Response to Referees

Simulation of cold powder avalanches considering daily snowpack and weather situations to enhance road safety

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Dear Editor and Referees,

We greatly appreciate your detailed and insightful feedback. This has been invaluable in enhancing the quality of the manuscript. We have copied your comments into the blue boxes and enumerated them so that we can address each part separately below. The responses to the comments from the first reviewer are marked as R1, and the responses to the comments from the second reviewer are marked as R2.

Sincerely,

Julia Glaus & co-authors

Response to Reviewer R2

General Comments

R2-1: The authors present a study that investigates the predictive capabilities of an existing coupled dense & powder flow model within the RAMMS:Extended software. To achieve this, they include a formulation of snow temperature and a formulation of snow cover entrainment with a variable distribution of erodible snow into their model.

R2-2: First of all, it is not clear if these formulations are new in this publication or arise from earlier publications about the extended version of RAMMS. For example, entrainment is included since at least Bartelt, 2012 or Bartelt, 2018a. And for the temperature formulation, I know at least of the work by Valero, 2015 which includes release temperature already. It would add to the paper's quality if some information about how these connect to this publication is added.

We will include a more detailed description of the historical development of RAMMS Extended and highlight the differences and new features more clearly. The goal of the RAMMS chapter is to summarise the current state again and emphasise it with additional details compared to the existing literature for better understanding

R2-3: I did not check the model equations, partially because the multitude of symbols is rather confusing. What I do not find is how the snow temperature alters the friction law. Eq. 15 states that the only temperature dependent parameter is beta. It is also completely unclear why alpha has no temperature dependence; to my understanding, the generation of the powder cloud is clearly temperature dependent. A discussion of why such a relation is chosen is missing.

- We will adjust the symbols according to Dieter Issler's comments in point R1-8.2 to enhance the readability of the equations.
- The snow temperature is correlated with the internal energy and random fluctuation energy, which are influenced by the friction parameters.
- Your observation that alpha is temperature-dependent is certainly valid. We are working on a new version where alpha varies with temperature, but given the scarcity of calibration data around the critical transition between wet and cold avalanches, this is a challenging task. We aim to address this in the discussion, emphasising the simplifications made.

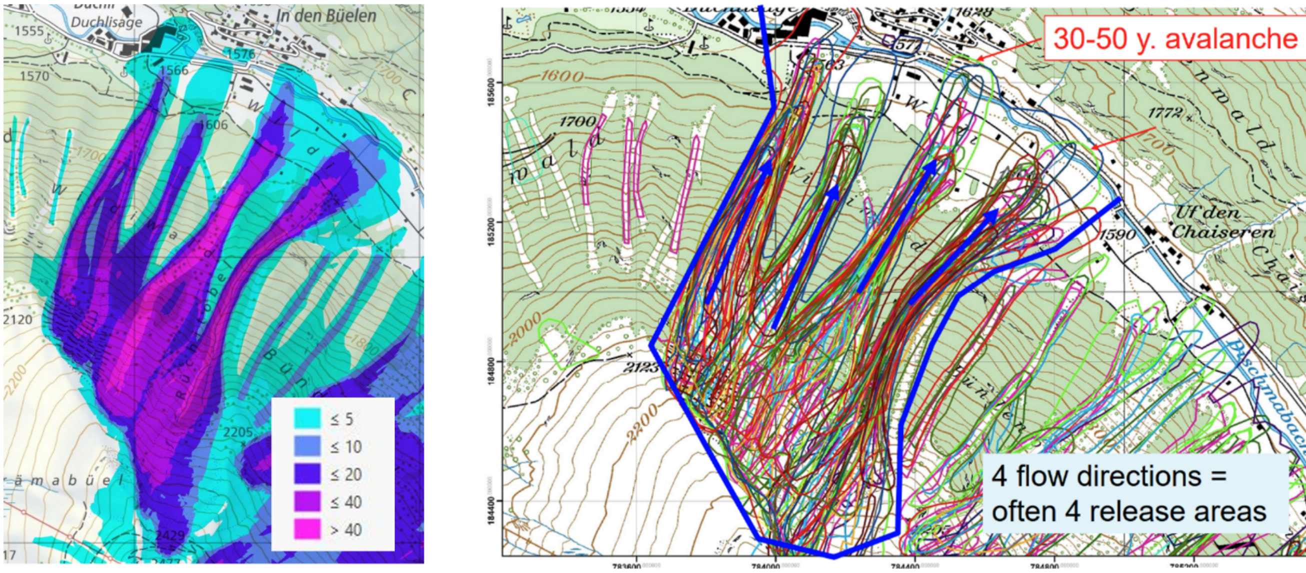


Figure R1: Observed avalanches at Brämabühl from 1964 to 2023. The left side of the graphic shows how many avalanches reached a certain distance. The right side shows the outlines of all observed avalanches. It can be seen that not all avalanches reach the valley, and most stop before the flat runout where the lower boundary of the forest is.

> R2-4: Most of the results and discussion of the paper are on a parameter variation for the model input (release temperature, entrainment and gradients thereof) on a synthetic topography. While this is a valuable standard approach to check the model and effects of the implementation, it is not sufficient as a proof for the formulated model assumptions, i.e., many explanations about the simulation study in sec. 4.1 sound too much like one would know these processes and effects from real avalanches (line 320ff., line 339ff).

Our simulation is indeed based on mechanical assumptions and was calibrated using observed avalanches from the Vallée de la Sionne, along with adjustments made from data on avalanches worldwide. We acknowledge that a definitive proof for such a complex system is challenging to achieve, given the inherent uncertainties and variations in real avalanche events. But all depth averaged models make the assumption that the flow is attached to the topography with no slope perpendicular velocity. So there will be never proof for the system, but we can gain confidence by comparing our results to well documented real avalanches.

> R2-5: It is unclear to me if the chosen synthetic topography is suited. The main parameter is runout distance or avalanche length (which needs precise definition, by the way), but you never give those distances on the topography. Where is 900m, where is 1600m? See comment below to Fig. 3. To my knowledge, the Bramabuhl avalanche track is very steep from top to bottom, and then completely flat. So, everything runs basically to the valley floor. How would the results change if you had chosen a parabolic profile?

- We will add the definition of avalanche length.
- Based on observations of avalanches at Brämabühl over recent years as shown in the graphic below, we would not agree that most avalanches reach the road.
- We will conduct simulations using the parabolic profile. If these simulations result in significant differences, we will consider including them in the publication or at least in the appendix as an additional perspective.

> R2-6: The comparison and discussion of the simulation on real topography with the measured data is weak. I do not understand how these three avalanches can support the claimed temperature and erosion gradient model formulation. These three avalanches experience the same snow cover. And Sec. 4.2 actually fits the friction parameters to one of the avalanches. However, a good point is that all three avalanches can be modelled with

the same set of friction parameters.

The calibration of the model was done based on the VdlS data and not with the Brämabühl avalanches. This study focus more on the sensitivity. In the future, we will compare for sure with more avalanches beside VdlS as soon as we have good data.

R2-7: I generally do not understand why you do not use data from your own test-site Vallee de la Sionne. Mass balances and snow temperatures have been measured there for more than a decade. Generally, the paper lacks comparison and discussion with recent advances and publications from experimental avalanche measurements.

We excluded the comparison with Vallee de la Sionne due to the counter slope. Additionally, the temperature data available for Valle de la Sionne are model-based (from SNOWPACK) rather than direct measurements. We decided for our test region, as all three avalanches have an unconfined run-out. To motivate our test region in the publication, we can add this "train of thoughts".

Specific Comments

R2-8: L53: Reference to r.avaflow missing. Or do you mean the AvaFrame (2023) reference, which points to a different model?

We will add both models incl the reference.

R2-9: Fig3: Right side: Please add color scale, potentially remove the black background, and add lines that indicate runout distance (or avalanche length?)

We will implement this as proposed.

R2-10: Fig4: Why did you swap the colormap direction between both panels? Please be consistent, see also Fig. 16. Add elevation contour lines, add map corner coordinates, draw avalanche outlines in left panel. The left panel is too small to see anything, what about having the left panel in textwidth and three smaller panels underneath showing each release area (and not only Ruechi). Where can I see the wind redistribution effects?

- We will unify the colour scaling according to Dieter Isslers inputs R1-8.1
- Adding counter lines we can try - but I expect it to reduce the readability of the figure.
- We can add the figure for all three avalanches

R2-11: L109: What is this post-processing tool and where are max. velocity, flow height and pressure used? In the ISSW publication and in here only runout distance is presented. BTW: I like Fig.4 from the ISSW publication, would have helped in here as well (Reference entry is missing ISSW, year and URL)

- The post processing tool is an in-house written python code that we can publish on Github
- Max velocity, flow height and pressure are used for comparison to the observed avalanches
- We try not to overload the publication - but we can add a reference to the (Glaus et al., 2023)

R2-12: Sec. 2.2: A precise definition of runout distance or avalanche length is missing. Please add.

As answered in R2-4.

R2-13: Fig5: Right panel: The smooth temperature gradient shows how bad the rainbow colormap is: The temperature gradient appears to have sharp changes at -8 and -6 degrees. Not to mention red/green color blindness. (A suggested good read on this topic is "Choosing Colormaps in Matplotlib" or “Somewhere over the rainbow...” https://journals.ametsoc.org/view/journals/bams/96/2/bams-d-13-00155.1.xml)

We can recolour the graphic to improve readability for colour-blind people. However, please note that the current version is the standard output from RAMMS, where I cannot adjust the basic colour scaling.

R2-14: Fig6: Why not include the values from the particular avalanche into the example box (from Tab1)?

We will implement this as proposed.

R2-15: L153: Are all three literatures relevant here? You are not dealing with water content as you state in the very next sentence.

Yes

R2-16: L156: All your measurements are from flat fields, but you project the temperatures onto a north facing slope. Some reasoning of why this is applicable would be helpful.

This is the traditional way that even the avalanche forecasting team is doing it. We are very interested in input on how to do it differently. We put a measurement station in an avalanche release zone, but it was destroyed by an avalanche. We know that the information is not perfect from the flat fields - but it is a safe approach. We performed additional measurements with thermal cameras confirming the validity of this assumption.

R2-17: L160: Missing Z of runout area.

We will implement this as proposed ($Z_{runout} = 1600 m.a.s.l$).

R2-18: L165: Christen, 2010, is a reference to normal RAMMS. Choose one for the extended version.

In the first sentence we talk about the original RAMMS model - so we keep the Christen reference. We can add a sentence that the latest publication on the new version was done by Zhuang et al 2023 and add this reference.

R2-19: L171: If all those citations are important, please elaborate what each contribution is. Please give a short statement on each or use them throughout the description of the model in this section.

This point will be covered by working on your comment R2-2.

R2-20: L234: Tab 3.2 is not typesetted as a table, caption missing.

Will be adjusted.

R2-21: L245: The experimental results from the cited publication must be discussed in respect to your results later in the publication. I guess there are more suited literature that backs the sentence here (e.g. Ancey 2007 or others)

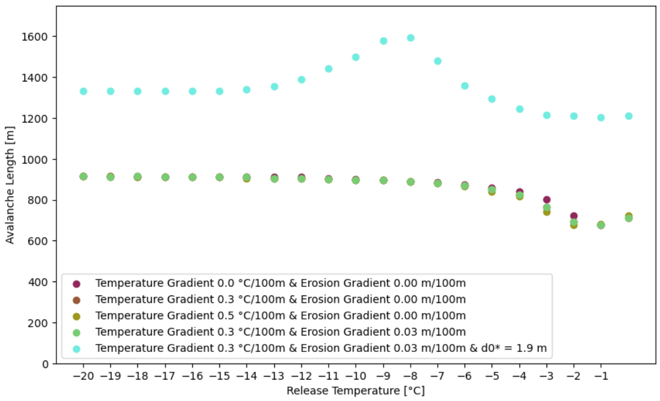
We can do this.

R2-22: L297: Sec.4.1 should be snow temperature+entrainment and Sec.4.3 comparison to measured avalanches

We will implement this as proposed.

R2-23: Fig8: You may indicate location of Fig.9 at $-6°$C with vertical line. Why is the chosen value for ΔT 0.3 instead of 0.5 as indicated in Tab.1?

- We can add the vertical line
- We can add the evaluation of ΔT equals 0.5 to have a more unified approach. The 0.3 was chosen as it is a commonly used value in the Alps. Overall, it will not influence the discussion.



R2-24: L305: I don't see that Dent (1998) backs your statement here.

Correct, we mistaken with the reference. Alternatively, we can refer to the paper (Li et al., 2020)

R2-25: L320: This is written as a fact, but fundamentally a model assumption. I suggest to discussion with your colleagues from Vallee de la Sionne about powder snow avalanches.

We will reformulate to "We assume .."

R2-26: L322: Why should -10°C be more realistic?

In the alps we don't observe normally snow covers which show an average snow temperature far below $-10°C$. Therefore, checking the temperature above $-10°C$ brings us in a region of the diagram where we represent more realistic the observed conditions.

R2-27: L323-326: Also quite speculative.

We describe our observations and try to give an interpretation of our investigation.

R2-28: L334 and Fig9: Wording d* maximum erosion depth or snow height, be consistent.

We will go with maximum erosion depth.

R2-29: Fig10: Please use same temperature range for colormap in all 3 panels (0 – -13°C), currently all three panels look basically the same. You may indicate the location of Fig.8 at 0.3°C/100m with a vertical line. Legend overlaps value of runout especially in middle panel.

- We will unify the colour scaling according to Dieter Isslers inputs R1-8.1
- We will mark the 0.3°C/100m

R2-30: L339: Which experience? I would say PSAs need a lot of new (erodible) snow but are rather independent of absolute snow height.

Yes, the way the model is run, we use the new snow to drive the erodible layer according to the Swiss Guidlines. In the ISSW abstract 2024 we discuss more details on

R2-31: L342: Large avalanches can erode much more than 1 meter, e.g., Fig 16 the middle part of the track is snow free.

Exactly, we will adjust the phasing to point out that this is a case specific statement.

R2-32: Fig11: Evolution over time can be shown with a plot over time. Your ISSW paper suggests you can easily extract runout distance for different time steps. Please show the results in a runout distance over time representation.

Sure, we can add this.

R2-33: L348ff: Please extend the discussion incorporating the prior mentioned publication Steinkogler,2015, Fischer,2018, Kohler,2018, Li,2020, Ligneau,2022 to suggest some.

Sure, we can add this.

R2-34: L352: Why show Wildi avalanche here and not Ruchi? What I understood is, that you use Ruchi as the main avalanche for Sec.4.2, so it would be good to show this avalanche in greater detail.

We can replace the graphic with Ruechi Tobel. Most of the investigations are primarily focused on Wildi, as we are also conducting the measurement campaign there (Ruttner-Jansen et al., 2023). In comparison, Ruechi Tobel is a simpler avalanche to evaluate because it doesn't split into two arms, making it easier for a general assessment.

R2-35: L358: Reaction to entrained snow temperature can be rather fast, see for example the rapid changes in front velocity reported by Kohler,2018.

We can add this fact and citation.

R2-36: Sec.4.2: By the way, what kind of parameter mu0, xi0, N0 are used in Sec.4.1?

We used a mu0 of 0.55; xi0 of 1800 and a N0 of 200 as described in the table on page 13 (caption will be added to the table)

R2-37: Eq24: As stated in Tab3.2, xi(t) limits the flow velocity and mu(t) the runout. How to find a good xi, when no velocity data is used?

We checked with the VdlS avalanches the friction values from the swiss guidlines. We tried out the same friction values for RAMMS extended and checked with the velocities from the radar measurement. as we still got good results, we fixed those values.

R2-38: L382: You never elaborate on the true runout distance of the avalanches.

We can add this as a discussion point.

R2-39: L384: Sentence is unclear. Explain in more detail.

We will rephrase this sentence. The initial calibration of RAMMS::EXTENDED was based on the Vallee de la Sion avalanches, where velocity data was also included. We aimed to reuse those friction values to determine if they yield realistic results for much smaller avalanches, such as those at Brämabühl.

R2-40: I believe the avalanche runout is at 1600-1650m, because this shows the best fit square. However, Fig 8, 9, 10 only show very few parameter constellations that are able to reach this far. Therefore, it seems the "high point" at $-8°C$ in Fig8 is absolutely needed... Please comment/discuss this. Also, your best fit parameters are on the border of your parameter space study (lowest row), how does this matrix extend to values of mu0 > 0.55?

Yes, this result arises because we used a different temperature gradient for this simulation. We will ensure that all simulations are conducted with the parameter set identified for the Brämabühl avalanches to enhance consistency and clarity. We can do the simulation again for mu0 > 0.55 - for this paper we defined the interval for mu0 by checking values which we normally used. Therefore the values from the back calculations are not in the centre of the diagram.

R2-41: L393: Missing mentioning of Fig14 in text. Before it was Fig13 and now Fig15? Please extend discussion on Fig14, also include the drone data into Fig14 for comparison. Fig15 shows the height of the dense core and a picture of the cloud. How can we compare both and get a "good agreement"?

We will include Fig14 in the text and add the drone data. We focused in the comparison on the spread of the cloud - we will work here again on the comparison.

L396: How do you know the air blast never exceeded 5kPa?

The powder cloud reached the barns, but we did not observe any damage to the windows or other infrastructure that got damaged.

F16: Please annotate the mentioned avalanche arm (L399). Do both panels show snow depth? Or does the simulation show the deposition depth? What is the bow shaped deposition in the simulation and why is the other deposition in the river/road only, and not as smoothly distributed as suggested by Glaus, 2023, Fig3? Please extend description and discussion on Fig16.

Sure we can annotate the avalanche arm. The left pannel shows the measured snow depth and the right pannel the deposition height. In Glaus 2023 we used a different parameter set and showed the snow height of the last calculation step vs in this graphic the deposition height. We will work on the discussion.

L405ff: Why is the simulated deposition volume outside the mapped area not taken into account?

In the area where the avalanche traverses the forest, our remote sensing measurement method reaches its limits. The presence of trees creates gaps in our snow measurements, leading to unreliable data in those regions. Therefore, we confined our comparison to the run-out area, where we are confident that our measurements accurately reflect the conditions.

L407ff: Sentence is unclear. Reformulate and extend.

We will reformulate

L409ff: The sentence comes rather unexpectedly. Where do I see wind scour? What does that mean for the simulations? Have you run the simulation with less snow?

Yes, we also conducted simulations using the snow measurements from individual avalanche tracks. We can provide these results to the reviewer if needed. We chose not to include them in the publication to avoid extending its length.

L415: Impact pressure of powder cloud does not play a role in this publication. I also doubt that it's the most relevant danger for cars and people.

It strongly depends on the region. If you have trucks on the road, the impact pressure will not be negligible.

L418: I don't believe the model assumptions are correct for temperatures near melting, and this already starts at -1 to -2°C. The Ruchi avalanche shows -8 to -5 degrees.

Correct, as the title of the publication states we focus on cold avalanches with this model. For warm avalanches, we don't have enough calibration data.

L429: Evolution of finger was not well discussed.

We will improve the discussion.

L433: Snow cover models are not needed to calculate cloud coverage. Snow cover models would directly give a snow temperature and more (see work of Wever,2016,2018). I don't believe that cloud coverage will alter the snow temperature more than 20cm into the snow cover, but relevant avalanches for the road have easily >1m release height.

Let's give it a try. This approach would be an unconventional method if we don't have a snowpack simulation or sensors in the snow cover. This also means that we would accept a larger margin of error. On a cloudy night, the temperature profile within the snowpack is quasi constant. Consequently, it might be possible to estimate the temperature using a surface sensor. As I mentioned before in the Alps we don't observe a very large range of average temperature values in the snowcover. Hence, we can at least try to get a rough approximation.

Comments on references

We will clean up the biblography and include all your inputs.

References

Glaus, J., Wikstrom-Jones, K., Buehler, Y., Christen, M., Ruttner-Jansen, P., Gaume, J., and Bartelt, P.: RAMMS::EXTENDED – Sensitivity Analysis OF Numerical Fluicized Powder Avalanche Simulationin Three-Dimensional Terrain, 2023.

Li, X., Sovilla, B., Jiang, C., and Gaume, J.: The mechanical origin of snow avalanche dynamics and flow regime transitions, The Cryosphere, 14, 3381–3398, doi: 10.5194/tc-14-3381-2020, 2020.

Ruttner-Jansen, P., Glaus, J., Wieser, A., and Buehler, Y.: A Measurement system for mapping snow distribution changes in an avalanche release zone, 2023.