Response to Referees

Probabilistic avalanche runout modelling for daily risk management of traffic routes

Julia Glaus, Jan Kleinn, Lukas Stoffel, Pia Ruttner, Katreen Wikstrom Jones, Johan Gaume, and Yves Bühler

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Dear Editor and Referee,

We greatly appreciate your detailed and constructive feedback. This has been invaluable for further enhancing the quality of our manuscript. We have listed your comments into the blue boxes and enumerated them so that we can address each part separately below. We have marked the comments from the anonymous reviewer as R2, and we have added our potential changes and insights. The provided lines numbers refer to the original manuscript. Sincerely,

Julia Glaus & co-authors

Response to Anonymous Referee

General Assessment

R2-0: **Comments on the paper:** Probabilistic avalanche runout modelling for daily risk management of traffic routes

By Julia Glaus, Jan Kleinn, Lukas Stoffel, Pia Ruttner, Katreen Wikstrom Jones, Johan Gaume, and Yves Bühler

The paper introduces an automated modelling framework to help local safety experts manage avalanche risk along alpine transport routes. Traditional hazard maps are too static for daily decisions such as road closures or avalanche control.

A real-time probabilistic framework for cold powder snow conditions is porposed. It combines weather observations, SNOWPACK snow-cover simulations, and the RAMMS::Extended avalanche model. Running multiple simulations for different release scenarios, it produces probability indication maps showing the likely extent and intensity of avalanche runout during a given forecast period.

General Comments

R2-1: This paper is well written and interesting but suffers a major drawback that needs more explanations. Its overall structure is unclear and hard to follow. The study site, avalanche locations, and meteorological installations should be presented fully earlier, with the relevant figures. The methodology section should clearly explain both the probabilistic approach and its validation, separating methods from results. More detail is also needed to make the study reproducible, especially on simulations and parameters.

Thank you very much. We will expand the description of the study site as proposed in Review comment R1-7 by including detailed maps of the avalanche paths. Additionally, we will add the measurement values and calculations in the Supplement to improve the reproducibility of the test cases, as proposed in Review comment R1-5. We will also revise the methodology section to more clearly separate the description of the probabilistic approach from the validation and results.

The reviewer's comment also led to an in-depth discussion within our group on the stability approach and how it is described in the manuscript. This helped us to improve the explanation of the stability approach. During this revision, we identified a typo in the code used for the stability-based release approach. Correcting this typo slightly reduces the resulting release probabilities, but does not affect the interpretation of the results or the conclusions of the manuscript. We corrected the calculations accordingly and updated the corresponding chapter and Figure 10. Please find a new version of the Stability Approach description here in the Appendix.

R2-2: The “probability” term in the title is not relevant, if it is not demonstrated that you reach a resolution of at least 1/1000 probability to reach the road, because you must give the argument about the threshold used. In the example it is mandatory to provide the total number of simulations used.

Response to reviewer

We acknowledge that we are not fully sure whether we correctly understood the reviewer’s question, but we have done our best to address it. As far as we know, rules of thumb such as a minimum of 1000 simulations mainly apply to Monte Carlo type approaches, where the output distribution is approximated by repeated random sampling. Since our approach is analytical, the required number of simulations is defined by the convergence of the model results rather than by a fixed sampling criterion. In the manuscript, we already used the term “probability indication map” to distinguish our result from a fully calibrated probabilistic hazard estimate. We will add a sentence to better motivate this terminology and will report the number of simulations used for each map directly in the corresponding figure caption and adjust the title.

To address the reviewer’s concern, we conducted a convergence analysis shown in Figure R1. For simplicity, this analysis uses a single representative release zone and varies the release height between 40 and 140 cm. The resulting probability indication maps show that the spatial hit-frequency pattern stabilizes after approximately 50 release-height scenarios, and adding the remaining available simulations does not materially change the map. This indicates that, for the objective of the presented maps, the relevant criterion is not a predefined probability resolution, but the convergence of the spatial pattern used for decision support.

We agree that this would be different if the proposed workflow were applied with an avalanche dynamics model in which the friction parameters μ and ξ have to be prescribed as fixed input parameters. In that case, additional simulations with varied friction parameters would be required to represent model-parameter uncertainty and we would have to apply a Monte Carlo approach.

We would therefore like to clarify that a fixed resolution of 1/1000 is not a necessary criterion for the objective of the presented maps. Such a value would be relevant if the aim were to estimate rare-event probabilities at a prescribed 10^{-3} level. This is not the purpose of our workflow. The maps are intended as probability indication maps, i.e. as spatial indicators of the relative frequency with which plausible avalanche scenarios reach a given location under the considered snow and weather conditions. Refining the probability resolution beyond the level at which the spatial pattern has converged would not provide a substantially improved decision basis for the intended traffic-safety application.

To give an example of our system: in our operational application, the release-height scenarios are combined with 96 potential release areas for Brämabüel, resulting in 6912 avalanche simulations for the Brämabüel 2019 small release zones case.

Title: *Probability indication maps for avalanche runout for decision support in daily traffic-rout risk management*

Line 107: *Because the probabilistic framework relies on a limited ensemble of input scenarios derived from measurement stations, the resulting values should be interpreted as relative probability indicators rather than absolute probabilities. We therefore refer to the outputs as probability indication maps.*

Discussion: *The presented dataflow is not limited to a specific avalanche dynamics model. However, applying it with another numerical simulation tool requires that the model is sufficiently sensitive to the snow-cover and flow regime represented in the input scenarios. In RAMMS::EXTENDED, the frictional behavior is dynamically calculated for different snow conditions, so we treat the friction parameterization as part of the calibrated model setup. If the workflow were applied with a model based on fixed Voellmy friction parameters, such as prescribed values of* μ *and* ξ *for cold snow, very cold snow, or highly erosive conditions, the uncertainty associated with these calibrated parameters would become more important. In such an application,* μ *and* ξ *should be included as additional uncertain input variables in the probabilistic calculation.*

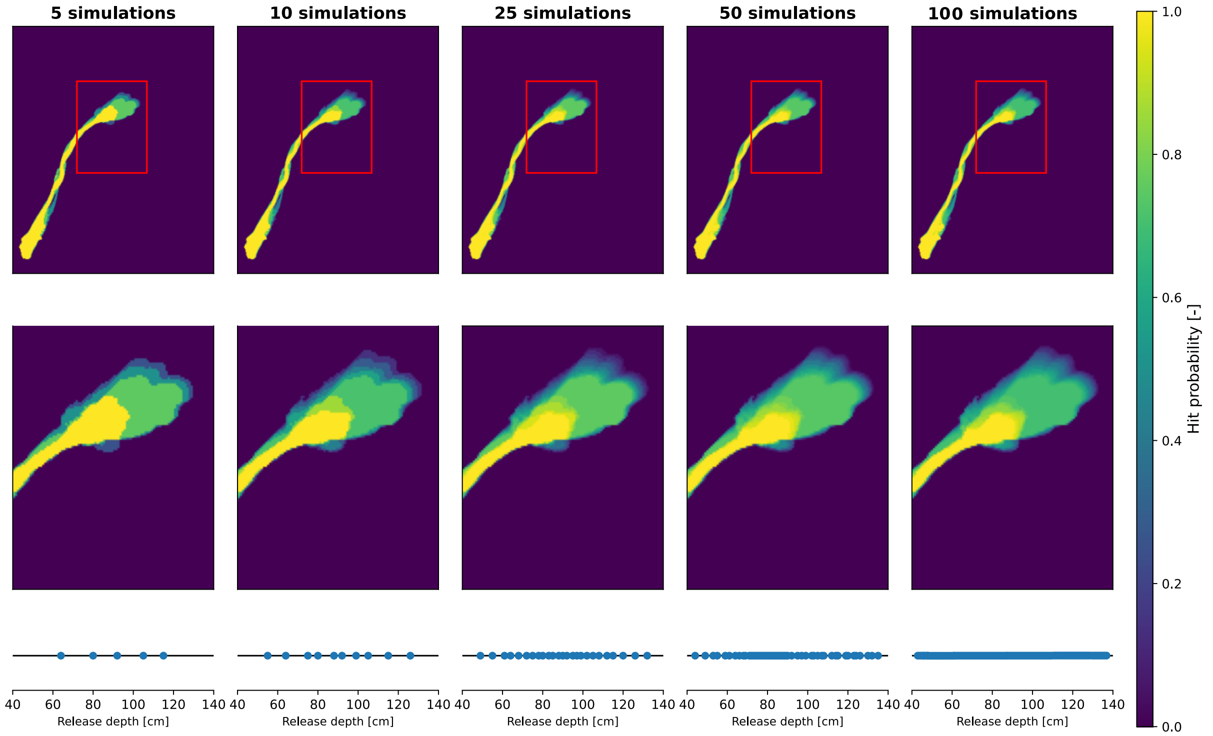
5 simulations 10 simulations 25 simulations 50 simulations 100 simulations

Figure R1: Convergence analysis for a single representative release zone located at Brämabüel in Track 2. The release depth is varied between 40 and 140 cm, representing a realistic range of potential snow depths in the release zone. The panels show unweighted hit probability maps for increasing numbers of release-depth scenarios. The runout area is marked with a red rectangle in the first row and shown as a zoom in the second row. The bars below the maps indicate the release-depth values included in each ensemble, sampled to approximate a Gaussian distribution over the investigated range. The similarity between the 50-scenario map and the 100- scenario set indicates that the spatial pattern of the probability indication map has converged for this case.

> R2-3: If the probability resolution is above 1/1000 it means that this is not a probability analysis but a worst-case scenario type of analysis. This must be mandatorily demonstrated. If the probabilistic approach is relevant, a clearer discussion and comparison of the probabilistic results with the observed data is needed. For example, the authors could report on the probability of reaching the observed runout and discuss those values.

We acknowledge that we are not fully sure we understand the reviewer's question. We did our best to answer it. We agree that the model results should be compared more clearly with the observed event. However, we only have information for the Brämabüel 2025 event that shows the number of explosive control attempts that didn't release an avalanche. This is not sufficient to calibrate or validate an absolute release probability for each track. We therefore do not use the observations to derive a real-world occurrence probability. Instead, we use them to assess whether the observed avalanche runout is reproduced within the simulated ensemble and whether it falls within a high- or low-frequency part of the probability indication map. We will add additionally the probability calculated in the probability indication maps for the very front of the measured avalanche outlines. This discussion can be added to the current discussion of the calculated probability along the road as the numbers will be almost the same for the avalanches that reached the road.

> R2-4: Artificially triggered avalanches help validate runout modelling, including fracture depth, entrainment, stopping distance, and road impact. However, they cannot by themselves validate the probabilistic release component, because triggering alters the failure process and fixes the timing, location, and loading. Validation should therefore separate runout validation given release from full probabilistic validation of natural avalanche impact. This needs to be discussed, or site clear study about this issue. Is it conservative or the inverse?

We agree that artificially triggered avalanches cannot fully validate the natural release probability, because the timing, location, and local loading are partly imposed by the control operation. We therefore clarify that these events are used mainly to validate the runout component conditional on release, and to assess whether the observed avalanche falls within relevant areas of the probability indication map. From an operational perspective, however, a successful artificial release in an area with non-negligible predicted release propensity still provides useful support for the practical relevance of the map, while not constituting a calibrated validation of natural avalanche occurrence probability.

See Review Answer R1-6

0.1 Specific Comments

R2-5: A clear definition of core hit and cloud hit would be helpful.

We added the definition directly after introducing the hit probability.
L221: *For the avalanche core, the hit probability is calculated based on the maximum avalanche height per pixel, and for the cloud, the maximum powder pressure. The avalanche height is capped below 10 cm, and the powder cloud below 0.5 kPa.*

R2-6: The figure captions could be improved to clearly indicate the study site (with a reference to the figure showing its location) and the method used (frequency or stability).

We added the study side name and method to all figure captions.

R2-7: Suggestion: include a sensitivity analysis of the DEM spatial resolution and/or the temporal resolution of the meteorological stations.

We thank the reviewer for this valuable suggestion. Sensitivity studies of avalanche dynamic modelling have been performed by (Bühler et al., 2011) and also an analysis of the DEM resolution for RAMMS::Extended has been conducted by (Miller et al., 2022), showing that too detailed DEM resolutions can introduce artificially high terrain friction, which is not representative for most cases where the avalanche flows over a surface that is smoothed out by the snow cover; since RAMMS::Extended is calibrated for a 5 m spatial resolution, we therefore decided to retain this resolution. Regarding the temporal resolution of the meteorological input, the relevant time window primarily depends on the timing of the snowfall event; in our examples, we calculate the probability indication map at 12:00, as this reflects the practitioners' working schedule in Davos. In principle, the maps could also be calculated at an hourly resolution, provided that the snowpack model runs at the same resolution, which could be beneficial for snowfall events lasting several days; however, for the local operational workflow, decisions regarding potential road closures have to be made substantially earlier, to allow the necessary preparations. We can include the temporal resolution of the input data in the discussion, while for this publication, we want to focus on presenting a general tool that can be adjusted to the needs of the specific region.
L348: *Consequently, probability indication maps should be regarded as time-dependent products valid only for the specific forecast window for which they are generated. The appropriate issuing time depends on the operational application. For example, a map may be useful before the onset of a forecasted snowfall event to support early road-closure decisions, or it may be updated during or after the event as new meteorological and snowpack information becomes available.*

R2-8: **Line 8:** "in this project" is not really relevant, is it research or research project, etc.?

We removed the wording "in this project".

R2-9: **Lines 32–37:** as RAMMS is commercial software, it would be fairer to give a more complete list of software open source, the name of avaflow is r.avaflow, and if would be also avaframe, etc. Omitting opensource software can be an ethical issue in science if only presenting commercial ones...

We thank the reviewer for this important comment and agree that the list should better reflect both commercial and open-source avalanche simulation tools. We will revise the sentence accordingly by correcting AvaFlow to r.avaflow and by adding further open-source frameworks (additionally to the already mentioned MoT-Voellmy) and reference

the ISeeSnow project as an overview of some simulation tools.
L32–L37: *Hazard maps are developed from historical event records and are increasingly complemented by numerical simulation tools for avalanche dynamics, such as RAMMS::Avalanche (Christen et al., 2010), SamosAT (Sampl, 2007), r.avaflow (Mergili et al., 2017), OpenFOAM (Rauter and Kowalski, 2024), MoT-Voellmy (Vicari et al., 2025), and ELBA (Keiler et al., 2006). A more complete list of depth-averaged tools is provided in the model intercomparison project in Wirbel et al. (2026).*

R2-10: **Line 122:** give the total number here!

We added the information to the paragraph. The original estimate of less than 10 was corrected because we did not include the avalanches from path 0 in this calculation.
L124: *Only 12 are documented as reaching the road between Duchli and Chaiseren from 1999 to 2025.*

R2-11: **Line 131:** mor information about the levels!

We added a description of the development of the avalanche problems and danger level during the snowfall.
L131: *The avalanche bulletins are issued twice daily, at 08:00 and 17:00 LT. From 11 January 2019 onwards, danger level 3 was forecast above 2000 m for all aspects due to new snow and wind-drifted snow. The danger level increased to 4 in the bulletin issued on 13 January 2019 at 17:00 LT, with medium-sized spontaneous avalanches expected and warnings that soft snow below weak layers could be easily eroded. By the evening bulletin of 14 January 2019, very large spontaneous avalanches were expected in nearby warning regions with danger level 5, while Brämabüel itself remained in a region forecast with danger level 4 but close to the level-5 warning region.*

R2-12: **Lines 156–158:** unclear!

We rephrased the paragraph:
L156–L158: *The potential release areas are identified using the automated algorithm by Bühler et al. (2018), which identifies release areas based on steepness, terrain shape, and surface roughness for small avalanches (volumes 5,000–25,000 m^3) and medium-sized avalanches (25,000–60,000 m^3) (Bartelt and Christen, 2025). Larger release volumes are not considered, as such events are typically associated with very high avalanche danger levels, under which road closures are implemented as a precautionary measure.*

R2-13: Maybe the paper of Fischer J-T, Kofler A, Huber A, Fellin W, Mergili M, Oberguggenberger M. Bayesian Inference in Snow Avalanche Simulation with r.avaflow. Geosciences. 2020; 10(5):191. `https://doi.org/10.3390/geosciences10050191` can be cited.

Thank you very much for this relevant reference. We have added it to the introduction.
L71: *Fischer et al. (2020) demonstrate a probabilistic back-calculation framework with r.avaflow, where uncertainties in observed avalanche data and model parameters are propagated into conditional runout probabilities.*

A Stability Approach

Stability Approach

The impact of an avalanche at a given pixel requires (i) the occurrence of a release with a given fracture depth and stability index, and (ii) sufficient avalanche propagation to reach the pixel. In the stability approach, the natural stability index is used to weight the scenario probability associated with the corresponding fracture depth and potential release area. We therefore do not directly calculate the absolute release probability of an avalanche, but use the stability index as a relative weighting factor. In the following, these two components are combined at the level of individual release areas to derive a spatially distributed indication of hit probability for each pixel.

First, we calculate the set of fracture depths $\mathcal{H} = h_1, h_2, \ldots, h_N$ in the same way as in the frequency approach. To account for the stability of each PRA under the predicted snow load, we calculate the natural stability index S_n (Jamieson and Johnston, 2001), defined as the ratio between weak-layer shear strength τ_p and the applied shear stress of the slab. The natural stability index is given by

$$S_n = \frac{\tau_p}{\rho g D \sin(\alpha)}, \tag{1}$$

where ρ is the slab density, g the gravitational acceleration, D the fracture depth (slope normal), and α the mean slope angle of the release area. The parameters τ_p, ρ, and D are obtained from SNOWPACK simulations, while α is derived from the terrain model.

To convert S_n into a release probability, an error function (ERF) is fitted as described in Appendix A, assigning high release probability for $S_n < 1$, a transition zone around $S_n \approx 1.5$, and low release probability for $S_n \geq 2$ (Monti et al., 2014). For each fracture-depth scenario h_j and release area i, the corresponding stability-based release probability is calculated as

$$p_{j,i} = f(S_{n,j,i}), \tag{2}$$

where $f(S_{n,j,i})$ denotes the normalized stability-to-probability mapping. In this way, release areas with lower stability indices receive higher release-probability weights.

The fracture depths are then grouped into K discrete bins b_k of width 0.1 m, with $k = 1, \ldots, K$. For each bin b_k and release area i, the bin-wise stability weight is obtained by summing the individual release probabilities of all fracture-depth scenarios falling within that bin and normalizing by the total number of fracture-depth scenarios,

$$w_{k,i} = \sum_{h_j \in b_k} \frac{1}{N} p_{j,i}. \tag{3}$$

Thus, $w_{k,i}$ represents the stability-weighted contribution of release area i for fracture-depth bin b_k.

For each release area i and fracture-depth bin b_k, simulation outputs are converted into binary hit indicators such that

$$I_{k,i}(x) = \begin{cases} 1, & \text{if the avalanche reaches pixel } x, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

If multiple simulations are available for the same (b_k, i) combination, a pixel is considered hit if at least one simulation reaches the pixel. This binary indicator describes whether the runout from a given release area and fracture-depth bin affects pixel x, while the corresponding probability weight is provided by $w_{k,i}$.

For a given pixel x, the hit probability is obtained by combining the weighted contributions of all combinations of release area and fracture depth. Assuming statistical independence between the individual scenarios, and with A being the total number of potential release areas, the hit probability is given by

$$P_{\text{hit}}(x) = 1 - \prod_{k=1}^{K} \prod_{i=1}^{A} \left(1 - w_{k,i} I_{k,i}(x)\right). \tag{5}$$

This formulation represents the probability that at least one scenario reaches pixel x, while keeping the resulting probability bounded between 0 and 1.

References

Bartelt, P. and Christen, M.: Snow Avalanche Dynamics with RAMMS::Extended, Technical manual, WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland, URL `https://ramms.ch/wp-content/uploads/RAMMS_EXT_Manual.pdf`, 2025.

Bühler, Y., Christen, M., Kowalski, J., and Bartelt, P.: Sensitivity of Snow Avalanche Simulations to Digital Elevation Model Quality and Resolution, Annals of Glaciology, 52, 72–80, doi: 10.3189/172756411797252121, 2011.

Bühler, Y., von Rickenbach, D., Stoffel, A., Margreth, S., Stoffel, L., and Christen, M.: Automated snow avalanche release area delineation – validation of existing algorithms and proposition of a new object-based approach for large-scale hazard indication mapping, Natural Hazards and Earth System Sciences, 18, 3235–3251, doi: 10.5194/nhess-18-3235-2018, 2018.

Christen, M., Kowalski, J., and Bartelt, P.: RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain, Cold Regions Science and Technology, 63, 1–14, doi: 10.1016/j.coldregions.2010.04.005, 2010.

Fischer, J.-T., Kofler, A., Huber, A., Fellin, W., Mergili, M., and Oberguggenberger, M.: Bayesian Inference in Snow Avalanche Simulation with r.avaflow, Geosciences, 10, 191, doi: 10.3390/geosciences10050191, number: 5 Publisher: Multidisciplinary Digital Publishing Institute, 2020.

Jamieson, B. and Johnston, C. D.: Evaluation of the shear frame test for weak snowpack layers, Annals of Glaciology, 32, 59–69, doi: 10.3189/172756401781819472, 2001.

Keiler, M., Sailer, R., Jörg, P., Weber, C., Fuchs, S., Zischg, A. P., and Sauermoser, S.: Avalanche risk assessment – a multi-temporal approach, results from Galtuer, Austria, Natural Hazards and Earth System Sciences, doi: 10.5194/nhess-6-637-2006, 2006.

Mergili, M., Fischer, J.-T., Krenn, J., and Pudasaini, S. P.: r.avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows, Geoscientific Model Development, 10, 553–569, doi: 10.5194/gmd-10-553-2017, 2017.

Miller, A., Sirguey, P., Morris, S., Bartelt, P., Cullen, N., Redpath, T., Thompson, K., and Bühler, Y.: The impact of terrain model source and resolution on snow avalanche modeling, Natural Hazards and Earth System Sciences, 22, 2673–2701, doi: 10.5194/nhess-22-2673-2022, 2022.

Monti, F., Schweizer, J., and Fierz, C.: Hardness estimation and weak layer detection in simulated snow stratigraphy, Cold Regions Science and Technology, 103, 82–90, doi: 10.1016/j.coldregions.2014.03.009, 2014.

Rauter, M. and Kowalski, J.: OpenFOAM-avalanche 2312: depth-integrated models beyond dense-flow avalanches, Geoscientific Model Development, 17, 6545–6569, doi: 10.5194/gmd-17-6545-2024, publisher: Copernicus GmbH, 2024.

Sampl, P.: SAMOS-AT – Beschreibung der Modelltheorie und Numerik, Tech. rep., AVL List GmbH, Graz, Austria, 2007.

Vicari, H., Tran, Q.-A., Juel, M., and Gaume, J.: The role of dilatancy and permeability of erodible wet bed sediments in affecting erosion and runout of a granular flow: Two-phase MPM–CFD simulations, Computers and Geotechnics, 185, 107 307, doi: 10.1016/j.compgeo.2025.107307, 2025.

Wirbel, A., Oesterle, F., Chambon, G., Faug, T., Gaume, J., Glaus, J., Hergarten, S., Issler, D., Ito, Y., Martini, M., Mergili, M., Rauter, M., Robl, J., Rosatti, G., Tsunematsu, K., Tollinger, C., Vicari, H., Zugliani, D., and Fischer, J.-T.: ISeeSnow v1.0 – a pilot study for snow avalanche model intercomparison of thickness-integrated shallow flow approaches and beyond, EGUsphere, pp. 1–56, doi: 10.5194/egusphere-2025-6053, 2026.