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

June 24, 2026

Dear Editor and Referees,

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 co-author team, Andrea Bruckmeier and Erich Peitzsch, as R1, and we have added our potential changes and insights. The provided lines numbers refer to the changelog manuscript. Sincerely,

Julia Glaus & co-authors

Response to Andrea Bruckmeier and Dr. Erich Peitzsch

General Assessment

R1-0: The manuscript introduces an innovative framework to support operational decision making for avalanche forecasting and road closures combining probabilistic avalanche runout modeling with meteorological input and snow cover simulations. Specifically, combining weather station data and snow cover simulation outputs to better assess potential fracture depths, snowpack characteristics and snow conditions within the avalanche path displayed in a probability indication map provide a huge potential for daily avalanche forecasting.

The maps present a hit probability for the avalanche path and runout that is calculated mainly based on the frequency approach. Only one scenario is additionally calculated based on the stability approach. The frequency approach considers the probability for a certain snow loading and weak-layer interaction to define fracture depth classes to calculate the hit probability. This approach does weigh the probabilities of new snow and buried weak layer equally and is less complex on necessary input variables as compared to the stability approach. The results for the 2019 event show that the higher probability values match the observed avalanche paths well using the frequency approach. In 2025, the probability indication maps differ from the real avalanche runout mainly due to differences in weak layer characteristics influenced by the slope exposure. This shows us how sensitive the framework is to the quality and availability of input variables.

The authors describe the background and the objectives well in the Introduction. The Methods are very detailed describing the used approaches. However, this section would benefit from additional clarification, particularly regarding the definition of the validation events (see comments). The Results are comprehensive, and the Discussion provides a reasonable interpretation of the findings and limitations. Additional detail on the study design, results, and broader context could further strengthen the overall manuscript (see comments).

I am very grateful for the opportunity to review this manuscript. Overall, I think this is a promising manuscript that provides a framework combining daily snowpack conditions and terrain with runout probability that can potentially be used in avalanche operations. The authors' approach to identifying the least amount of input parameter necessary for the most representative daily snowpack conditions makes this paper particularly meaningful and potentially applicable in different regions. After minor revisions, this paper is a valuable contribution and relevant advancement for operational decision-making processes for avalanche risk management along infrastructure corridors.

This is a co-review with my supervisor, Dr. Erich Peitzsch.

General Comments

R1-1: **Validation dataset:** Considering the complexity, data availability, time requirements, and resources necessary to analyze each event in the level of detail presented in this manuscript, the reduced number of analyzed events appears justified. Nevertheless, it may be beneficial to acknowledge this more explicitly as a potential limitation within the discussion section, rather than only briefly mentioning it in the conclusion. While the arguments for the selective approach are logical, clarifying this point earlier in the manuscript could strengthen the transparency of the study.

We agree that it takes a lot of time to prepare test cases, especially to find avalanche events that are well documented and for which the forecast and measurement data can be reconstructed. We plan to add the two following statements:

L131: *Due to the limited data availability and the time requirements associated with detailed event reconstruction, we focus on two winter seasons with well-documented avalanche events. We additionally apply the framework to older events in the same region, for which fewer input data are available, such as detailed information on release depth.*

L413: *A limitation of this study is that the framework was evaluated using a limited number of avalanche events from one specific region, Davos. The selected cases primarily involve situations in which the avalanche tracks were snow-covered from the release area to the runout zone. These conditions may not hold in other cases, as for example in late-season conditions where avalanches subsequently flow over snow-scarce or grass-covered slopes at lower elevations. Such conditions make snow-height information along the full elevation gradient essential, requiring representative input from both valley and mountain stations. Future work should therefore test the framework operationally over longer periods and across different climatic regions to assess its transferability and data requirements.*

R1-2: **Dataset description:** As a reader, I found the description of the analyzed dataset somewhat difficult to follow. In the Test Site and Data section (Section 2), four avalanche events for validation are introduced, although only three of these are described in greater detail. It is not entirely clear whether these refer to the same avalanches, whether each avalanche event contains multiple avalanches, or whether each case study includes several individual events, as implied later in the manuscript (L255).

In Figure 5, I can only identify three events. The dashed and dotted lines may indicate additional avalanches occurring on specific days; if so, this could be clarified in the figure caption. Furthermore, Section 4.3 introduces additional historical avalanche events. Although this is briefly mentioned in the final paragraph of Section 2, Figure 3 gives the impression that more avalanches were analyzed, rather than only four additional years.

To improve clarity, it may be helpful to display only the avalanches included in the analyses and to distinguish more clearly between validation data and additional datasets. In addition, displaying all events in a table including event, location, trigger and runout location and consistently referring to each event throughout the manuscript using a standardized naming code could greatly improve readability and help the reader follow the analysis.

Thank you very much for pointing out this inconsistency. We will add an overview of all events in the Chapter 2 Test Site and Data, as shown in Table 1. For Figure 5, we had 3 avalanches artificially released from the helicopter directly after each other. We will clarify this in the caption and added it in the graphic as shown in Figure R1. Additionally, we can add in the attachment an overview of the avalanche outlines (including making it consistent by using the dashed line for the Brämabüel events and dotted for Breitzug).

Table 1: Overview of the avalanche events used in this study.

Date	Time [CET]	Region	Path	Trigger	Mapping	Release depth	Runout	Data use
29 Jan 2025	08:00	Brämabüel	Track 1	Artificial	Drone	lidar	Slope	Validation dataset
28 Jan 2025	17:00	Breitzug	Breitzug	Artificial	Manual	lidar	Runout	
15 Jan 2019	10:00	Brämabüel	Track 1–3	Artificial	Drone	Drone	Road	
15 Jan 2021	12:00	Brämabüel	Track 1–3	Natural	Manual	–	Runout	Additional dataset
23 Jan 2018	Night	Brämabüel	Track 1	Natural	Manual	New snow	Road	
23 Jan 2018	08:30	Brämabüel	Track 1	Artificial	Manual	New snow	Road	
10 Mar 2017	07:00	Brämabüel	Track 1,3	Artificial	Manual	–	Runout	
20 Feb 1999	08:50	Brämabüel	Track 1–3	Natural	Manual	–	Road	

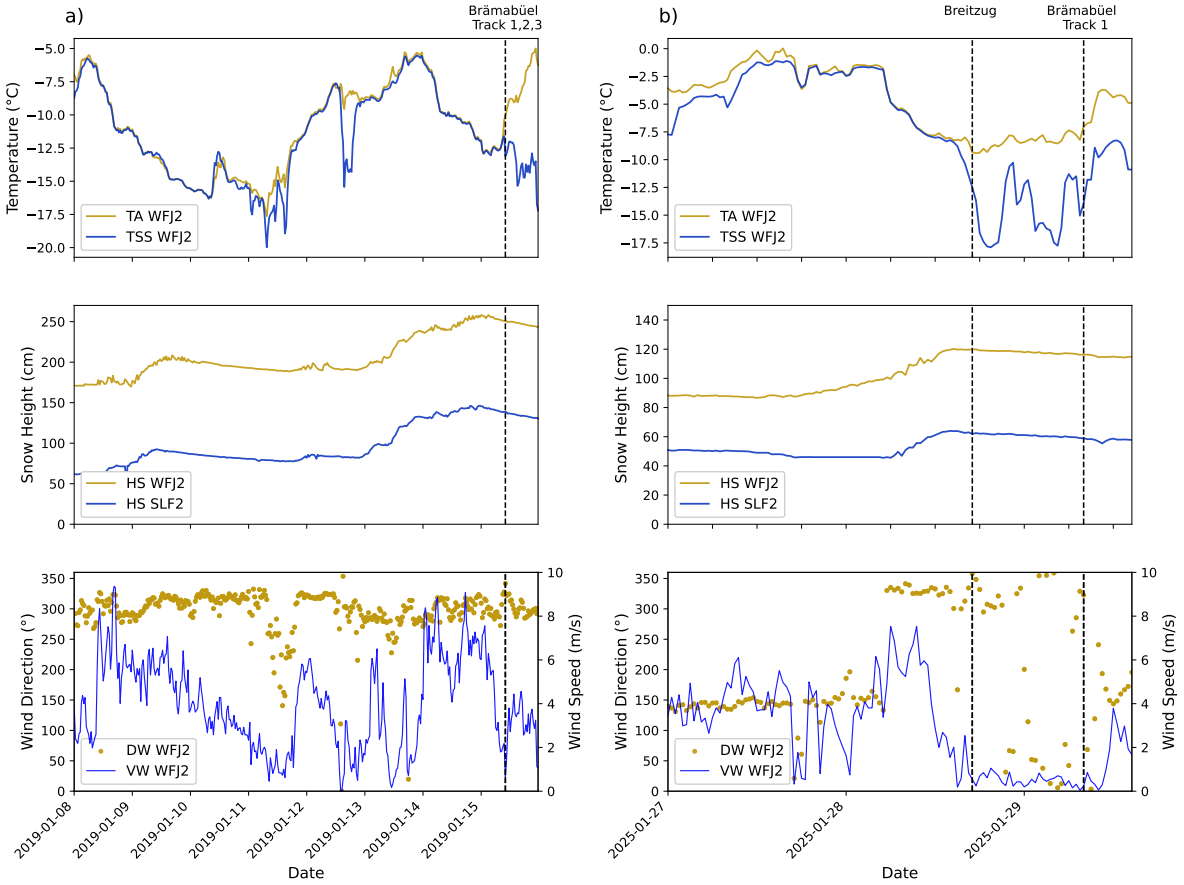


Figure R1: Time series of meteorological observations recorded at the Weissfluhjoch (WFJ2) and Davos valley (SLF2) IMIS stations during the snowfall events preceding the evaluated avalanche releases. Shown are air temperature (TA), snow surface temperature (TSS), total snow height (HS), wind direction (DW), and wind speed (VW). The timing of avalanche release and name of the track is indicated by vertical bars. Columns (a) and (b) correspond to the snowfall periods in 2019 and 2025, respectively. Data source: IMIS

R1-3: **MAE for data-sparse areas:** Many data-sparse forecasting regions often rely on only one or two

weather stations. Therefore, rather than emphasizing the reduction from seven to six or five weather stations, a more detailed comparison using only one or two stations may provide a more practically relevant assessment.

We agree that, in this project, we first present an "artificial" number of weather stations to determine whether this really improves our system. One of the main takeaways from our approach to reducing the number of weather stations is that increasing density didn't improve the quality of the probability indication map. Resulting in the takeaway that the correlation of the weather station with the avalanche release zone is more relevant than having many weather stations. Still, we decided not to reduce the analysis to a single station in the first draft, as this would move away from the probabilistic approach and back to the system presented in Vera Valero et al. (2016). Additionally, the snow cover and temperature gradient estimates require at least two weather stations at different altitudes. We could include the corresponding maps for the individual stations where the gradients are set to zero in the supplements (e.g., the calculation based solely on the IMIS station WFJ, as shown in Figure R2). However, this shifts the focus toward how well each weather station correlates with a specific avalanche release zone. The goal in this project is to show a potential workflow. In the end, the input data needs to be discussed on a case-by-case basis. We will add this as a paragraph in the discussion.

L442: *The calculations could also be run with a single weather station by setting these gradients to zero. However, this would prevent the system from representing situations in which avalanches flow into lower-elevation areas with little or no erodible snow cover, or into zones with a warmer snowpack.*

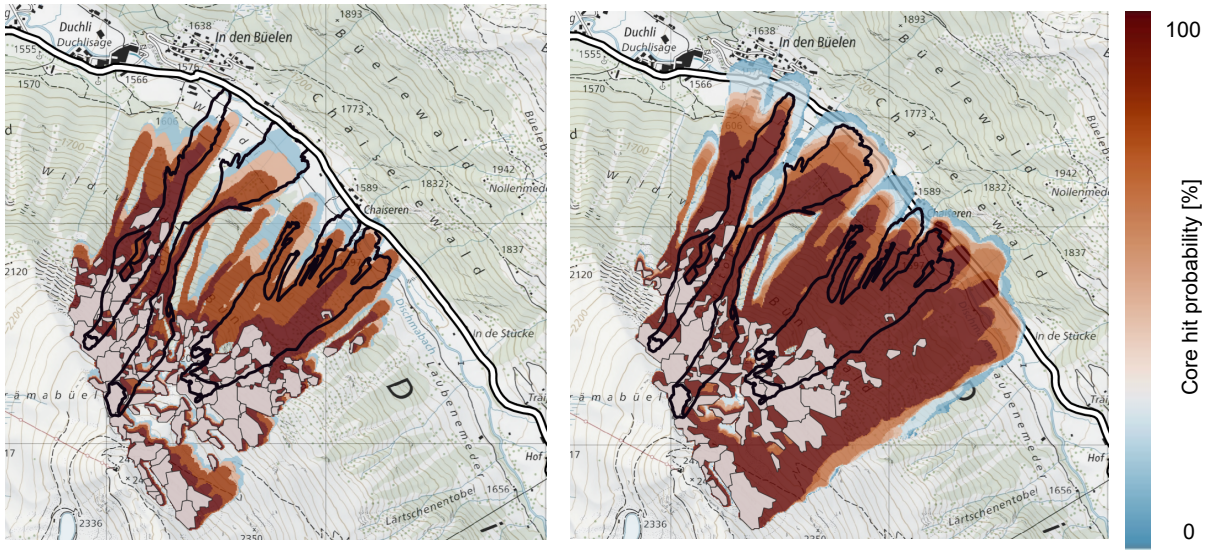


Figure R2: Calculation of the probability indication map for the core for small and medium size release zones at Brämabüel for the 2019 case study.

R1-4: **Frequency and stability approach:** It would be helpful to include a brief explanation around L256 regarding the decision to use the frequency approach instead of the stability approach. Although both methods are described in detail in the methods section, the stability approach is only applied in one specific scenario. Expanding the discussion of the two approaches (L336-L342), particularly emphasizing the advantages and applicability of the frequency approach, would strengthen the manuscript.

We agree that the rationale for applying the frequency approach rather than the stability approach should be explained more clearly. We will add a sentence around L256 pointing out that we only do the stability approach on one example due to calculation effort. We have therefore expanded the discussion to clarify that the frequency approach was selected not only as a simplification, but also because it has practical advantages for large scenario ensembles.

L311: *We focus only on one example case for the stability approach due to the additional calculation and storage needs.*

L476: *We tested two approaches to weight the release scenarios: a frequency-based approach, in which storm-snow and old-snow releases are weighted equally, and a stability-based approach, in which the weighting depends on the natural stability index derived from SNOWPACK calculations. Overall, we get similar probability indication maps*

from these two approaches, but the map generated based on the stability approach shows a more differentiated picture of the runout distances. The frequency-based approach is intentionally simple and computationally efficient, as it requires only an aggregated avalanche overlap map for each scenario. This simplicity is advantageous for operational applications and avoids introducing additional uncertainty from simulated weak-layer stability. In contrast, the stability approach is more data-intensive because it requires storing individual avalanches and introduces an additional source of uncertainty by relying on weak-layer stability information simulated with SNOWPACK. Moreover, the stability approach is based on the natural stability index and therefore provides a more nuanced representation of spontaneous release conditions. For artificially triggered releases, however, this information is not directly transferable, since the released weak layer and release depth may depend on the applied release method. In such cases, the stability approach may yield a conservative probability indication map. Nevertheless, the stability approach may be advantageous in situations with a broad range of release-zone steepness, as it reduces the influence of comparatively flat release zones in the probability indication map. In practical applications where limited information on weak-layers is available—for example, when only a single snowpit provides indications of weak-layer properties—this weighting could be adjusted based on expert judgement. Alternatively, the stability of the weak-layer could be parametrized based on the shear strength as a function of fracture depth, following the formulation proposed by Bažant et al. (2003) and further refined by Gaume et al. (2014); Meloche et al. (2024). This would allow the stability index to be estimated in a manner more aligned with the stability approach. With evolving research on the prediction of snowpack stability and release-zone size, additional statistical models could be coupled to the dataflow (Gaume et al., 2012).

R1-5: **Meteorological input data:** I would suggest including an overview of the parameters and variables derived from the weather stations that were used to force SNOWPACK, as well as the parameters applied for forecasting daily conditions.

In addition to weather station density, the availability of specific meteorological variables may represent a critical limitation for implementing this approach in other regions. Discussing this aspect could improve the broader applicability of the study.

We will include the detailed input values and the weight calculations in the ´supplements. An example for the input data for the Brämabüel 2019 test case is shown in Tables 2 and 3.
Regarding station density, we like to refer to our answer for review question R1-3. For our specific case study at Brämabüel, we have ongoing work within the same SNF project that further investigates this aspect by comparing lidar-derived snow heights in the release zone of track 1 at Brämabüel with flat-field IMIS station measurements over the season. Preliminary results indicate that the measured snow heights at the geographically closest station, such as Lukschalp in Fig. R3, do not necessarily show the strongest correlation with the average snow heights measured at the Brämabüel release zone. In the example provided for the 2023/2024 winter season, the snow depths recorded at the IMIS station in Frauentobel correspond most closely with those at Brämabüel. This may be related to the fact that Frauentobel is not located at a completely horizontal flat-field site, but in gently inclined terrain. While this is still not comparable to the steep Brämabüel release slopes, it suggests that station representativeness depends not only on geographic distance, but also on local topographic setting. A robust interpretation requires several seasons of high-resolution release-zone measurements to relate snow-height dynamics in steep terrain to nearby measurement stations, but we have had our measurement setup for only two seasons yet.

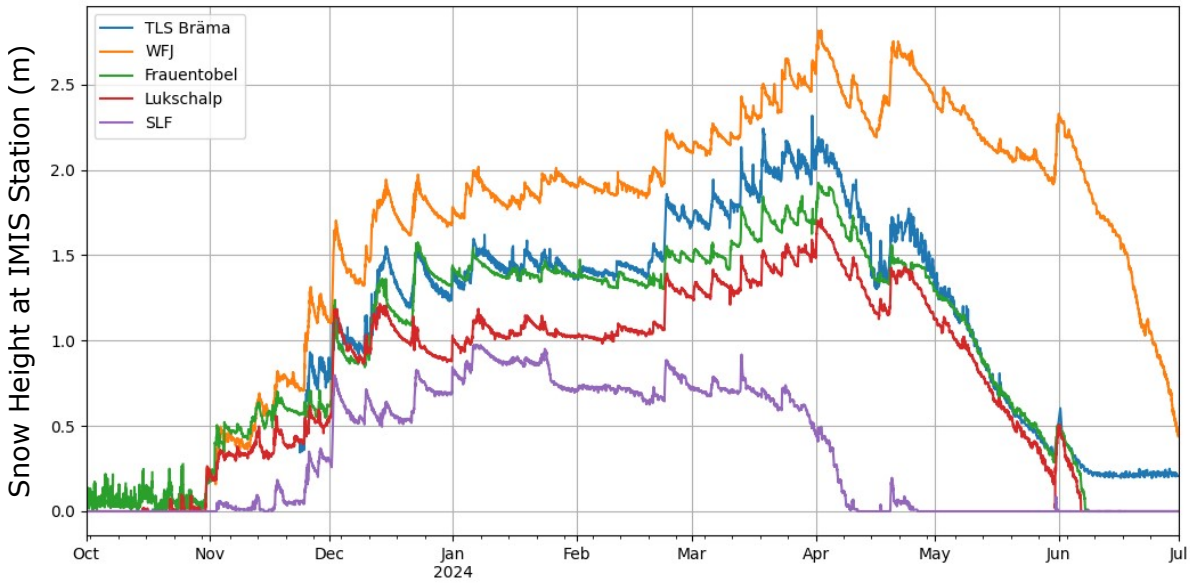


Figure R3: Snow heights of winter season 2023/2024, measured at the IMIS stations WFJ, Frauentobel, Lukschalp, and SLF, and derived from Terrestrial Laser Scanner (TLS) acquisitions in the release zone of avalanche track 1 at Brämabüel. The stations' locations are shown in the main paper in Figure 1.

Table 2: Station-based input values used to derive the release-height scenarios. The SLF2 station is located lower in the valley and was used only to estimate the temperature and snow-height gradients, not directly for the release-height calculation.

Station	Release temperature (°C)	New snow (cm)	Weak layer (cm)
SLF2	3.0	50	–
WFJ2	8.2	47	84
DAV2	9.9	48	71
DAV3	5.6	51	66
FLU2	8.4	57	105
PAR2	8.0	51	61
KLO2	8.9	50	71

R1-6: **Artificial Triggering vs. Natural Avalanches:** It appears that the three avalanches as described in Section 2 were all artificially triggered. How does using artificially triggered avalanches to validate the probability maps whether using frequency or stability approach factor into the results? In other words, are the release probability and subsequent runout independent of triggering mechanism (natural vs. explosive/artificial)? When using the historical data (Section 4.3) for evaluating the workflow/model chain, were these avalanches naturally occurring or artificially triggered? Additionally, the authors mention that "the release zones are derived using a return-period-based algorithm" (Line 360). Is this return period based on natural or artificial triggering. I think this topic deserves some explanation given the validation avalanches are all artificially triggered.

We thank the reviewer for raising this important point. We agree that the distinction between natural and artificially triggered avalanches needs to be discussed more explicitly, as it affects the interpretation of the probability indication maps. We add a paragraph to the discussion and mention in the avalanche overview (Figure 1) whether each is a natural avalanche or an artificial release.
Regarding the return period of the PRA's: In Switzerland, release areas for hazard mapping are commonly calibrated based on return periods of the observed runouts so that the resulting simulations reproduce the corresponding runouts. The algorithm described in Bühler et al. (2018) follows this logic by identifying potential release areas from terrain and surface characteristics for a given return period.

Table 3: Release-temperature and release-height scenarios used for the Brämabüel 2019 simulations, including their scenario weights.

Release temperature (°C)	Release height (cm)	Weight
-8	50	0.069
-8	60	0.028
-8	70	0.069
-8	80	0.069
-8	90	0.028
-8	100	0.097
-8	110	0.056
-8	120	0.042
-8	130	0.028
-8	140	0.000
-8	150	0.000
-8	160	0.014
-9	50	0.069
-9	60	0.028
-9	70	0.069
-9	80	0.069
-9	90	0.028
-9	100	0.097
-9	110	0.056
-9	120	0.042
-9	130	0.028
-9	140	0.000
-9	150	0.000
-9	160	0.014

L418 *A general challenge in evaluating probability indication maps using documented avalanche events is that an observed runout confirms that a scenario was possible under the given conditions but does not directly provide information about its occurrence probability. To assign such a probability, the non-occurrence probability of comparable avalanches under similar conditions would also need to be known. This limitation is particularly relevant for organized measurement campaigns, where avalanches are artificially triggered to collect detailed measurements. The triggering method and explosive type may influence which weak layer is released and, therefore, the resulting release depth. Once the release depth and release area are defined, however, the subsequent runout is mainly governed by the released volume, terrain, snow cover conditions, and flow parameters. Artificially triggered avalanches can therefore be used to assess whether simulated runout scenarios are plausible, but they cannot directly validate the absolute probability of a natural release. The probability indication maps presented here should thus be interpreted primarily as conditional scenario maps that indicate which runout may result if a release occurs, rather than as direct estimates of the absolute probability of avalanche occurrence. However, we acknowledge that this may lead to a conservative interpretation.*

0.1 Specific Comments

R1-7: **Figure 2a:** Without reading the accompanying text, it is not immediately clear what the values 0, 1, 2, and 3 represent, or why the distances of 1 km, 2 km, and 3 km are important in this context.

Additionally, from the map alone it is difficult to identify the terrain flattening where most avalanches stop. Including a slope profile may help illustrate this more clearly.

We will adjust the caption of Figure 2 and add a figure below showing the steepness of Brämabüel and Breitzug, including the avalanche paths numbered in the way scatched in Figure R4.

Figure 2a / New Caption: *Overview of the mapped avalanche activity affecting the Dischma road near Brämabüel between 1999 and 2025. (a) Number of observed avalanches reaching each map pixel. (b) Number of observed avalanches intersecting the Dischma road, shown as distance along the road. The labels 0–3 indicate the main avalanche path sections, and the distance markers in panel (a) correspond to the distance axis in panel (b). Map*

source: Federal Office of Topography.

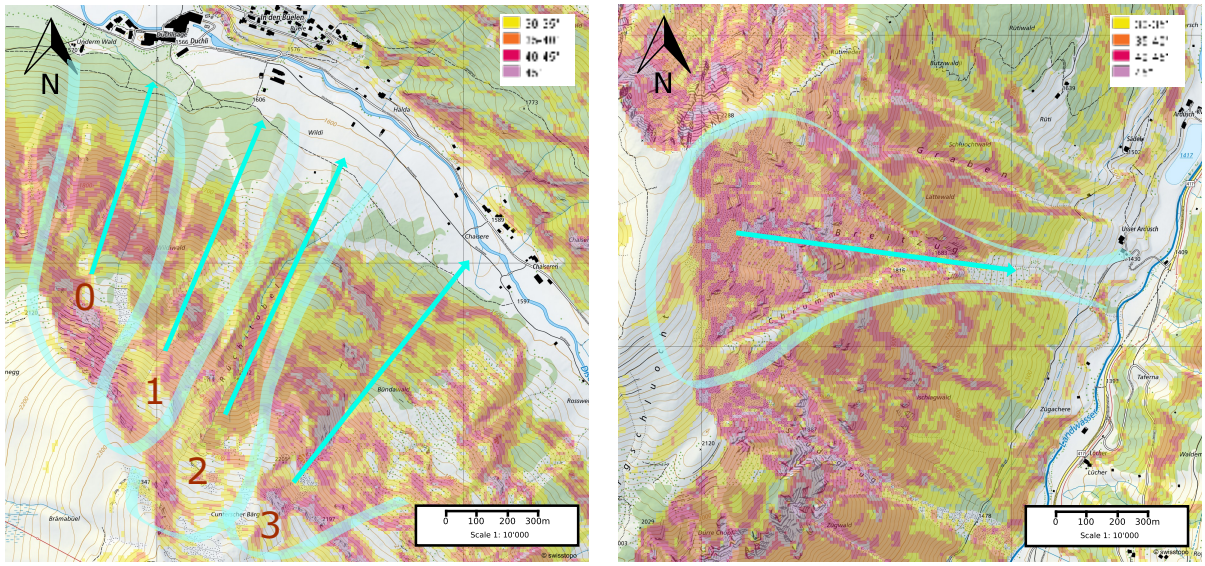


Figure R4: Only a sketch of the graphic!: Overview of the two test cases Brämabüel (left) and Breitzug (right), including the slope steepness and a high-level sketch of the differentiation of the main paths of the avalanche tracks. For Brämabüel, we have an avalanche track of up to 3, while we focus on Breitzug just on the main avalanche track.

R1-8: **Figure 2b:** It is unclear what the blue line represents. Does it indicate dependencies of the avalanches? For example, from 3.4 to 4.0 km the line remains at one avalanche: does this indicate that one single avalanche reached this road section, and it was the same avalanche for this entire section? Maybe you could include a short explanation in the figure description?

The blue line between 3.4 and 4.0 km indicates that one avalanche reached this part of the road. So there was, e.g., one avalanche where the release connected avalanche track 1 and 2, which resulted in a wide avalanche reaching the road in the runout area of avalanche track 1 and 2. The same is the case after 3.5 km where only one avalanche is documented that reached that part of the road.

R1-9: **L136:** "on January 28" please use the standard English date format consistently throughout the manuscript (Month Day, Year). This comment applies generally across the manuscript.

Thank you very much. In the cryosphere guidelines they ask for the format dd month yyyy.

R1-10: **Figure 3:** The distinction between "Road closures" and "Days with road closures" is not immediately clear and could be clarified further.

Additionally, consider replacing "November till May" with "November to May" for more formal language.

We can include the description in the caption. The idea is to include in the graphic the sum of the days of road closure to indicate the significance of the road closures. And yes, we will adjust the legend to formal language.
Figure 3 / Caption: *Add: The number of closure days is included to indicate the overall duration and therefore the relative significance of individual road-closure events.*

R1-11: **Figure 4:** I think this conceptual diagram of the workflow could use some improvement. I think including the specific input data for "Meteorological Data & Forecast" that is used in SNOWPACK is important. Additionally, include where the frequency and stability approaches are used in the workflow. Finally, include which data (historical and 2019 and 2025 events) are used for validation and how that is incorporated to tune the workflow.

We agree that the figure is misleading, and we will split the data path for the input data from the IMIS station, which is used to run SNOWPACK and the forecast as shown in Figure R5.

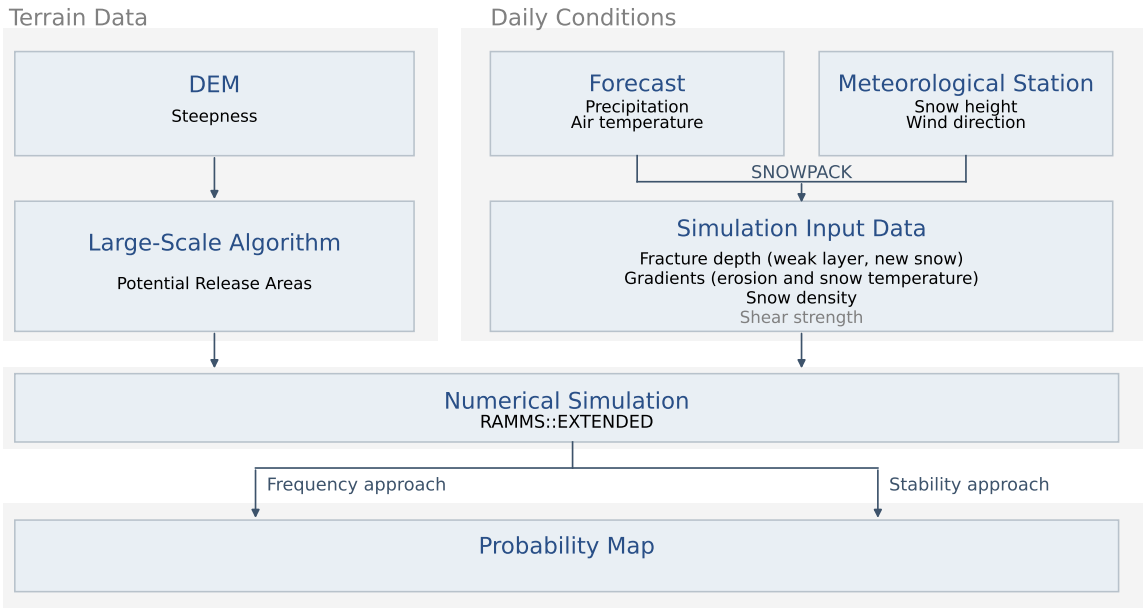


Figure R5: Conceptual presentation of the data flow to produce a probability map. Greyed out the parameters that are only needed for the stability approach.

R1-12: **Figure 5:** Please clarify the meaning of the dashed versus dotted lines in the caption. Additionally, the x-axis may not need to be labeled as "Date."

We will adjust the caption and use the same line style for the Brämabüel and Breitzug event as shown in Figure R1 in R1-2.

R1-13: **Figure 7:** Consider labeling each panel as a, b, c, etc. The graphs at the bottom may benefit from including y-axis scales. Additionally, the legend order of weather stations should begin with seven stations and decrease sequentially, as placing seven at the end is somewhat counterintuitive. Including a one-weather-station scenario may also be informative. In the final graph, the lines are very close together, making differences between scenarios difficult to distinguish.

We will adjust the figures as proposed by the reviewer.

R1-14: **L301:** Instead of stating "stronger influence on the result," could this effect be described more specifically? For example, does it reduce the hit probability in the avalanche runout, and if so, by approximately how much?

We rephrased the paragraph with a more detailed discussion of what we observe in the runout and quantified the resulting probability along the road.

L356: *In the next step, we applied the stability approach to the Breitzug event as an example and conducted the same analysis. In Fig. 10, we present the resulting map. Scenarios from steeper or less stable release areas receive higher weights, whereas those from flatter or more stable release areas receive lower weights. Overall, the predicted hit probability averaged along the road below Breitzug changed little compared to the frequency-based result. In both approaches, small PRAs yield very low hit probabilities at the road, whereas medium PRAs produce low but non-zero probabilities. The frequency approach indicates an average hit probability of approximately 10–15 % along the affected road section for medium PRAs, while the stability-based approach yields a similar or slightly lower value of*

about 10 %. The main difference between the two approaches is therefore not a substantial change in the predicted road impact in this case, but a more nuanced spatial distribution of hit probability within the avalanche path.

R1-15: **L313:** What was the reason for including the 2017 event that evolved into a wet-snow avalanche? This is very interesting: is RAMMS::EXTENDED capable of simulating the transition in avalanche type?

We included the 2017 event because it did not start as a pure wet-snow avalanche but was released under cold-snow conditions. However, the deposition pattern indicates warmer snow temperatures compared to a pure cold powder-snow avalanche. RAMMS::Extended can represent such transitional cases by including the temperature gradient within the snow cover, provided the avalanche does not enter a very warm flow regime in the lower path. For such warm regimes, the generation parameter α would need to be adjusted, as discussed in Glaus et al. (2025).

R1-16: **L366–L369:** Consider including supporting citations in this section.

We added the reference of the forest implementation for RAMMS.
L466: *Feistl et al. (2015)*

R1-17: **L373:** A citation may also be appropriate here.

We added the publication Sovilla et al. (2010).
L472: *Finally, interpretation of modelled results requires consideration of the avalanche history of individual tracks as it affects the potential amount of erodible snow Sovilla et al. (2010).*

R1-18: **L401:** It may be worth considering an assessment of data sparsity in a climate more comparable to Davos, rather than addressing the additional caveats associated with high-altitude or Arctic climates.

Indeed, first, some smaller tests would be needed. We will rephrase the final sentence to clarify the next steps.
L518: *Future work should first test the workflow along the full road corridor and across different Alpine regions to assess its transferability under comparable climatic conditions, before adapting it to more data-sparse regions such as Alaska or the Himalayas.*

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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

June 24, 2026

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 change file. 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 expanded the description of the study site as proposed in Review comment R1-7 by including detailed maps of the avalanche paths. Additionally, we added the predicted scenarios and calculations in the Supplement to improve the reproducibility of the test cases, as proposed in Review comment R1-5. We also reviseed 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.

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Line 112: *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.*

L459: *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 parametrization 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.*

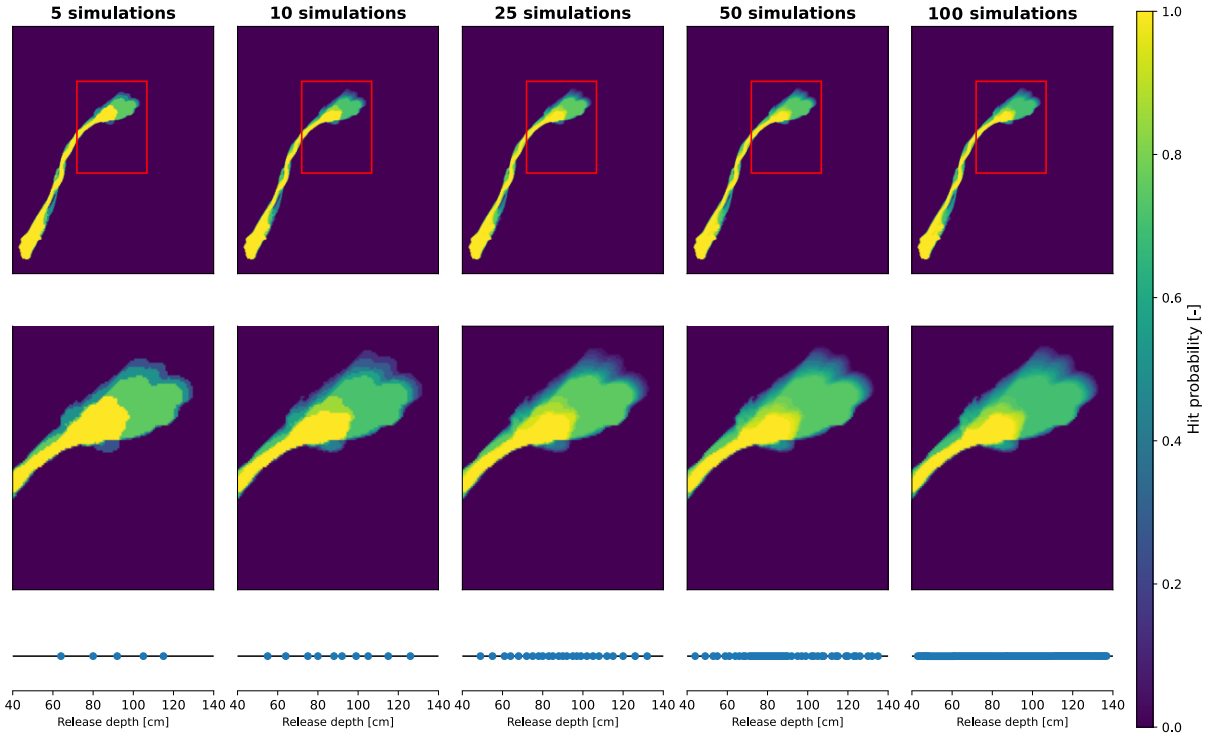


Figure R1: Convergence analysis for a single representative release zone located at Brämabüel in Track 2. The release depth is varied between 40 and 140 cm, representing a realistic range of potential snow depths in the release zone. The panels show unweighted hit probability maps for increasing numbers 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.
L258: *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.
L433: *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 34–36:** 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.
L141: *Only 12 avalanches are documented as reaching the road sectioni 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.
L149: *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:
L191: *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 (Mergili et al., 2017), 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.

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