mesh-free approaches like SPH (Abdelrazek et al., 2014). Both PFEM and MPM use a set of Lagrangian particles and a background mesh to solve mass and momentum conservation of a system. In contrast to PFEM, each particle in MPM has fixed mass, as it allows to naturally guarantee mass conservation. However, the fixed mass meanwhile leads to difficulty in adding or removing particles from the system (Larsson et al., 2020). The computational cost of MPM is lower than that of PFEM according to simulations with same formulation (Papakrivopoulos 2018).

References:

- Abdelrazek, A. M., Kimura, I., and Shimizu, Y. (2014). Numerical simulation of a small-scale snow avalanche tests using non-Newtonian SPH model. *Journal of Japan Society of Civil Engineers*, 70(2):I_681-I_690.
- Eglit, M., Yakubenko, A., and Zayko, J. (2020). A review of Russian snow avalanche models-From analytical solutions to novel 3D models. *Geosciences*, 10(2):77.
- Gaume, J., Gast, T., Teran, J., van Herwijnen, A., and Jiang, C. (2018). Dynamic anticrack propagation in snow. *Nature Communications*, 9(1):1-10.

- Larsson, S., Prieto, J. M. R., Gustafsson, G., Häggblad, H. Å., and Jonsén, P. (2020). The particle finite element method for transient granular material flow: modelling and validation. *Computational Particle Mechanics*, 1-21.
- Mast, C. M., Arduino, P., Miller, G. R., and Mackenzie-Helnwein, P. (2014). Avalanche and landslide simulation using the material point method: flow dynamics and force interaction with structures. *Computational Geosciences*, 18(5):817-830.
- Naaim, M., Durand, Y., Eckert, N., and Chambon, G. (2013). Dense avalanche friction coefficients: influence of physical properties of snow. *Journal of Glaciology*, 59(216):771-782.
- Papakrivopoulos, V. (2018). *Development and Preliminary Evaluation of the Main Features of the Particle Finite Element Method (PFEM) for Solid Mechanics*. Master's thesis, Delft University of Technology.
- Rauter, M., Kofler, A., Huber, A., and Fellin, W. (2018). faSavageHutterFOAM 1.0: depth-integrated simulation of dense snow avalanches on natural terrain with OpenFOAM. *Geoscientific Model Development*, 11:2923-2939.
- Raymond, S. J., Jones, B., and Williams, J. R. (2018). A strategy to couple the material point method (MPM) and smoothed particle hydrodynamics (SPH) computational techniques. *Computational Particle Mechanics*, 5(1):49-58.
- Salazar, F., Irazábal, J., Larese, A., and Oñate, E. (2016). Numerical modelling of landslide-generated waves with the particle finite element method (PFEM) and a non-Newtonian flow model. *International Journal for Numerical and Analytical Methods in Geomechanics*, 40(6):809-826.
- Stomakhin, A., Schroeder, C., Chai, L., Teran, J., and Selle, A. (2013). A material point method for snow simulation. *ACM Transactions on Graphics (TOG)*, 32(4):1-10.

2. p5 line 106, Table 1: here you particularly highlight the parameters for the MPM modeling. To me it appears that this could be misleading. All parameters refer to the material model (section 2.2.). No numerical parameters are discussed therefore the it would be interesting to: 1) comment the role of the numerical parameters and how they were chosen and to 2) clarify the role/interplay of the numerical technique and the material model (see comment on paper title above).

Reply: Indeed, the parameters in Table 1 include snow parameters. In addition to that, the information of slope geometry is also listed. Numerical parameters (i.e. mesh size, time step, and frame rate) have been added to Table 1 in the revision. To avoid the confusion of "MPM model" and "material model", "Model parameters" in the title of Table 1 has been revised to "Parameters".

1) Numerical parameters govern the accuracy and stability of the modelling. The determination of the adopted numerical parameters (i.e. background mesh size, time step, and frame rate) has been detailed in the revised manuscript. The size of the background Eulerian mesh in MPM is selected to be small enough to guarantee the simulation accuracy and resolution, and meanwhile be large enough to shorten the computation time. The time step is constrained by the CFL condition and the elastic wave speed to secure the simulation stability. The simulation data are exported every 1/24 s.

2) The relation between the numerical framework and the material model has been clarified in the revision. Different material models can be implemented to the MPM numerical framework to simulate different processes. For example, a non-associated Mohr-Coulomb model was applied to model landslide and dam failure (Zabala and Alonso, 2011; Soga et al., 2016), and a non-associated Drucker-Prager model was used to simulate sand (Klár et al., 2016). In this study, we specifically use the associated Modified Cam Clay model developed for snow, which reproduces mixed-mode snow fracture and compaction hardening (Gaume et al., 2018). The important role of the material/constitutive model has also been clarified in the revision.

References:

- Klár, G., Gast, T., Pradhana, A., Fu, C., Schroeder, C., Jiang, C., and Teran, J. (2016). Drucker-prager elastoplasticity for sand animation. *ACM Transactions on Graphics (TOG)*, 35(4):1-12.
- Gaume, J., Gast, T., Teran, J., van Herwijnen, A., and Jiang, C. (2018). Dynamic anticrack propagation in snow. *Nature Communications*, 9(1):1-10.
- Soga, K., Alonso, E., Yerro, A., Kumar, K., and Bandara, S. (2016). Trends in large-deformation analysis of landslide mass movements with particular emphasis on the material point method. *Géotechnique*, 66(3):248-273.
- Zabala, F., and Alonso, E. E. (2011). Progressive failure of Aznalcóllar dam using the material point method. *Géotechnique*, 61(9):795-808.

3. p7 line 145: Could you briefly explain a bit more what this threshold means and if or if not this is connected to the (numerical?) fluctuations that appear e.g. in Figure 3 b) around 5s for the cold dense and 7.5-10s for the warm shear simulations?

Reply: 1% of the particles at the flow front is excluded in the determination of the front position, because scattered particles are observed at the flow front in some of the flows (i.e. the warm shear flow and sliding slab flow in supplementary video 2). These scattered particles separate from the main body of the flow and do not reflect the actual front of the flow. Further clarification has been provided to address this comment.

The sharp drop appeared in the front evolution of the cold dense flow at around 5 s is chiefly due to the change of the slope geometry, since the flow front enters the connecting arc zone at around 5 s. The fluctuations observed in the warm shear case from 7.5 s are mainly because of the discrete nature of the granules at the front of the flow (see supplementary video 1). The above discussion has been made in the revision.

4. p15 line 276: Could you briefly comment on what the plateau stage means and if or if not any of the avalanches reach some kind of final velocity / steady state?

Reply: Indeed, the maximum velocity of a flow v_{max} at the plateau stage reaches the theoretical prediction v_{max}^{b} with consideration of a rigid block sliding on a frictional bed. This means the maximum velocity is controlled by the frictional behaviour between the flow and the bed, which has been clarified in the revised manuscript.

5. p16 l 291, ...To calibrate and benchmark our MPM modeling...: is this really a calibration or rather a parameter variation/test with respect to the material / flow model rather than the numerical MPM approach?

Reply: Calibration of numerical modelling covers different parameters, including those from physical models implemented in the numerical framework (e.g. friction in Blagovechshenskiy et al. (2002)). In this study, we calibrated the MPM modelling by changing the bed friction, according to the data reported in the literature. “MPM modelling” here denotes the entire MPM simulation framework composed of the MPM numerical scheme and the material model. To avoid the confusion, it has been further specified that the bed friction is the calibrated parameter. Please note the adopted snow properties are based on the description of the snow type in the literature, as described in Lines 294-299 in the original manuscript.

Reference:

- Blagovechshenskiy, V., Eglit, M., and Naaim, M. (2002). The calibration of an avalanche mathematical model using field data. *Natural Hazards and Earth System Science, Copernicus Publications on Behalf of the European Geosciences Union,* 2(3/4):217-220.

6. p16 l 307-310: I think here you have to clarify in more detail: 1) how are the avalanche velocities measures (different measurement techniques will lead to different velocities (front / core), see e.g. Rammer et al. (2007); Gauer et al. (2007)) and 2) if the measurements are comparable are the simulated velocities transformed correspondingly such they can be directly compared to the measurements (see e.g. Fischer et al. (2014))?

References:

Fischer, J. T., Fromm, R., Gauer, P., and Sovilla, B. (2014). Evaluation of probabilistic snow avalanche simulation ensembles with Doppler radar observations. Cold Regions Science and Technology, 97(0):151–158.

Gauer, P., Kern, M., Kristensen, K., Lied, K., Rammer, L., and Schreiber, H. (2007). On pulsed Doppler radar measurements of avalanches and their implication to avalanche dynamics. Cold Regions Science and Technology, 50(1):55–71.

Rammer, L., Kern, M., Gruber, U., and Tiefenbacher, F. (2007). Comparison of avalanche velocity measurements by means of pulsed Doppler radar, continuous wave radar and optical methods. Cold Regions Science and Technology, 50(1-3):35–54.

Reply: It has been clarified in the revision that different measurement techniques were used to obtain the front velocity, including Doppler radar devices and photo analyses. Particularly, continuous wave Doppler-radar was employed for the avalanches in Case I and Case II. Pulsed Doppler-radar was used for the avalanche in Case III. Timed photographs were used for the avalanches in Case IV and Case V.

It is noticed that different measurement approaches may give different velocities, which are generally consistent with one another (Rammer 2007). The comparison basis between velocities from numerical modelling and real measurements is sometimes questionable (Fischer et al., 2014; Rauter and Köhler, 2020). For example, depth-averaged velocities from numerical modelling cannot be directly compared to peak intensity velocities from Doppler radar measurements (Rauter and Köhler, 2020). In this study, the front velocity from MPM is determined as the approach velocity (Rauter and Köhler, 2020), which is calculated from the front position evolution with time and is assumed to be comparable with the data from the different measurement techniques. The approach velocity has a different definition from the velocity at the flow front, although their values are almost the same in our simulations as shown in Figs 1-5 below. The above discussion has been added to the revised manuscript.

References:

- Fischer, J. T., Fromm, R., Gauer, P., and Sovilla, B. (2014). Evaluation of probabilistic snow avalanche simulation ensembles with Doppler radar observations. *Cold Regions Science and Technology*, 97:151-158.
- Rammer, L., Kern, M. A., Gruber, U., and Tiefenbacher, F. (2007). Comparison of avalanche-velocity measurements by means of pulsed Doppler radar, continuous wave radar and optical methods. *Cold Regions Science and Technology*, 50(1-3):35-54.
- Rauter, M., and Köhler, A. (2020). Constraints on Entrainment and Deposition Models in Avalanche Simulations from High-Resolution Radar Data. *Geosciences*, 10(1):9.

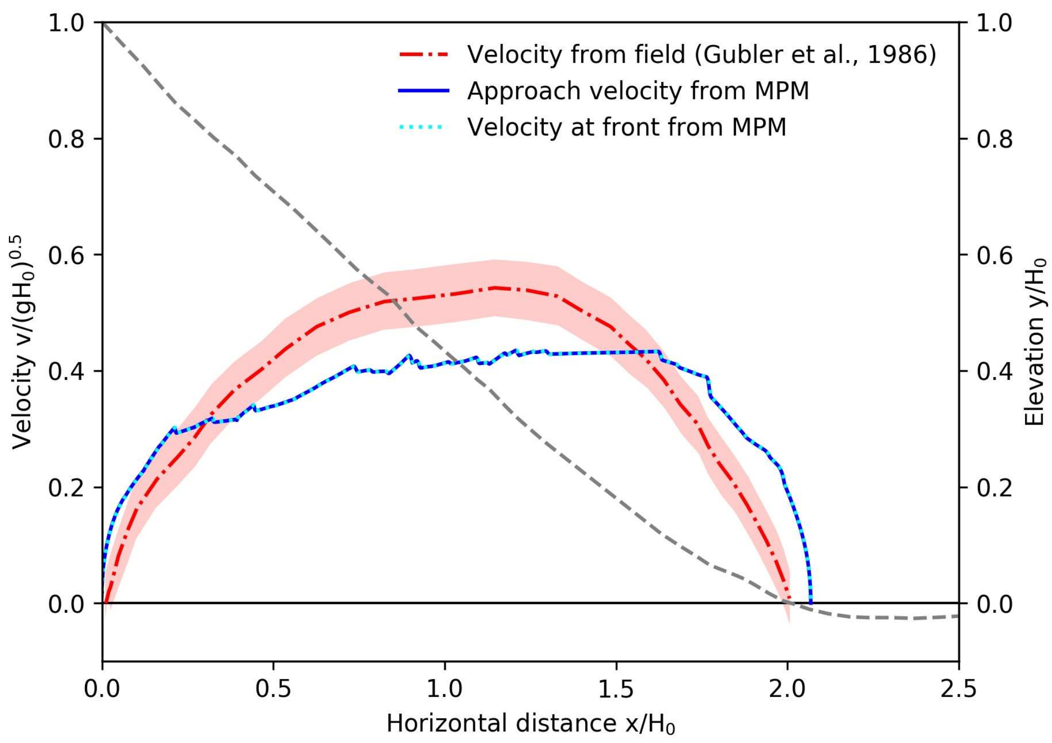

Figure 1. Front velocity distribution along the flow path for Case I: Weissfluh-Northridge 1982-03-12 a1 (Davos, Switzerland). Drop height H_0 = 236 m.

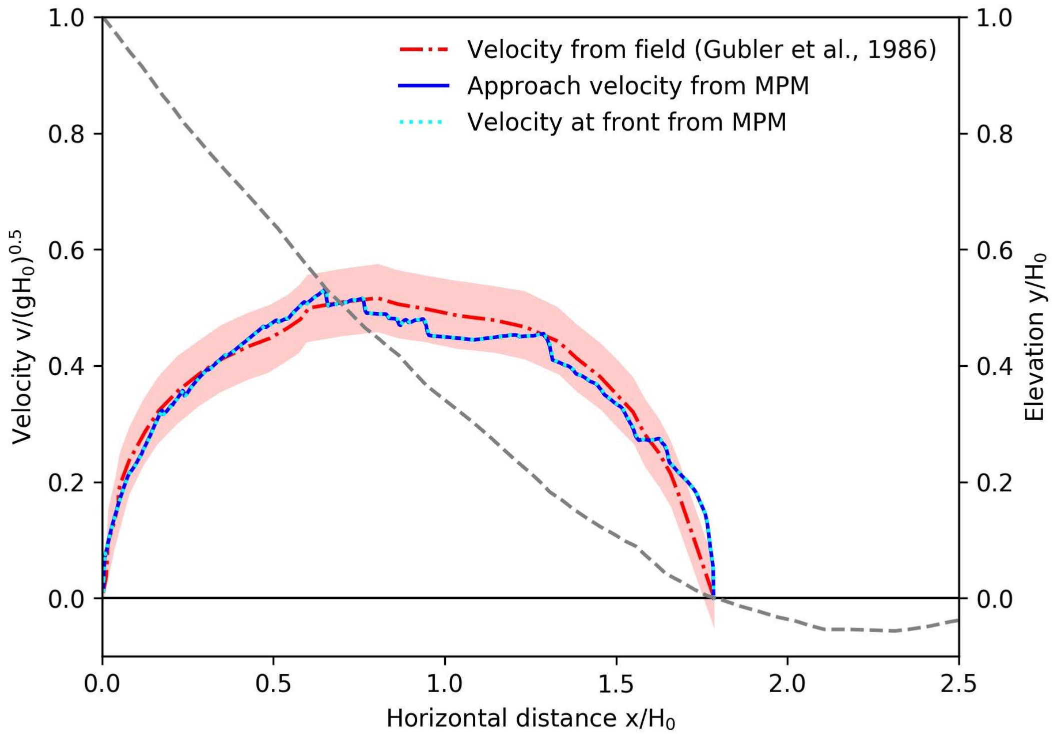

Figure 2. Front velocity distribution along the flow path for Case II: Weissfluh-Northridge 1982-03-12 a2 (Davos, Switzerland). Drop height H_0 = 177 m.

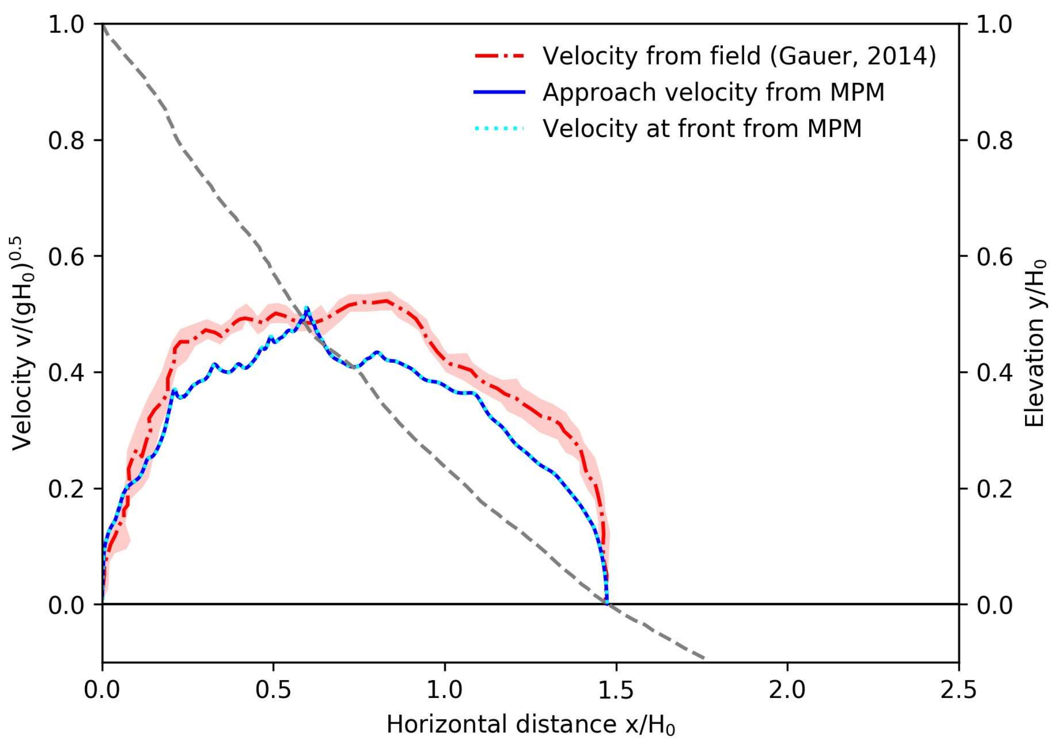

Figure 3. Front velocity distribution along the flow path for Case III: Himmelegg 1990-02-14 (Alberg, Austria). Drop height H_0 = 352 m.

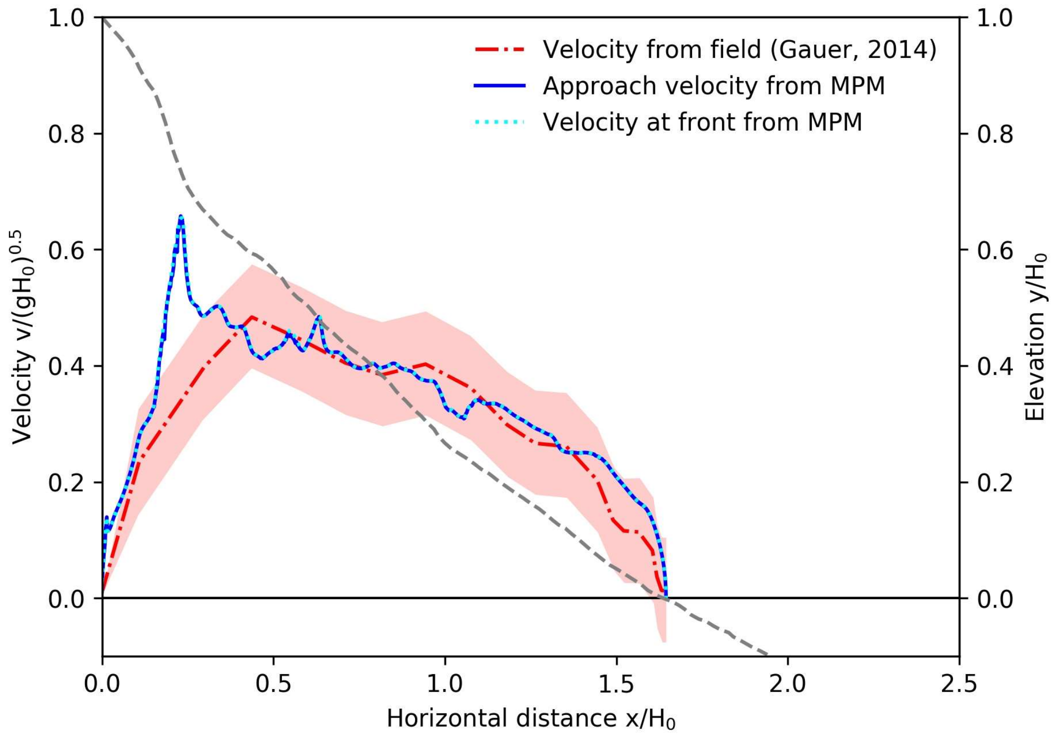

Figure 4. Front velocity distribution along the flow path for Case IV: Ryggfonn 2006-05-02 (Stryn, Norway). Drop height H_0 = 303 m.

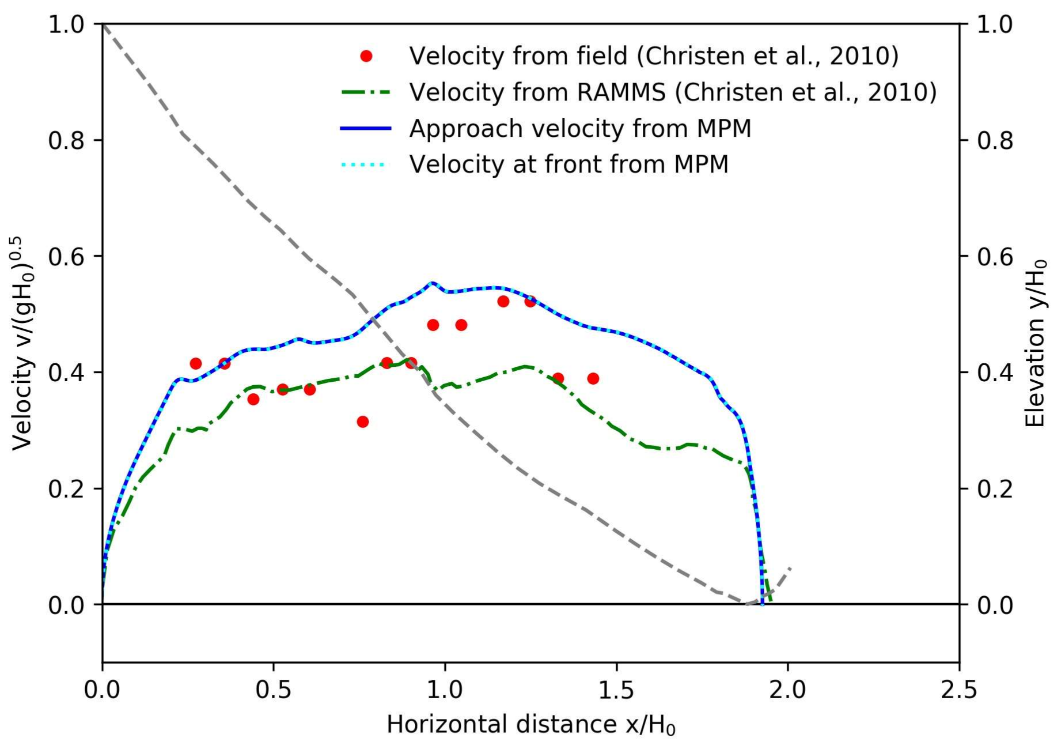

Figure 5. Front velocity distribution along the flow path for Case V: VdlS 2003-01-31 (Sion, Switzerland). Drop height H_0 = 1246 m.

Technical corrections:

Generally text and Figures are clear and the supplementary material is very helpful. Possible corrections include:

1. Figure2 and supplementary material: Fig2 is missing a spatial scale and the corresponding video is missing a legend (velocity/epsilon scale) as well as a spatial and temporal scale.

Reply: Spatial scale has been added to Fig. 2. The supplementary videos have been revised to include spatial and temporal scale as well as legend.

2. Figures 11-15 and supplementary material: absolute scales are missing and prohibit valuable data interpretation (at least total fall height should be stated in a Table or the caption).

Reply: Drop height has been clarified in the caption of Figs 11-15 and added to the supplementary data.

3. Wording: α should be referred to as runout angle.

Reply: "α angle" has been revised to "runout angle".

4. Wording: H/L and H0/L0 should be referred to the other way around (H/L=tan α is usually the convention why H/L refers to the topography inclination in this paper).

Reply: The definitions of H/L and H0/L0 have been exchanged.

5. Wording: what the authors refer to as "benchmark" appears more as a model "test" to me.

Reply: "MPM model is benchmarked" in the abstract has been revised to "MPM modelling is calibrated and tested". "To calibrate and benchmark our MPM modeling" in Lines 292 has been modified to "To testify the capability of the MPM modelling in capturing key dynamic features (i.e. front velocity and position) of snow avalanches".

6. Wording: please check by a native speaker if the choice of plural/singular is appropriate throughout the paper (e.g. behaviours, literatures, terrains, ...).

Reply: Thanks for the reminder. We have checked and revised the words with a native speaker.