Response to Referees

Probabilistic avalanche runout modelling for daily risk management of traffic routes

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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 original 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:
L121: *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.*
Paragraph for Discussion: *A further 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	

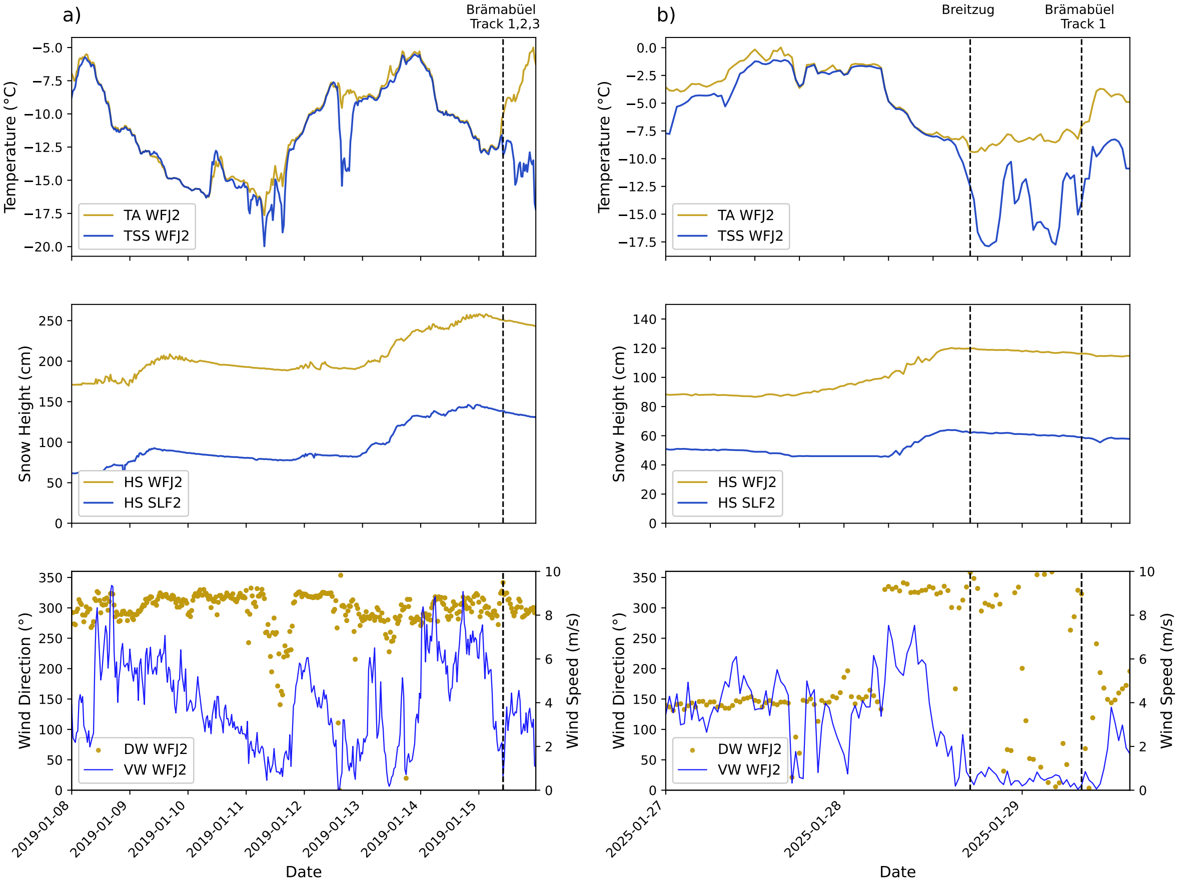

Figure R1: Time series of meteorological observations recorded at the Weissfluhjoch (WFJ2) and Davos valley (SLF2) IMIS stations during the snowfall events preceding the evaluated avalanche releases. Shown are air temperature (TA), snow surface temperature (TSS), total snow height (HS), wind direction (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.

Discussion *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.*

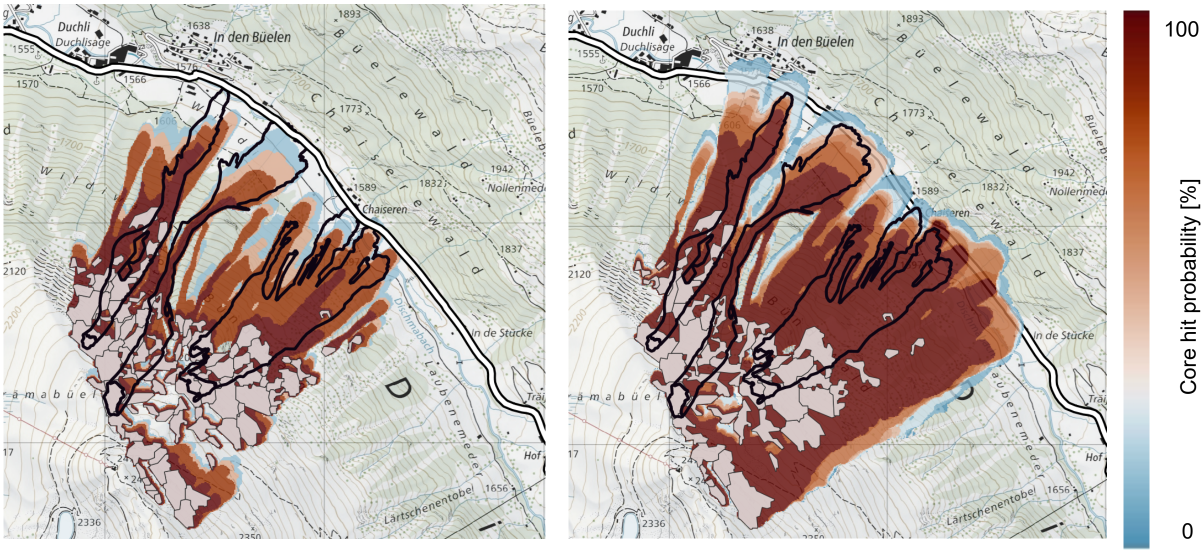

Figure R2: Calculation of the probability indication map for the core for small and medium size release zones at Brämabüel for the 2019 case study.

> 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.

L262: *We focus only on one example case for the stability approach due to the additional calculation and storage needs.*

Discussion *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. 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.*

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.

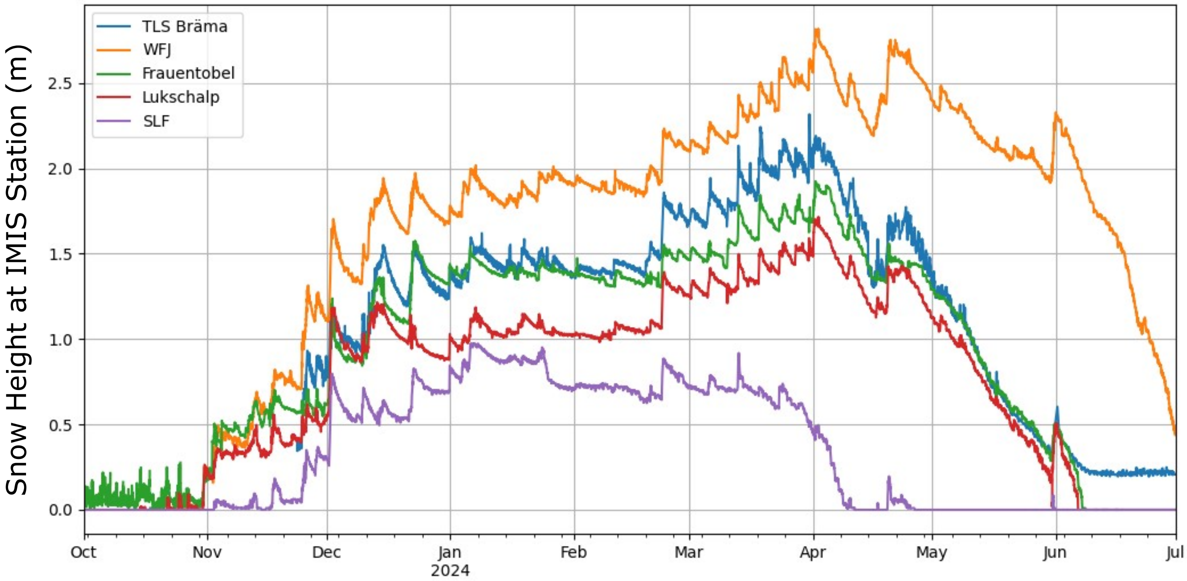

Figure R3: Snow heights of winter season 2023/2024, measured at the IMIS stations WFJ, Frauentobel, Lukschalp, and SLF, and derived from Terrestrial Laser Scanner (TLS) acquisitions in the release zone of avalanche track 1 at Brämabüel. The stations' locations are shown in the main paper in Figure 1.

Table 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

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.

Discussion *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.*

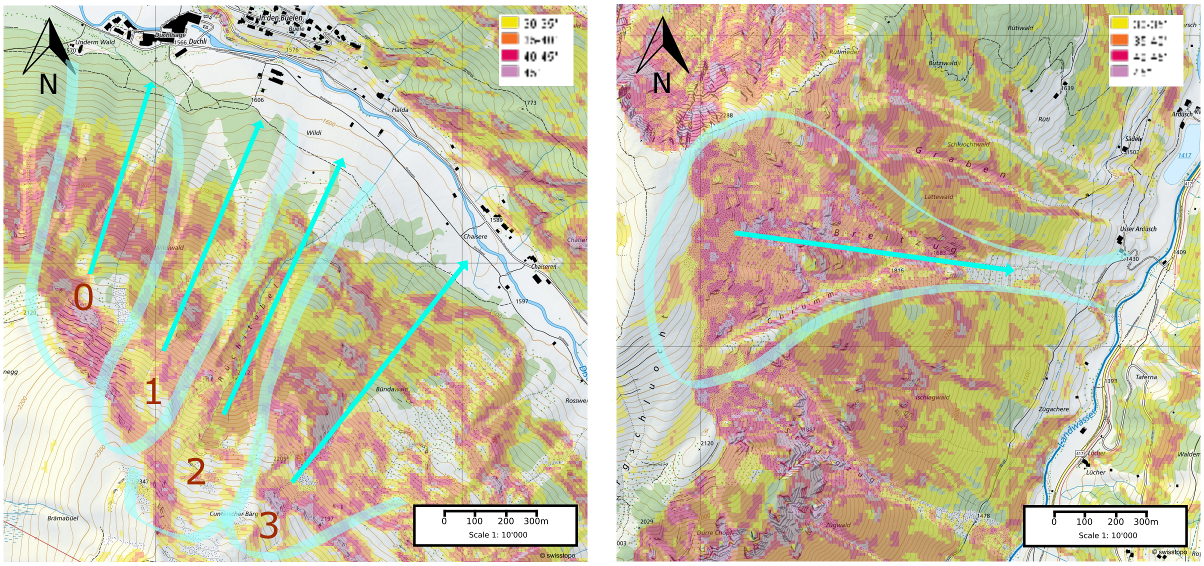

Figure R4: Only a sketch of the graphic!: Overview of the two test cases Brämabüel (left) and Breitzug (right), including the slope steepness and a high-level sketch of the differentiation of the main paths of the avalanche tracks. For Brämabüel, we have an avalanche track of up to 3, while we focus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

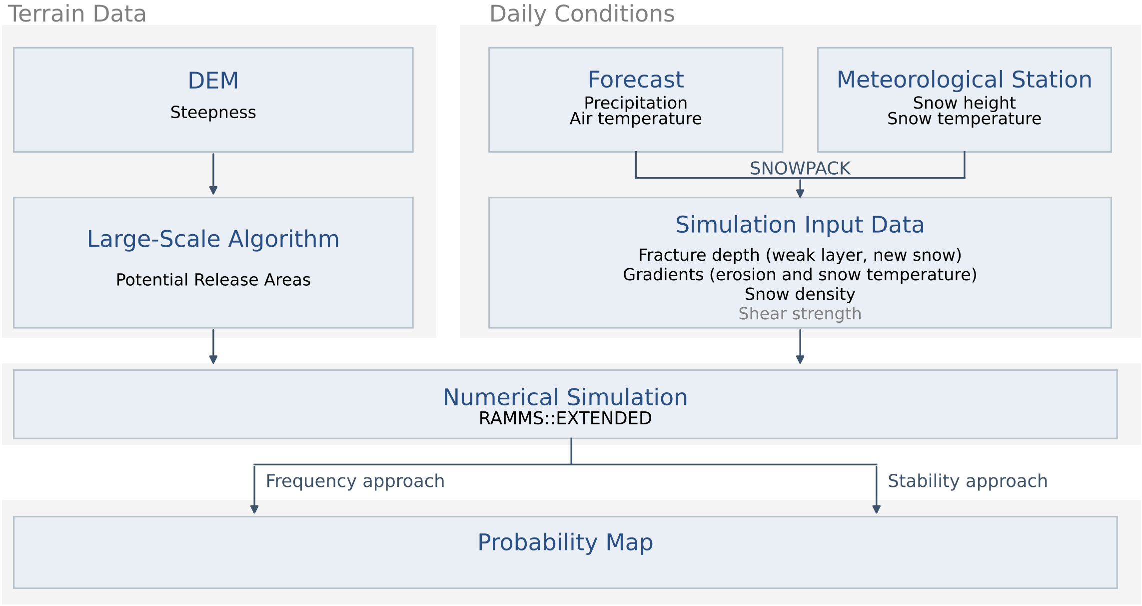

Figure R5: Conceptual presentation of the data flow to produce a probability map. Greyed out the parameters that are only needed for the stability approach.

> 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.
L301: *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.
L366–L369: *Feistl et al. (2015)*

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

We added the publication Sovilla et al. (2010).
L373: *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.
L400: *Future work should first test the workflow along the full road corridor and across different Alpine regions in Switzerland to assess its transferability under comparable climatic conditions, before adapting it to more data-sparse regions such as Alaska or the Himalayas.*

References

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