## Response to review by J.-T. Fischer

*In this paper, the authors present a model chain for the back calculation of twelve well documented (mostly wet) snow avalanches. The snowcover simulation model SNOWPACK is used to derive snow cover properties as input data (release and model parameters) for avalanche simulations. Avalanche simulations are performed with the toolbox RAMMS, employing a classical flow model with Voellmy friction relation and an extended thermomechanical flow model. Different statistical scores are introduced to evaluate the simulation performance regarding the comparison of simulated flow depths and documented deposition patterns. With these statistical scores and runout estimates the simulation sensitivity is investigated with respect to different kinds of input sources (simulation input, model parameters, grid resolution). Topic and content of the paper fit well to the audience of NHESS. However the reader may be confused because important links and a central theme seems to be missing. A possible solution to finalize this paper could be to either concentrate on one of the three main subjects or to somehow relate them in a consistent way. The presented model chain consists of the two components: a snow cover model, which runs on measured meteo data and avalanche simulations, which use the snow cover properties provided by the snow cover model. Statistical scores and runout comparison appear as very useful tool to objectively evaluate the avalanche simulation, i.e. the last part of the model chain - variations of snow cover model performance and variability are not presented. The analysis can be divided in three main (somehow mixed but independent!) contributions: (i) model chain performance check and cross comparison to the classical approach, (ii) sensitivity analysis of the thermomechanical avalanche simulations with respect to avalanche path location (model input parameters), (iii) avalanche simulation sensitivity analysis with respect to computational/terrain resolution. Although the presented approaches appear to be highly interesting and promising some parts are incomplete or at least not well structured/distinguished. Throughout the paper there is a need to clarify what (and why) the authors exactly do: general questions:*

**ANSWER: We thank Dr. Fischer for his review and very constructive and helpful comments. We changed the abstract and introduction to make our motivation more clear.**

**ANSWER: The first version of the paper did not contain a description of the model. We abandoned this version because we could not rationally describe the simulation results and statistical analysis without refering to model input and output. Section 2 serves to define what the model input is, and what the model produces. It is central in understanding the model chain. We stress the goal of the paper is not to make a model comparison, or to present a method of statistical analysis. The goal of the paper is to identify what boundary conditions MUST be ACCURATELY specified in order to produce reliable simulation results. We found that SNOWPACK can be used, however, there are difficulties. Our approach is to keep the avalanche dynamics parameters (more-or-less) constant, but specify the initial and boundary conditions based on SNOWPACK simulations. The model description serves to help the reader distinguish between material parameters (for wet snow) and initial and boundary conditions. Without the model description we found that it was impossible to clearly separate the two. For this reason we need a description of the model. We perfectly understand the comments of the reviewer. It is not our purpose to write a long paper; but without the model description it is impossible for the reader to judge the results of the simulations, and therefore the model chain. Our goal is to present the entire model chain, from snowpack simulations (which we don't describe in detail), through avalanche dynamics simulations and statistical analysis. In order to appease the reviewer, we have restructured the model description, allowing the interested reader to read only those parts of interest.**

**CHANGED: The second reviewer also had difficulties with our motivation. We revised the introduction to clearly state the main goal of the paper. For the sake of clarity we also restructured the model description. See the track changes file.**

- *What is the main goal of the analysis? A new simulation evaluation approach? Introducing or testing a new flow model? Sensitivity study with respect to grid resolution?*

**ANSWER: The goal of the paper is NOT a new simulation evaluation approach. The goal of the paper is NOT to test a flow model. Our goal is to pinpoint the primary difficulty of modelling wet snow avalanches. Our goal is to show that accurate boundary conditions are**

**necessary for thermomechanical avalanche dynamics models. However, We come to the somewhat surprising sub-conclusion: "Reliable estimates of avalanche mass (height and density) in the release and erosion zones is identified to be more important than an exact specification of temperature and water content." Moreover: we come to the conclusion that snowcover models must be able to identify where meltwater accumulates (this defines the amount of release mass.) This is the result that we want to bring forward. We clearly state this goal and result in the abstract. The evaluation approach, which we do not consider new, is used to support this claim. We repeat: we DO NOT want to develop a general method to evaluate model results.**

**CHANGED: We revised the introduction to clearly state the main goal of the paper. For the sake of clarity we also restructured the model description.See the track changes file**

- *What exactly is deposition in terms of simulation results (deposition is not directly modeled in RAMMS, hence 20cm flow depth are compared to observed deposition, but when does an avalanche simulation stop? why is this an appropriate choice?). Why is the runout analysis separated from the statistical scores and not equally treated?*

**ANSWER: We agree with Dr. Fischer that it is not appropriate to compare 20cm flow depth with measured depositions of 1m or 2m. We added the sentence "Variations in modelled and observed deposition heights are not captured with this procedure" in section 3.3 to clarify our approach and address the concerns of the reviewer. Our philosophy is to adopt a practical approach: as a first step we comparted the measured and simulated inundation areas, independent of the deposition heights. This is how the simulation models would be applied in practice. We admit that the measured and simulated flow heights WITHIN the deposition area might differ (the reviewer is CORRECT), but suggest the first necessary step is to compare the measured and calculated inundation areas. The models are simply NOT that accurate (yet) to make deposition height comparisons, which are often a function of very, very local conditions. This is why we restrict the paper to the inundated areas. Regarding the comment on runout distance: runout distances provide an intuitive measure. It is also a variable that is used avalanche classification systems. For this reason, we are motivated to show our results for runout distance. The contigency table analysis needs four classes that can only defined in a two-dimensional terrain analysis. Runout, on the other hand, provides only a binary result, hit or miss and therefore NO statistical score. We placed the sentence "This two-dimensional procedures avoids the problem of defining a one-dimensional measure of avalanche runout" in section 3.3.**

- *What is the advantage of four different statistical scores, when they are based on two independent measures that could deliver the same general message (variation of simulation results)?*

**ANSWER: No, they do not deliver the same general message. We consider all FOUR statistical scores to be relevant and necessary. Again, this has to do with the use of inundation areas to describe model performance. We simply want to know when the simulated model results are correct (hits), or when they predict inundated areas where they were not (false alarms). The HKS and ETS are summarizing statistics, giving an overall statistical score, but they don't allow for much interpretation. A low HKS may result from low probability of detection or high false alarm rate. Note that it is important not to use only probability of detection, as it is easy to cheat this score: just make the avalanche as large as possible and you'll optimize the probability of detection. For this reason, most studies using contingency table analysis show multiple statistical scores, to allow for interpretation of the scores.**

- *How are simulation input, model parameters, boundary and initial conditions distinguished (e.g. density is a snow cover property in terms of snowpack simulation, describing the release mass and also a flow model parameter in terms of avalanche simulations?)?*

**ANSWER: We include Table 2 and 3 refer to boundary conditions (snow properties for release and erosion); Table 4 shows the model parameters, for the guidelines and the thermomechanical models. Snow properties are supplied by the SNOWPACK model. It would be**

**really nice to have measure snow properties everywhere, but this is simply an impossibility. Second, we apply ONLY ONE set of friction parameters (those for wet snow avalanches). We change snow properties (initial and boundary conditions) but do NOT change model parameters. This is one reason why we describe the model in section 2 to distinguish between the model parameters and the snow properties. The reader should obtain this information by reading sections 2 and 3. This is why we want to keep the model description in order to clearly identify what the difference snow properties and model paramters.**

- *Is section 2 needed or would it be more beneficial to discuss the evaluation approach in more detail and simply refer to Valero et al. (2016)?*

**ANSWER: We restructured the modelling section. A first draft of the paper did not include the model description. We found, however, that when discussing the results that physical knowledge of wet snow avalanche modelling is needed. For example, we cannot talk about LWC without defining how LWC is included in the avalanche dynamics model. These initial conditions (based on physical modelling) need to transferred to the avalanche dynamics model. Again, the purpose of the paper is to highlight what we regard to be an important PHYSICAL result: we need to know where meltwater accumulates with the snowcover (e.g. base or interior layer) to establish the initial conditions of the simulation. This problem, which is immense, might exclude the application of avalanche dynamics models to perform "real time hazard mapping" in future. Because our results QUESTION the application of models, we believe the model and model performance should be presented in the same paper. CHANGED: We restructured the model description.See the track changes file**

- *How does the snow cover simulation perform in comparision to field data (e.g. field observations on fracture depths, densities, . . . )?*

**ANSWER: For a few case studies, additional information is available for fracture depths, (laser scan and drone measurements in some of the case studies. see modified Table 1. There have been many papers written validating the SNOWPACK model. In the manuscript there are five references that validate the performance of the snow cover model. Three of them were written by one of the co-authors and are related to wet snow modelling using field data from the area where 7 of our case studies occured. We consider that the snow cover model was tested enough and we do not consider this manuscript as the place to re-evaluate the snow cover model performance. CHANGED: We revised Table 1 to include fracture depths where possible.**

*Overall the manuscript is well written and the derived figures 4-9 appear useful to interprete the statistical outcome of the sensitivity analysis. However, for better comparability, the figure axis should have the same limits (e.g. HKS of figures 6-7). Same holds for the figures in supplemental material (e.g. supp. A, figure S8 a-b). Generally it should be stated what exactly is shown in the supplement figures (A+B) (deposit depth is not a direct simulation result - is it flow depth at a certain (which?) time step? What is depicted by the red outlines (which are very hard to distinguish) in supplement B (20 cm flow depth outlines?)?).* **ANSWER: The supplement has been modified. Thank you for the suggestions and we apologize for the omission of a complete figure description in the supplement. In Supplement B, the color bar denotes deposits height (i.e., flow height in last time step $> 20$ cm) of the simulation with the initial conditions corresponding to the event. The outlines of the simulated deposits (i.e., flow height in last time step $> 20$ cm) for each of the other 11 different initial conditions are shown in varying degrees of rosa to red color. CHANGED: We have modified the figures and the supplement according with your suggestions.**

## specific questions:

*(In section 3.2.(i) model chain performance check and cross comparison to the classical approach) the authors outline their performance evaluation strategy (guideline parameters with classical flow model vs. modeled snow pack properties + ad hoc parameter assumptions for the new thermomechanical flow model). It appears that some crucial questions remain unclear:*

- *Can the simulation approaches really be compared like this? Is this a comparison of simulation strategies/procedures or of flow models?*

**ANSWER: We emphasize the main result of the paper: if you want to mix snowcover models with avalanche dynamics simulations you must be very certain that the snowcover model is predicting the right fracture depth. Otherwise, simple model (VS) or more complicated models (wet snow) will provide the wrong results. That is, it is NOT about the flow model; good results can be obtained by both simple and more complicated procedures. This is our primary result. CHANGED: The introduction has been modified to make the goal of the paper more clear.**

- *Why does it make sense to use a mix of modeled snow cover parameters (depth) and guideline parameters?*

**ANSWER: In a "real" hazard mitigation analysis, the release depth is set by meteorological extremes. A specific avalanche is not modelled, but an event with a specific return period. Here we have a problem, which the reviewer has correctly identified: Our avalanche data base contains events with different return periods, most of them smaller than an extreme event. Frankly, we don't know the return period of our avalanches. To circumvent this problem we adopt the following approach: We take the modelled snow cover parameters (height, density) for the release, coupled with the entrained snow amounts, and use extreme friction parameters. We demonstrate that this approach CAN lead to good results. In fact, considering the procedure contains ONLY TWO friction parameters, and does not require detailed snowcover conditions, the results are surprisingly good! We apply this approach for all avalanches to make it general. Here we want the reader to come to the conclusion that maybe the guideline model is superiour to the more detailed wet snow avalanche calculation. Thus, our results indicate that good results, at small cost, can be achieved by mixing modeled snow cover parameters with guideline procedures.**

- *The growth indices should depend on the choice of flow and the entrainment model/parameters, so they are a result of the model chain?*

**ANSWER: Yes and no. Yes, the growth indices are clearly a result of the snowpack simulations which predict the snow distribution. They are therefore a result of the "model chain". The entrainment parameters do not vary strongly, but are limited to a small range. The growth indices are thus largely independent of the model parameters.**

- *With the thermomechanically modelled growth indices, the initial mass of the classical simulations are set. But since classical VS parameters where calibrated implicitly including entrainment (field observations that include entrainment) this should not be necessary?*

**ANSWER: The reviewer is correct. The classical model will provide the "same" results with or without the entrained mass. By including the entrain mass, however, we can argue that we have more "extreme" like events, and therefore can use extreme friction parameters which we apply. Again we find the procedure provides solid results at very low cost (i.e. less detail).**

- *Why is it appropriate to choose model parameters for small, frequent avalanches for all events, when release volume of e.g Gatschiefer is up to 330.000 m?*

**ANSWER: Because we restrict ourselves to wet snow avalanches. For wet snow avalanches the friction paramters are (more-or-less) independent of size. This is a procedure often applied in practice. The reviewer is correct: we could not use the approach in general, especially for dry snow avalanches.**

- *How can the ad hoc model parameter choices for the thermomechanical model be justified (that vary for different avalanche paths, e.g. Entrainment coefficient (0.6-0.8) and $\alpha$ parameter)? Or does the choice not matter because the result influence is negligible?*

**ANSWER: They are very small variations. The influence on the results is neglible. In fact, we argue differently: a range of values provides very similar results and we cannot distinguish between specific values (e.g. simulations with entrainment coefficient 0.6 provided the same results as entrainment coefficient 0.8). Note that all other parameters remain constant for wet snow. Of course the exact quality of snow and terrain will vary, and thus the parameters. These parameters were varied for the avalanche path but once fixed were not varied in the permutations**

*In section 3.5 ((ii) sensitivity analysis of the extended avalanche simulations with respect to avalanche path location) three different approaches to study the sensitivity of the thermomechanical model are performed (interchanging all or combinations of the model parameters that are related to the snow cover model - fracture and erosion depths, density, snow temperature and LWC). The sensitivity analysis is evaluated on a qualitative level, e.g. no single parameters ranges are investigated (varied with respect to their absolute values) with a quantification of the output variability (which would actually be the advantage of the introduced statistical measures). Open questions are:*

- *The snow cover model parameters are permuted by event location. With this no quantitative evaluation is possible with respect to the absolute variation of avalanche simulation input, which are (as depicted in table 2) $\approx$ 26% for release depth, $\approx$ 16% for densities and $\approx$ 46% for LWC and $\approx$ 151% for temperatures (compared to the respective mean value). Considering these differences (in magnitudes) a direct, systematic comparison and sensitivity analysis is hardly possible - how can we finally conclude which parameters are more important if the are not equally treated?*

**CHANGED: We revised section 3.5 to address the comments of the reviewer. ANSWER: We think that the original manuscript failed to clearly describe our goal of the sensitivity study. One of the novel approaches we present is to use a physics-based snowcover model to determine the initial and boundary conditions for avalanche dynamics calculations. An important role of the sensitivity study is to determine if this approach add information in the simulation process. Here, we consider that all 12 cases represents a variety of wet snow avalanche cases, and the 12 simulations provide realistic, self-consistent initial conditions. Therefore, we decided to interchange the simulated initial conditions, instead to perturb the simulated values. For example, one could vary temperature over a range of -20 to 0 °C separately from LWC, but in this case, a well below freezing snowcover with a noticeable amount of liquid water is provided to the avalanche dynamics model. This is, however, not a realistic scenario. Therefore, we decided to interchange the sets of snowpack conditions from the SNOWPACK model.**

*In section 4.3 ((iii) avalanche simulation sensitivity analysis with respect to computational/terrain resolution) the sensitivity with respect to grid size is evaluated. Main questions are:*

*As i understand it - this analysis treats the computational grid resolution. How is the DEM resolution treated (resampled to the computational resolution)?*

**ANSWER: The measured DEM is resampled to the computational resolution. This is the standard procedure.**

*The main result is that the presented method (statistical scores) can show that parameter values are bound to certain spatial resolutions. Since this has been observed before (e.g. by Bühler et al., 2011, as stated by the authors) this section could maybe be moved to the appendix to smooth the entire manuscript.*

**ANSWER: The other reviewer also mentioned this point. We can consider removing the**

**section. However, we wanted to put the variation in our simulations that arise from interchanging the initial conditions in perspective. We show that the information added by using the SNOWPACK model is noticeable compared to changing calculation grid size resolution. Precisely because previous studies addressed already the influence of grid cell size on avalanche dynamics simulations, and researchers are aware of it, we consider it a good benchmark for the effect of initial conditions. We will revise the manuscript to make this more clear.**

## Minor comments

*Please find some more detailed line-by-line comments/questions below:*

- *title The title of the paper "Modeling the influence of snowcover temperature and water content on wet snow avalanche runout" could focus more on the main contributions (simulation evaluation/sensitivity) and results of the paper (as stated in the abstract Reliable estimates of avalanche mass (depth and density) in the release and erosion zones is identified to be more important than an exact specification of temperature and water content. - which slightly contradicts the title).*

**ANSWER: Valid point. It is about wet snow avalanche runout – but we find that it depends on the depth of the meltwater accumulation. I wonder if an alternative title could be, "The role of meltwater accumulation depth in wet snow avalanche modelling" or "Including snowpack properties in release areas for wet snow avalanche modelling". Is this a more appropriate title?**

- *abstract Do height and depth have different meanings? Is it consistent throughout the paper?*

**ANSWER: No, this is an inconsistency from our side. We will check for consistency when revising the manuscript. Because we denote the "depth" with "h" we will use height throughout.**

- *3, 66, . . . deposits area . . . deposition area prediction*

**ANSWER: Changed.**

- *3, 67, Instead of parameter optimization, . . . This is a crucial point. If you pursue a flow model comparison, both models should be equally treated, i.e. performing a full optimization and comparing the result performance, not to compare apples and oranges (c.f. Rauter et al., 2016, where a extended flow model is also compared to a Voellmy friction relation with different measures). If you pursue a comparison of simulation approaches/strategies, guidelines should not be mixed with model chain results.*

**ANSWER: Again our goal is not to "pursue" a flow model comparision. Both models appear to work well – if the snowcover model accurately predicts the meltwater accumulation zone. We hope that some readers will conclude that the VS approach is not too bad. Perhaps both models could be applied.**

- *3, 74, 3. . . . , Fig. 1 To me it appears that the "model chain" is the combination of snowpack and avalanche simulations. The statistical scores/analysis is valid tool to evaluate the results (jointly with the runout estimates) but not a part of the chain. Similar evaluations have been performed for operational avalanche simulations Naaim et al. (2013) (snow properties and simulated avalanche runout) or Fischer et al. (2015) and recently for other mass flows Mergili et al. (2017) (introducing statistical scores to evaluate model performance).*

**ANSWER: Yes we agree: different statistical methods could be used to evaluate the simulation results. We argue that some statistical procedure is necessary to compare the numerical results and therefore be included in the "model chain". We recognize that different models exist. However, we couple a three-dimensional avalanche dynamics model with a three-diemsional method to calculate statistical scores. This common component led us to include the statistical method in the modelling chain. We include the references.**

- *Section 2: Wet snow avalanche modeling In this section the underlying avalanche flow model is described. Since it corresponds to Valero et al. (2016) it could be omitted or transferred to the avalanche dynamic modeling (section 3.2 or appendix) part, as it distracts from the main topic of this paper.*

**ANSWER: We restructured this section so that it is easier to read.**

- *9, 219, . . . apply a three-dimensional avalanche dynamics model Maybe better: Two dimensional model operating in three dimensional terrain.*

**ANSWER: Changed.**

- *9, 221-223, The small elevation difference between the release zones and the weather stations . . . provides the sufficient conditions to . . . What do you mean with "sufficient conditions", i.e. sufficiently small?*

**ANSWER: We agree that the wording was not precise, we will formulate it as: "We argue that the elevation differences between the release zones or deposits zones and the weather stations (see Table 1) are sufficiently small to provide representative snowcover simulations to estimate the initial and boundary conditions of the case studies."**

- *13, 294, class Small avalanches. Same class for all release volumes from 4.000 $m^3$ up to 330.000 $m^3$ - is this in correspondence to (Salm et al., 1990)?. There are also reasons to assume that no mass/volume dependency is necessary and that parameters cannot be interchanged between locations (especially regarding non extreme events, c.f. Issler et al., 2005; Gauer et al., 2010).*

**ANSWER: We consider only wet snow avalanches. The procedure we apply cannot be used generally, that is, for dry avalanches. Because lubrication is the frictional mechanism driving wet snow avalanches, they are less dependent on size. (Unlike fluidization, which depends strongly on avalanche size, etc.)**

- *13, 298, Section 3.3 Contingency table analysis for deposition area How do these scores compare to similar approaches evaluating snow avalanche simulations (Fischer et al., 2015; Rauter et al., 2016) and other mass flow simulations Mergili et al. (2017)? Would it also be possible to show the result variability with only two of the scores (since they are based on two independent measures)?*

**ANSWER: In many ways we regard the methods of Fischer and Rauter to be superiour to the procedure adopted here. At least these methods consider other avalanche flow properties such as velocity. We simply can't apply these methods (and therefore make comparisons) because we are working on a set of documented case studies of wet snow avalanches. Thus, our method is simpler, but reduced. This does not mean that it should not be applied. Perhaps a hybrid method could be developed? But this is out of the scope of the paper.**

- *14, 316, section 3.4 Avalanche runout This is an interesting definition of runout in a simulation framework - what are the advantages and disadvantages of this definition (are there limitations for multipath effects?, c.f. Fischer, 2013)? Some more details on how the final time steps or simulation patterns are determined would be interesting (dependence on numerical parameters, e.g. cut off for flow depths? what are the stopping criteria/simulation times?, c.f. Teich et al. (2014)?).*

**ANSWER: Yes, the reviewer is correct. The two advantages of this approach are that (1) it is simple and (2) it is independent of the inundation area analysis. The disadvantage of this approach is that it does not consider the distribution of mass in the runout area (20cm cutoff etc.). The runout approach was designed to supplement the statistics of the inundation area hit, miss, false alarms. This statistical data can be misleading – therefore we think the combination of the two methods is appropriate. We will include information concerning the flow-depths and stopping criteria in the revised paper. We added information how we stopped the avalanches to section 3.4.**

- *14, 323, section 3.5 Influence of initial conditions on avalanche runout: sensitivity study and 17, 403, section 4.2 Sensitivity analysis The intention of an objective sensitivity analysis seems promising, but a systematic approach, which leads to clear and quantifiable results regarding the influence of single parameter/input variables is missing (see general questions above). The general result, that interchanging model parameters from one event to another, reduces the simulation performance is not surprising.*

**ANSWER: Section 3.5 has been modified. See also an earlier comment: the idea of exchanging event parameters is to maintain a consistent set of simulated snow covers. In the paper, we want to demonstrate that snowcover conditions that are required to drive the RAMMS-Extended model can be successfully derived from physics based snow cover models. In this regard, we were actually surprised that the connection between simulated snow cover conditions and the avalanche situation was so tight. One can argue that interchanging "true" initial conditions leads to the unsurprising result that the model performance reduces, but we consider it quite significant that this also holds for "simulated" initial conditions. In any case, we want to show that the simulations for an event indeed add information about the specific event. This motivated the exchange of snow cover conditions on an event basis. We think that our study showed that the snowpack model indeed contributes with accurate information about the snowcover conditions in the release area. In our opinion, a sensitivity study, as proposed by the reviewer, would address a different question, namely, purely focusing on the effect of single parameters. However, this approach would not guarantee consistent snowpack conditions. For example, varying the temperature while maintaining the liquid water content constant could lead to an non realistic condition of wet snow at temperatures well below freezing. So it may be considered a trivial result that event based snowpack conditions contribute to good model performance, but it is generally difficult to know the exact snowpack conditions of the release. Often it is dangerous to access release areas and particularly in wet snow avalanches, changes in the snow cover state can be very rapid, such that manual observations often miss the interesting period. Section 3.5 has been modified.**

- *16, 372, the guideline-VS model. The*

**ANSWER: Changed.**

- *25, 540, . . . such as speed, dynamic flow depths . . . . Is it possible to give an estimate on the magnitude of their variability?*

**ANSWER: In the discussion Sect. 5 we eplicitely state, "Other important avalanche variables, such as speed, dynamic flow heights and impact pressures are not considered in the analysis, although they are crucial in many aspects of assessing avalanche risks." We have compared our model to available velocity data. However, this data is often restricted to specific test sites (e.g. VdlS) and is often incomplete, in the sense that snowcover data is missing. In our paper we attempt to model the interaction between snow AND terrain and therefore believe it is better to have different terrain, although the velocity data is missing.**

- *25, 540-542, . . . avalanche risks. What would be the benefit of using further modeling results? Why is it not necessary to consider them ( compare, e.g. for avalanche velocities Sailer et al. (2002); Ancey and Meunier (2004); Gauer (2014) or Sovilla et al. (2007); Fischer et al. (2015) for growth indices/mass balance)?*

**ANSWER: If you have the data then one MUST use them (speed, entrainment). However, this is not the usual case. We would like to turn the problem around: how can you best use a massive amount of data (inundation areas) to the greatest possible advanatage. We understand that the analysis is not complete. But we are considering a sub-class of avalanches (wet snow avalanches) where even velocity data is sparse. Data obtained from test sites is likewiselimited because it contains only one terrain geometry, or overlapping avalanche events.**

- *26, figure 11 For better comparability the same scaling of the y-axis of the single figures (a), (b) and (c) would be desirable.*

**ANSWER: Thanks for the suggestion. The figures have been modified accordingly.**

- *28, 635, . . . depth and spatial extent of the avalanche release area was known. How does the SNOWPACK model perform regarding the documented release depths - are there any measurements available?*

**ANSWER: We cite five SNOWPACK papers concerning model validation in the text. Three of them were written by one of the co-authors and are related to wet snow modelling using field data from the area where seven of our case studies occured. We consider that the snow cover model was tested enough and we do not consider this manuscript as the place to re-evaluate the snow cover model performance. Only for some case studies are there fracture depth measurements performed with a laser scan, see Table 1.**

# Response to review by G. Chambon

*I commend the authors for the impressive amount of work summarized in this paper: the compilation of data, systematic SNOWPACK and RAMMS simulations, and extensive sensitivity study provide an unprecedented set of results concerning the modelling of wet snow avalanches and the influence of various parameters such as initial mass and snow temperature / LWC on avalanche deposits and runouts. Despite the complex chain of models that is used, the authors made the effort to try to isolate the most influential physical processes, which I find particularly interesting. I am henceforth fully favorable to the publication of this paper in NHESS. I think however that several aspects of the paper could be improved to provide a better account of this nice study. First, the paper is a bit lengthy and redundant at places, and the structure of certain sections could be improved. Most importantly, I feel that the choice made by the authors to base most of the discussions on the statistical scores coming from the contingency table analysis, sometimes tend to "soften" the results and "dilute" the differences among the models. Putting more emphasis on more physical outputs, such as the raw results shown in supplementary material and the runout distances, would help counterbalance this trend. Finally, I consider that the discussion of the sensitivity analysis needs to be complemented with more quantitative comparisons and discussions. The specific comments below provide more detailed suggestions on these issues.*
**ANSWER: We thank G. Chambon for his positive judgment of our work as well as the constructive comments. Please find a detailed response to the issues raised by him below.**

## Specific comments

*1/The introduction would benefit from being more to the point at certain places. The second paragraph, in particular, appears a bit off-topic and overly speculative. If the goal is to explain that wet snow avalanches are characterized by relatively large values of apparent viscosity and cohesion, there is probably no need to discuss the so-called "compactive strength" of snow and its hypothetical relation with viscosity. On the other hand, in the third paragraph, a more in-depth discussion of the advantages and drawbacks of the different approaches used in past studies to model wet snow avalanches would be in order.*

- **ANSWER: We agree with you. We removed the speculative part of paragraph. This makes the text clearer and less redundant. Please see the track changes file**

*2/Section 2, presentation of the model: A clearer structure (e.g., avoiding redundancies and introducing subsections / subtitles to better distinguish between the different elements of the model) would improve the readability of the section. Moreover, certain mathematical notations could probably be simplified, and some physical relations better explained.*
**ANSWER: We broke up the section into different subsections and removed the all the redundancies we could find. Please see the track changes file**

Some suggestions below:

- Why using the subscript $\Phi$ everywhere? Is it really useful?
  **ANSWER: In order to make this work consistent with previous works it is important to keep the $\Phi$. All variables subscripted with $\Phi$ refer to the avalanche dense/flowing part.**

- The variable $N_K$ present in Eq.(1) would need to be defined earlier after this.
  **ANSWER: Yes, you are right. We define $N_K$ earlier. Line 114 of the new manuscript**

- What is the parameter $\gamma$ in Eq. (3)?
  **ANSWER: Yes, you are right. We removed the $\gamma$ from the Eq. 3 (Eq. 7 in the new manuscript) and define the parameter $\gamma$ in the lines inmediately below. Thank you.**

- What are the quantities $h_\Phi s$ and $\rho_\Phi s$ in line 117?
  **ANSWER: These variables represent the co-volume height and density. The co-volume represents the densest possible packing of snow granules in the avalanche core. We don't want to talk about this too much because it goes into too much detail, so we simply placed a citation in the text. See the track changes file**

- Indicate the physical meaning of $S_\Phi$ (shear stress).
  **ANSWER: We now write "The shearing stress ..." We have created an entire section entitled "Flow friction" where the shear stress is described in detail. See the track changes file**

- The sentence starting with "The basal boundary converts ..." on line 129 is not very clear. This point would maybe be better explained in conjunction with Eq. (7)?
  **ANSWER: yes, you are correct, we placed this text after Eq. 7.**

- What is the relation between the quantities $\dot{P}_\Phi$ and $R_\Phi$? Why not denoting the former simply as $\dot{R}_\Phi$.
  **ANSWER: The variable $P$denotes the input of energy (source term) whereas the variable $R$ denotes the value of energy after ALL processes (advection, sinks) have been considered. We too would like them to be the same, but this is mathematically impossible. Commented in the lines 144-159 in the new manuscript**

- Idem: what is the relation between $\dot{P}_\Phi V$ and $R_\Phi V$?
  **ANSWER: Please see above.Lines 144-159 new manuscript**

- What is the coefficient $c$ in Eq. (11)?
  **ANSWER: Corrected. It is the specific heat. The subscript $\Phi$ is missing in the equation. Eq. 11 in the new manuscript**

- The sentence starting with "Equation (14) takes into account..." in line 174 is not very clear.
  **ANSWER: We now write, "Equation ... takes into account the thermal energy contained in the entrained snow." This is better, because we avoid the use of the word "production" which confuses everything.See track changes file**

- The specific form chosen for the cohesion, i.e. the factor $(1 - \mu)$ and the exponential term, should be commented.
  **ANSWER: This specific form of the cohesion function is based on results from snow chute experiments. These experiments show that the shear stress increases from zero $S_\phi = 0$ when the normal stress is zero $N$=0. Basically the form of this function comes from fitting measurements. In the text we write, "The form of Eq. 16 ensures that the shear stress $S_\mu$=0 when $N$=0, in accordance with shear and normal force measurements in snow chute experiments."**

*3/Section 3.1. It is not fully clear whether SNOWPACK simulations were performed only for the release zones, or also for the deposition zones (in cases where data are available for these zones).*
**ANSWER: SNOWPACK simulations were also performed when a station in the valley was available (9 out of 12 cases). This is shown in Table 1. For the valley simulations, the virtual slopes were not considered, and only the flat field simulations were used. This corresponds**

**to the fact that deposits area for large avalanches are relatively flat, compared to the release area. See line 253-265 from th new manuscript.**

*4/Section 3.1, Table 3. How is the erodibility coefficient obtained? This parameter is not discussed in the text, although its influence on the results is probably far from negligible.*

**ANSWER: Yes, the reviewer is correct. We selected the erodibility coefficient based on extensive back-calculation of wet snow avalanche events. The selection process is reported in a previous paper. We don't want to clutter up the paper here, but we introduced the sentence in section on entrainment: "The value of the erodibility coefficient depends on snow quality. Values for warm, wet snow are reported in Vera et al. (2015, 2016).". See track changes file.**

*5/Section 3.2. The value chosen for the parameter $\zeta$ involved in Eq. (7) should also be discussed.*

**ANSWER: we made a notation mistake here. The parameter $\zeta$ does not exist, it should be $\gamma$. We also write, "The fluidization parameters $\alpha$ and $\gamma$ (please see Bartelt et al. (2006) and Vera et al. (2016)), are fixed to a pre-determined values based on the terrain characteristics for each avalanche path. Once these parameters are fixed they are not tuned for the remaining set of simulations.". See the track changes file.**

*6/Section 3.2. Besides data on avalanche release area, the authors probably also have data on fracture depths for at least some of the avalanches. How do these data compare to the fracture depths predicted by SNOWPACK? Where they used in way to optimize the results of SNOWPACK?*

**ANSWER:There are fracture depth data in the avalanche measured with laser scan and drone. The fracture depths measured are obviously not constant but taking avergae values are in good agreement with the values estimated by SNOWPACK, see Table 1. The reported fracture depth data was used to constrain the SNOWPACK simulaitons. This data was therefore very helpful in determing the quality of the SNOWPACK simulations.**

*7/Section 3.2. Regarding the Voellmy-Salm model, and if I understood well, the authors chose to use the same friction parameters for all studied avalanches. Would not it make more sense to optimize these parameters for each avalanche? I do not see any reason why all these avalanches should be characterized by identical friction parameters. In addition, giving the value of these parameters would also be useful, for the sake of comparison with the parameters used in the RAMMS model.*

**ANSWER: We did not change the parameters of the thermomechanical model – they were fixed to values. We tried to run the thermomechanical model, changing only the initial and boundary conditions. We wanted to do the same for the Voellmy model. It is extremely important to us that WE DO NOT optimize the friction parameters for a particular avalanche – either for the thermomechanical model or the Voellmy. We have a set of "wet snow parameters" that we use for all wet snow avalanches. The initial (release) and boundary conditions (terrain, snowcover) are changed for each avalanche. We emphasize this result in the conclusions. In practice a user of the Voellmy model will follow the same approach – they will use the guideline parameters. We are not comparing models: we are comparing two approaches: A thermomechanical modelling approach where we change only the initial and boundary conditions against the standard Voellmy model.**

*8/Section 3.5 is not very clear and some redundancies could be avoided. In the first paragraph, in particular, it is difficult to understand what the 432 simulations represent, whereas this issue is better explained afterwards.*

**ANSWER: We rephrased this section completely, also to address the comment by the other reviewer that the motivation for the way the sensitivity study was set-up was not clearly explained. See the track changes file.**

*9/Section 4.1. While the different statistical scores used by the authors effectively show that the thermomechanical model performs better than the Voellmy-Salm model, this issue is even more evident from observation of the model outputs provided as supplementary material. Hence I would encourage the authors to add, at least, a short description of these raw outputs in the main text prior to discussing the statistical scores. Adding a figure showing one or two illustrative examples of raw results in the main text could also be option. Similarly, moving the runout comparisons (currently presented in 4.4) before the statistical score comparisons could also help to better illustrate the differences among the models.*

**ANSWER: We agree. We inserted the following text before we begin to discuss the statistical scores: "The results of the model runs are presented extensively in the paper supplements.**

**The graphs in the supplement A facilitate a direct comparison between the thermomechanical approach, the standard Voellmy-Salm procedure and the actual avalanche measurements, including the location of the deposits with respect to the observed release zone. Supplement B contains the results of the model permutations. This graphical output enables a quick assessment of the model sensitivity. In the following we statistically analyze model performance."**

*10/Section 4.1. The sentence starting by "The fact that the difference in ETS score ... "in line 379 seems in contradiction with what is said just before (lower difference in ETS than in HKS between the two models).*

**ANSWER: You are correct, it's in contradiction. The sentence was wrong and referred to an earlier version of the graph. We removed it from the manuscript. The difference in POD between the thermodynamics model and Voellmy-Salm model is larger than the FAR. So in the results presented, the Hanssen-Kuiper skill score is not biased towards the Voellmy-Salm model anymore, as the POD is not higher.See the track changes manuscript**

*11/Section 4.2, line 407. Why do the authors refer to the friction parameters used in the VS model as "extreme" here?*

**ANSWER: extreme refers to avalanche with return periods greater than 300 years. We now state in the text, "The primary result of the preceding section is that guideline-based avalanche dynamics models with extreme friction parameters (avalanches with return periods greater than 300 years) will have difficulty reconstructing individual case studies and that they are not easily linked to snowcover conditions."**

*12/Section 4.2-4.3-4.4. I encourage the authors to provide more quantitative evidences of the conclusions drawn from their sensitivity study. In the current manuscript, it is sometimes difficult to relate the assertions made in the text to the presented data. One probable reason is that the authors rely throughout on the same type of figures, whereas alternative representations, such as boxplots or distributions / percentiles, would probably allow for easier quantitative comparisons between, e.g., the different initial conditions (mass versus temperature/LWC) or the different grid resolutions. I indicate below a few examples of overly qualitative statements that would need to be supported by more quantitative evidences:*

- *line 426: "generally higher"* ***CHANGED: removed "generally". They are higher, see graphs 5 and 6.***
- *line 431: "the simulation with the original initial condition is among ..."* ***CHANGED: removed. Adds no additional information.***
- *line 440: "are more sensitive to"* ***CHANGED: removed. Adds no additional information.***
- *line 452-453: A small variation (...) would lead to a large variability (While Fig. 6 shows that simulations with other initial conditions are sometimes as good as simulations with the correct initial conditions.)* ***CHANGED: We now quantify small. A change in the fracture depth of 10cm can lead to a large variability in the predicted avalanche runout. This is a problematic result because it indicates the critical role of fracture depth as an input parameter in avalanche simulations.***
- *line 459: "less sensitive"* ***Removed and shortened the text.***
- *line 465: "The variation was strongest"* ***CHANGED: We write: The strong variation on long avalanche tracks with a smooth transition to runout zone demonstrates, once again, that path geometry dominates over changes in snowcover boundary conditions.***

*13/Section 4.2.2: Could the authors also discuss the relative influence on the results of mass in the release area versus mass in the entrainment zone?*

**ANSWER: The statistical scores show superior scores when the correct entrainment conditions are modelled. However, The results are controlled by the water content/warmth of the entrained snow. The problem is, and we have stated this in the work, that the water content/warmth of the entrained snow did not vary strongly, because we are considering only wet avalanches. The role of entrainment would change dramatically, if we were to include dry and wet snow avalanches. We have added the text, "The role of mass entrainment is difficult to**

**identify in the statistical scores because we considered only warm/moist snowcovers. Moreover, the permuations did not include dry, cold snowcovers. This result suggests that the snow quality (temperature, moisture) is more important than the snow amount.". see track changes manuscript.**

*14/Section 4.3: The description of the effect of grid size on the statistical scores could probably be shortened, and redundancies avoided. I suggest however to extend the – currently very short – last paragraph describing the interplay between initial conditions and resolution. To me, this latter issue constitutes the real novelty of the sensitivity study conducted by the authors with respect to grid resolution.*

**ANSWER: The reviewer is correct. The very short paragraph should not stand alone as it begs for further detail and explanation. We deleted it from the results. The contents are covered in the discussion section.**

*15/Section 5: The sentence starting with "Moreover, the connection between friction and initial starting mass" in line 597 is not very clear.*

**ANSWER: Yes, we agree. It adds no further information. We deleted it from the paper.**

*Table 1. The caption mentions virtual slope, but this information does not seem to appear in the table?*

**ANSWER: The third column in the table should have been interpreted as, for example, KLO3-NE means AWS is KLO3, virtual slope is North-East (NE). Changed the table caption and table layout to make this more clear.This info is in table 2 too.See track changes file.**

*Line 249-252: The sentence starting with "In case of avalanches with new snow ..." is not fully clear: does it apply only to the cases where meteorological data in the deposition zone are not available, or to all cases?*

**ANSWER: This indeed is not clear. We only use data from the measurment stations, which are located in the release zones. No data is really available for the deposition zones, which are based on snowcover modelling. Therefore, it applies to ALL cases.**

*Line 308: The reference to Table 2 seems wrong here.*

**ANSWER: Thank you for pointing out, it should have been Fig. 2 instead of Table 2.**

*Fig. 3, caption: word missing after "the longest calculated".*

**ANSWER: Thank you for pointing out, changed to: "the longest calculated flowline (red dot)"**

*line 477: typo: "courser"*

**ANSWER: Thank you for pointing out, changed to "coarser".**

*Fig. 10: Why the asterisk with the specific value corresponding to the CV-1 case?*

**ANSWER: For this case study we had a 1m digital elevation model, obtained from a drone flight. We added in the caption: "It was necessary to simulate the CV-1 case with a 1m grid resolution to better account for a vertical wall."**

*line 524: why the "(not shown)", instead of a reference to section 4.3 where variations of ETS and HKS with resolution are extensively discussed?*

**ANSWER: We removed "not shown" Made referene to section 4.3.**

*Fig. 11: (a), (b), (c) need to be added to the plots.*

**ANSWER: Thank you for pointing out, the figure was corrected.**

*line 609: word missing after "the maximum LWC"?*

**ANSWER: Rephrased the sentence to: The bulk LWC of the slab above the depth of the maximum local LWC was used to initialize the simulations.**

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# Modeling the influence of snowcover temperature and water content on wet snow avalanche runout

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**Abstract.** Snow avalanche motion is strongly dependent on the temperature and water content of the snowcover. In this paper we use a snowcover model, driven by measured meteorological data, to set the initial and boundary conditions for wet snow avalanche calculations. The snowcover model provides estimates of snow depth, density, temperature and liquid water content. This information is used to prescribe fracture heights and erosion depths for an avalanche dynamics model. We compare simulated runout distances with observed avalanche deposition fields using a contingency table analysis. Our analysis of the simulations reveals a large variability in predicted runout for tracks with flat terraces and gradual slope transitions to the runout zone. Reliable estimates of avalanche mass (height and density) in the release and erosion zones is identified to be more important than an exact specification of temperature and water content. For wet snow avalanches, this implies that the layers where meltwater accumulates in the release zone must be identified accurately as this defines the height of the fracture slab and therefore the release mass. ~~This is an interesting result because it indicates the critical role of fracture depth as an input parameter in avalanche simulations.~~ Advanced thermomechanical models appear to be better suited ~~than existing guideline procedure~~ to simulate wet snow ~~avalanches when~~ avalanche inundation areas in comparison to existing guideline procedures if and only if accurate snowcover information is available.

## 1 Introduction

Avalanche hazard mitigation has historically concentrated on catastrophic avalanches releasing from dry, high alpine snowcovers. There are many regions in the world, however, where wet snow avalanche problems are dominant. Increasingly, avalanche engineers require methods to consider the avalanche hazard arising from frequent wet snow slides (Naaim et al., 2013).

The runout of wet snow avalanches is especially difficult to calculate because temperature and liquid water content (LWC) have a strong influence on the mechanical properties of snow (Denoth, 1982; Voytokskiy, 1977; Salm, 1982). ~~There are two primary effects. Firstly, the compactive hardness of snow decreaseswith increasing water content (Salm, 1982) and secondly, the shear viscosity decreaseswith increasing temperature Voytokskiy (1977).~~ When warm snow contains liquid water, the deformation mechanics is controlled by the liquid ~~water content~~ film at the grain to grain contact~~,~~ (Salm, 1982). Wet snow can be plastically deformed until it reaches "packed density". The low compactive strength of wet snow is revealed in granulometric investigations of avalanche deposits: wet snow granules are large, heavy and poorly sorted in comparison to granules in dry avalanches (Jomelli and Bertran, 2001; Bartelt and McArdell, 2009). Thus, the initial compaction of wet snow facilitates the formation of large, dense granules, leading to a significant increase in the *bulk* flow viscosity and cohesion of the avalanche (Bartelt et al., 2015). Another indication of the viscous and cohesive character of wet snow flows are the formation of levees with steep vertical shear planes in wet snow avalanche deposits (Bartelt et al., 2012b).

~~To model the increase in~~ An increased bulk flow viscosity~~of wet snow avalanches (that is,~~ , however, is not the only mechanical change induced by warm, moist snow. The presence of liquid water on interacting snow surfaces *decreases* the magnitude of the *bulk* sliding friction coefficient. This decrease has been observed and quantified in many experiments, particularly those involving ski friction (Glenne, 1987; Colbeck, 1992). The decrease in sliding friction results in long-runout avalanches Naaim et al. (2013), making wet snow flows particularly dangerous.

To model the lower flow velocities associated with wet snow flows~~)~~, the Swiss guidelines on avalanche calculation recommend increasing the velocity squared turbulent friction (Salm et al., 1990). Wet snow avalanches are therefore treated as dense granular flows in the frictional flow regime (Voellmy, 1955; Bozhinskiy and Losev, 1998). Because measured velocity profiles of wet snow avalanches exhibit pronounced visco-plastic, plug-like character, they are often modeled with a Bingham-type flow rheology (Dent and Lang, 1983; Norem et al., 1987; Salm, 1993; Dent et al., 1998; Bartelt et al., 2005; Kern et al., 2009). Bartelt et al. (2015) uses cohesion to reduce the random kinetic energy of the avalanche core which effectively hinders avalanche fluidization and prevents the formation of mixed flowing/powder avalanches (Buser and Bartelt, 2015).

~~An increased bulk flow viscosity, however, is not the only mechanical change induced by warm, moist snow. The presence of liquid water on interacting snow surfaces decreasesthe magnitude of the bulksliding friction coefficient. This decrease has been observed and quantified in many experiments, particularly those involving ski friction (Glenne, 1987; Colbeck, 1992). The decrease in sliding friction results in long-runout avalanches Naaim et al. (2013), making wet snow flows particularly dangerous.~~

The sensitivity of wet snow avalanche flow on temperature and moisture content makes predictions of avalanche runout difficult. For example, wet snow avalanches often occur after extreme precipitation events followed by intense warming. Because of differences in snowcover temperature and water content between the release and runout zones, wet snow avalanches can start in sub-zero temperatures and run into moist, isothermal snowcovers. That is, sub-zero release areas can lead to the formation of dry mixed flowing/powder type avalanches that transition at lower elevations to moist, wet flows. Clearly, a wet snow avalanche model must account for the initial temperature and water content of the snowcover.

In this paper we use snowcover models to establish the initial and boundary conditions for wet snow avalanche dynamics calculations. ~~The primary goal is to investigate if better snowcover temperature and water content predictions can improve the calculation of wet snow avalanche runout. We specify snow cover~~ We specify snowcover information that is derived from detailed physics based snowcover model simulations using **SNOWPACK** (Bartelt et al., 2002; Lehning et al., 2002). ~~Avalanche~~ Unlike existing approaches, for example citepGruber2009, avalanche dynamics parameters will not be tuned, but are fixed within the framework of empirical functions parameterized by snow density, temperature and moisture content (Vera et al., 2015, 2016). Our goal is to obtain accurate runout and ~~deposits area~~ deposition predictions without ad-hoc modifications to avalanche model parameters. Instead of parameter optimization, we specify snow depth, density, temperature and moisture content in both release (initial conditions) and entrainment zones (boundary conditions) as input data for the model.

The approach consists of three basic steps (see Fig. 1):

1. Simulation of snowcover conditions using measured weather data as input.

2. Simulation of avalanches using initial conditions defined by snowcover conditions.

3. Contingency table analysis to define the statistical score of avalanche runout calculation.

The procedure is applied to simulate twelve documented avalanche events, for which extensive field measurements are available, including measurements from airborne laser-scans, drones and photography and hand-held GPS devices. To determine how the procedure performs we compare the area covered in the simulations with the deposit area measured in the field. Simulated runout patterns are compared to field observations. The correspondence of observed deposits and calculated deposits is checked using a dichotomous contingency table, splitting the terrain in four different classes: hits, misses, false alarms and correct negatives.

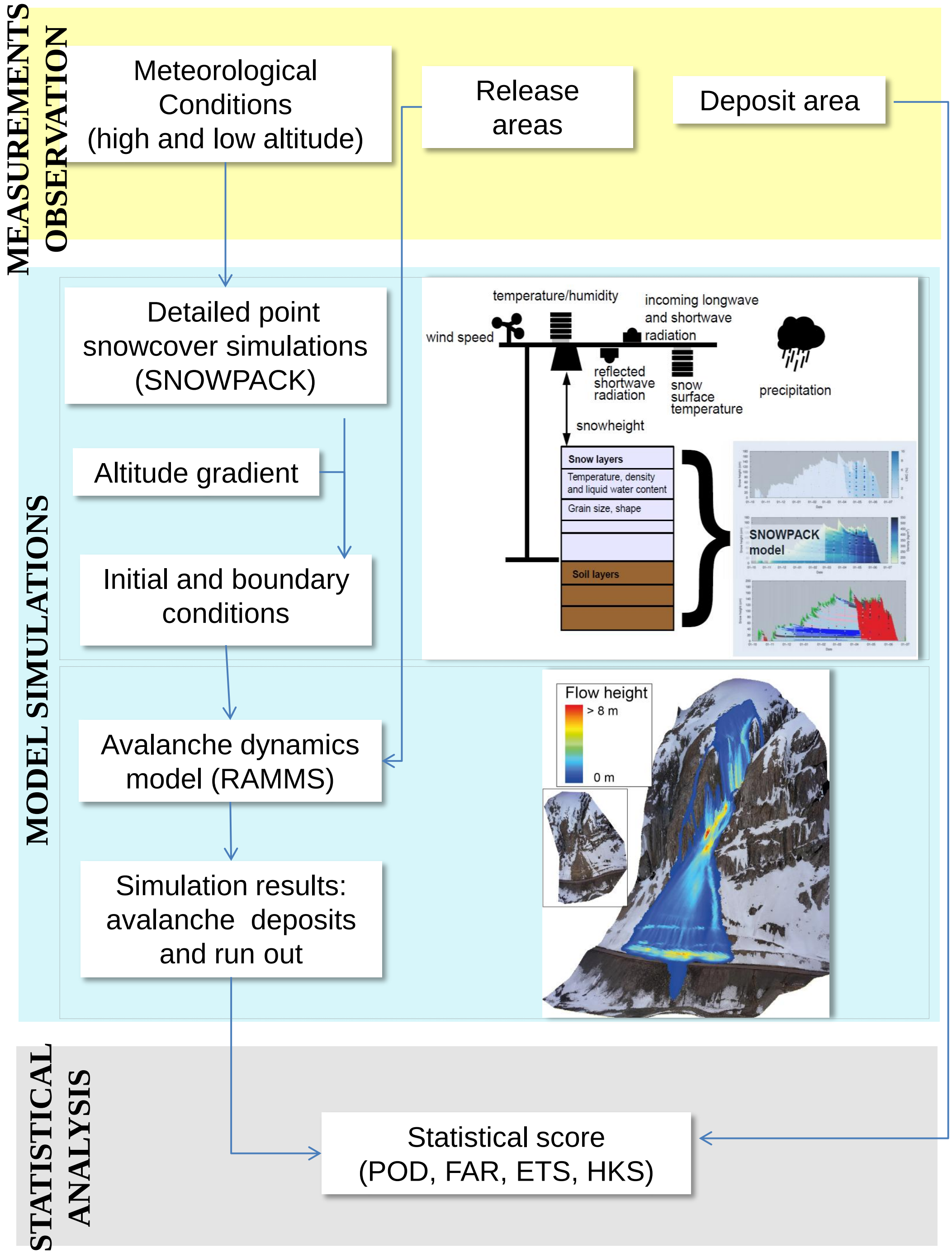



Fig. 1: Flow diagram depicting the three step model chain. The procedure begins by simulating snowcover conditions using measured weather data as input. Next, avalanche runout is simulated using initial and boundary conditions defined by snowpack modeling. Finally, a statistical score of the avalanche runout modeling is calculated.

Additionally, a sensitivity study is performed by interchanging the initial and boundary conditions of the twelve case studies and by varying the calculation grid cell size. The same contingency analysis and runout comparison is performed with the results obtained from the sensitivity analysis. This establishes to what extend the initial and boundary conditions indeed control the model performance.

## 2 Wet snow avalanche modeling

Wet snow avalanche modeling necessitates the simulation of four physical processes (Vera et al., 2015, 2016):

1. The rise in avalanche temperature by frictional dissipation.
2. Phase changes and the production of meltwater.
3. Entrainment of snow mass *and* the associated internal (thermal) energy change of the avalanche.
4. Constitutive models describing how the avalanche flow rheology changes as a function of temperature and moisture content.

One model that fulfills these requirements was developed by Vera et al. (2015, 2016). ~~In this model, the~~

### 2.1 Avalanche core

The flow of the dense avalanche core (subscript $\Phi$) is described by nine independent state variables:

$$\mathbf{U}_\Phi = (M_\Phi, M_\Phi u_\Phi, M_\Phi v_\Phi, R_\Phi h_\Phi, E_\Phi h_\Phi, h_\Phi, M_\Phi w_\Phi, N_K, M_w)^T. \tag{1}$$

These variables include the core mass $M_\Phi$ (which contains both the ice mass *and* the water mass $M_w$), the flow height $h_\Phi$, depth-averaged velocities parallel to the slope $\mathbf{u}_\Phi = (u_\Phi, v_\Phi)^T$ and in the slope perpendicular direction $w_\Phi$, the sum of the kinetic and potential energies associated with the configuration and random movement of snow particles $R_\Phi$ and the internal heat energy (temperature) $E_\Phi$. The formulation includes the dispersive pressure $N_K$ (Buser and Bartelt, 2015; Bartelt et al., 2015).

The model equations can be written as a single vector equation:

$$\frac{\partial \mathbf{U}_\Phi}{\partial t} + \frac{\partial \mathbf{\Phi}_x}{\partial x} + \frac{\partial \mathbf{\Phi}_y}{\partial y} = \mathbf{G}_\Phi \tag{2}$$

where the components ($\mathbf{\Phi}_x$, $\mathbf{\Phi}_y$, $\mathbf{G}_\Phi$) are:

$$\mathbf{\Phi}_x = \begin{pmatrix} M_\Phi u_\Phi \\ M_\Phi u_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ M_\Phi u_\Phi v_\Phi \\ R_\Phi h_\Phi u_\Phi \\ E_\Phi h_\Phi u_\Phi \\ h_\Phi u_\Phi \\ M_\Phi w_\Phi u_\Phi \\ N_K u_\Phi \\ M_w u_\Phi \end{pmatrix}, \; \mathbf{\Phi}_y = \begin{pmatrix} M_\Phi v_\Phi \\ M_\Phi u_\Phi v_\Phi \\ M_\Phi v_\Phi^2 + \frac{1}{2} M_\Phi g' h_\Phi \\ R_\Phi h_\Phi v_\Phi \\ E_\Phi h_\Phi v_\Phi \\ h_\Phi v_\Phi \\ M_\Phi w_\Phi v_\Phi \\ N_K v_\Phi \\ M_w v_\Phi \end{pmatrix}, \; \mathbf{G}_\Phi = \begin{pmatrix} \dot{M}_{\Sigma\to\Phi} \\ G_x - S_{\Phi x} \\ G_y - S_{\Phi y} \\ \dot{P}_\Phi \\ \dot{Q}_\Phi + \dot{Q}_{\Sigma\to\Phi} + \dot{Q}_w \\ w_\Phi \\ N_K \\ 2P_\Phi^V - 2N w_\Phi / h_\Phi \\ \dot{M}_{\Sigma\to w} + \dot{M}_w \end{pmatrix}. \tag{3}$$

The flowing avalanche is driven by the gravitational acceleration in the tangential directions $\mathbf{G} = (G_x, G_y) = (M_\Phi g_x, M_\Phi g_y)$. The model equations are solved using the same numerical schemes outlined in (Christen et al., 2010).

The model assumes non-zero slope perpendicular accelerations and therefore calculates the slope perpendicular velocity of the core $w_\Phi$ (Buser and Bartelt, 2015; Bartelt et al., 2015). The center-of-mass of the granular ensemble moves with the slope perpendicular velocity $w_\Phi$. When $w_\Phi > 0$, the granular ensemble is expanding; conversely when $w_\Phi < 0$, the volume is contracting. The densest packing of granules defines the co-volume height ${}^0h_\Phi^s$ and density ${}^0\rho_\Phi^s$ (Buser and Bartelt, 2015; Bartelt et al., 2015). The co-volume has the property that $h_\Phi^s \geq^0 h_\Phi^s$ and $\rho_\Phi^s \leq^0 \rho_\Phi^s$.The normal pressure at the base of the column $N$ is therefore no longer hydrostatic, but includes the impulsive reaction $N_K$ associated with the slope perpendicular accelerations,

$$N_K = M_\Phi \dot{w}_\Phi. \tag{4}$$

The total acceleration in the slope perpendicular direction is denoted $g'$; it is composed of the slope perpendicular component of gravity $g_z$, dispersive acceleration $\dot{w}_\Phi$ and centripetal accelerations $f_z$, (Fischer et al., 2012). The total normal force at the base of the avalanche is given by $N$,

$$N = M_\Phi g' = M_\Phi g_z + N_K + M_\Phi f_z. \tag{5}$$

Changes in density are induced by shearing: ~~Shearing~~ The shearing stress in the avalanche core $\mathbf{S}_\Phi$ induces particle trajectories that are no longer in line with the mean downslope velocities $\mathbf{u}_\Phi$ (Gubler, 1987; Bartelt et al., 2006). The kinetic energy associated with the velocity fluctuations is denoted $R_\Phi^K$. The ~~basal boundary plays a prominent role because particle motions in the slope-perpendicular direction are inhibited by the boundary and reflected back into the flow. The basal boundary converts the production of random kinetic energy $R_\Phi^K$ into an energy flux that changes the $z$-location of particles and therefore the potential energy and particle configuration within the core. The potential~~

~~energy of the configuration of the particle ensemble~~ potential energy associated with the dilation of the core is denoted $R_\Phi^V$.

The production of free mechanical energy $\dot{P}_\Phi$, is given by an equation containing two model parameters: the production parameter $\alpha$ and the decay parameter $\beta$, see (Buser and Bartelt, 2009)

$$\dot{P}_\Phi = \alpha\left[\mathbf{S}_\Phi \cdot \mathbf{u}_\Phi\right] - \beta R_\Phi^K h_\Phi. \tag{6}$$

The production parameter $\alpha$ defines the generation of the total free mechanical energy from the shear work rate $[\mathbf{S}_\Phi \cdot \mathbf{u}_\Phi]$; the parameter $\beta$ defines the decrease of the kinetic part $R_\Phi^K$ by inelastic particle interactions. The energy flux associated with the configurational changes is denoted $\dot{P}_\Phi^V$ and given by

$$\dot{P}_\Phi^V = \cancel{\zeta}\gamma \dot{P}_\Phi. \tag{7}$$

The parameter ~~$\zeta$~~ $\gamma$ therefore determines the magnitude of the dilatation of the flow volume under a shearing action. When ~~$\zeta = 0$~~ $\gamma = 0$ there is no volume expansion by shearing. For wet snow flows the value of ~~$\zeta$~~ $\gamma$ is small, ~~$\zeta <$~~ $\gamma <$ 0.2. The basal boundary plays a prominent role because particle motions in the slope-perpendicular direction are inhibited by the boundary and reflected back into the flow. The basal boundary converts the production of random kinetic energy $\dot{P}_\Phi$ into an energy flux that changes the $z$-location of particles and therefore the potential energy and particle configuration within the core. The potential energy of the configuration of the particle ensemble is denoted $P_\Phi^V$.

### 2.2 Avalanche temperature

We model temperature dependent effects by tracking the depth-averaged avalanche temperature $T_\Phi$ within the flow (Vera et al., 2015). The temperature $T_\Phi$ is related to the internal heat energy $E_\Phi$ by the specific heat capacity of snow $c_\Phi$

$$E_\Phi = \rho_\Phi c_\Phi T_\Phi. \tag{8}$$

The avalanche temperature is governed by (1) the initial temperature of the snow $T_0$, (2) dissipation of kinetic energy by shearing $\dot{Q}_\Phi$, as well as (3) thermal energy input from entrained snow $\dot{Q}_{\Sigma\to\Phi}$ and (4) latent heat effects from phase changes $\dot{Q}_w$ (meltwater production), see Vera et al. (2015). Dissipation is the part of the shear work not being converted into free mechanical energy in addition to the inelastic interactions between particles that is the decay of random kinetic energy, $R_\Phi^K$

$$\dot{Q}_\Phi = (1-\alpha)\left[\mathbf{S}_\Phi \cdot \mathbf{u}_\Phi\right] + \beta R_\Phi^K h_\Phi. \tag{9}$$

A fundamental assumption of this model is that liquid water mass is bonded to the ice matrix of the snow particles and therefore is transported with the flowing snow. Mathematically, the governing equations treat moisture content as a passive scalar. Meltwater production is considered as a constraint on the flow temperature of the avalanche: the mean flow temperature $T_\Phi$ can never exceed the melting temperature of ice $T_m$ = 273.15 $K$. The energy for the phase change is given by the latent heat $L$

$$\dot{Q}_w = L\dot{M}_w \tag{10}$$

under the thermal constraint such that within a time increment $\Delta t$

$$\int_0^{\Delta t} \dot{Q}_w dt = M_\Phi c_\Phi (T_\Phi - T_m) \qquad \text{for} \qquad T > T_m. \tag{11}$$

Obviously, when the flow temperature of the avalanche does not exceed the melting temperature, no latent heat is produced, $\dot{Q}_w = 0$.

### 2.3 Snow entrainment

Another source of thermal energy is snow entrainment. The total mass that is entrained from the snowcover ($\Sigma$) is given by

$$\dot{M}_{\Sigma \to \Phi} = \rho_\Sigma \kappa \left\| \mathbf{u}_\mathbf{\Phi} \right\|. \tag{12}$$

where $\rho_\Sigma$ is the density of snow and $\kappa$ the dimensionless erodibility coefficient. The value of the erodibility coefficient depends on snow quality. Values for warm, wet snow are reported in (Vera et al., 2015, 2016). The liquid water mass entrained by the avalanche is therefore,

$$\dot{M}_{\Sigma \to w} = \theta^w_\Sigma \dot{M}_{\Sigma \to \Phi}. \tag{13}$$

where $\theta^w$ is the LWC of the entrained snow. The thermal energy entrained during the mass intake is

$$\dot{Q}_{\Sigma \to \Phi} = \left[ \theta^i_\Sigma c_i + \theta^w_\Sigma c_w + \theta^a_\Sigma c_a + \frac{1}{2} \frac{\left\| \mathbf{u}_\mathbf{\Phi} \right\|^2}{T_\Sigma} \right] \dot{M}_{\Sigma \to \Phi} T_\Sigma \tag{14}$$

where $c_i$, $c_w$ and $c_a$ are the specific heat capacity of ice, water and air, respectively. When the snow layer contains water $\theta^w_\Sigma > 0$, then the temperature of the entire layer is set to $T_\Sigma$ = 0° C. Equation 14 takes into account the ~~production of heat energy during the entrainment process~~thermal energy contained in the entrained snow.

### 2.4 Flow friction

To model frictional resistance $\mathbf{S}_\Phi = (S_{\Phi x}, S_{\Phi y})$ in wet snow avalanche flow we apply a modified Voellmy model(Voellmy, 1955; Salm et al., 1990; Salm, 1993; Christen et al., 2010),

$$\mathbf{S}_\Phi = \frac{\mathbf{u}_\Phi}{\left\| \mathbf{u}_\Phi \right\|} \left[ S_\mu + S_\xi \right]. \tag{15}$$

consisting of both a Coulomb friction $S_\mu$ (coefficient $\mu$) and a velocity dependent stress $S_\xi$ (coefficient $\xi$). The friction terms $S_\mu$ and $S_\xi$ are given by

$$S_\mu = \mu N - (1-\mu) N_0 \exp\left(\frac{N}{N_0}\right) + (1-\mu) N_0 \tag{16}$$

and

$$S_\xi = \rho_\Phi g \frac{\|\mathbf{u}_\Phi\|^2}{\xi}. \tag{17}$$

In the Coulomb friction term, $N_0$ is the cohesion; see Bartelt et al. (2015) for values of $N_0$ for wet snow. The form of Eq. 16 ensures that the shear stress $S_\mu$=0 when $N$=0, in accordance with shear and normal force measurements in snow chute experiments. To model the decrease in friction from meltwater lubrication, we make the Coulomb stress dependent on the meltwater water content $h_w$. We use the following lubrication function to replace the standard Coulomb friction coefficient $\mu$:

$$\mu(h_w) = \mu_w + (\mu_d - \mu_w)\exp\left[-\frac{h_w}{h_s}\right]. \tag{18}$$

where $\mu_d$ is the dry Voellmy friction coefficient, $\mu_w$ is the limit value of lubricated friction (Voellmy assumed this value to be $\mu_w$ = 0 in the limiting case) and $h_s$ is a scaling factor describing the height of the shear layer where meltwater is concentrated. The dry friction $\mu_d$ depends on the avalanche configuration:

$$\mu_d = \mu_0 \exp\left[-\frac{R_\Phi^V}{R_0 + N_0}\right], \tag{19}$$

where $\mu_0$ is the dry Coulomb friction associated with the flow of the co-volume, which we take to be $\mu_0$ = 0.55, see (Buser and Bartelt, 2015). The parameter $R_0$ defines the activation energy for fluidization. Cohesion enhances the activation energy and therefore hinders the fluidization of the avalanche core (Bartelt et al., 2015).

## 3 Selected wet snow avalanche events and modeling procedure

We apply the numerical model to simulate documented wet snow avalanches. The data set includes twelve wet snow avalanches that occurred in the Swiss Alps and in the Chilean central Andes between 2008 and 2015. The avalanches were selected for three reasons: (1) the avalanche was located in the vicinity of an automatic weather station (henceforth AWS), (2) the release area and the area inundated by the avalanche were measured either by hand held GPS, drone or terrestrial laser scanning and (3) a high resolution digital elevation model (i.e. 2 m or higher) is available to simulate the terrain. This information is summarized in Table 1. The avalanche release volumes varied between 7,000 m$^3$ and 330,000 m$^3$. Most avalanches released from a wet snowcover and entrained additional wet snow. However, in three events (Grengiols, Braemabuhl Verbauung and Gatschiefer) the avalanche released as a dry slab at subzero temperatures, but entrained warm, moist snow at lower elevations. The release, transit and deposit zone of ten of the twelve case studies were additional photographed from a helicopter. The two remaining avalanches (Drusatscha and Braemabuhl 2013) were photographed by the authors from the deposition zone. The measurements from the release areas and deposits outlines for every avalanche path are shown in Supplement A in the online supplement.

Table 1: Case study, date and estimated time of occurrence, (AWS) automatic weather station ~~and virtual slope used~~ at the top, followed by a dash and ~~at valley bottom~~ the virtual slope (v. slope) used for the release zone and altitude of the AWS, AWS and its altitude in the valley bottom used for deposits area, type of field measurement and altitude of the release and of the deposits in m.a.s.l. For the laser scan and drone measurements, the estimated fracture depths from these measurements are listed.

| heightAvalanche | Date/Hour | ~~AWS-slope Top/Valley (altitude AWS m.)~~ AWS Release (altitude in m) | ~~Measurements~~ AWS Valley (altitude in m) | Fracture Method/Depth (m) | Altitude release Deposits (m) |
|---|---|---|---|---|---|
| Gruenbodeli | 23.04.2008 ≈ 14h00m | KLO2-NE (2140) ~~/~~ | SLF2 (1550) | Laser scan / 0.70 | 1900/1600 |
| Salezer | 23.04.2008 15h00m | WFJ2-W (2560) ~~/~~ | SLF2 (1550) | Laser scan / 1.1 | 2400/1500 |
| Gastschiefer | 23.04.2008 16h00m | KLO3-N (2310) ~~/~~ | SLF2 (1550) | Laser scan / 2.0 | 2400/1200 |
| Braemabuhl 2013 | 18.04.2013 15h00m | WFJ2-NE (2560) ~~/~~ | SLF2 (1550) | GPS profile | 2200/1600 |
| Drusatcha | 15.04.2013 17h00m | WFJ2-W (2560) ~~/~~ | SLF2 (1550) | GPS profile | 2200/1700 |
| MO-4 Andina Chile | 15.10.2013 19h15m | CAND5-SE (3520) ~~/~~ | Lagunitas (2770) | Ortophoto | 3700/3200 |
| Grengiols | 26.12.2013 13h00m | GOMS-NE (2450) ~~/~~ | Estimated | GPS profile | 2300/1400 |
| Verbier Mont Rogneux | 13.03.2014 17h00m | ATT2-W (2545) ~~/~~ | Estimated | GPS profile | 2400/1700 |
| Verbier Ba Comb | 13.03.2014 17h00m | ATT2-SW (2545) ~~/~~ | Estimated | GPS profile | 2200/1600 |
| Braemabuhl verbauung | 03.04.2015 12h00m | WFJ2-NE (2560) ~~/~~ | SLF2 (1550) | GPS profile | 2200/1600 |
| Braemabuhl Wildi | 04.04.2015 ≈ 14h00m | WFJ2-NE (2560) ~~/~~ | SLF2 (1550) | Drone ~~photogrametry~~ / 1.1 | 2200/1600 |
| CV-1 Andina Chile | 19.10.2015 17h00m | CAND5-E (3520) ~~/~~ | Lagunitas (2770) | Drone ~~photogrametry~~ / 1.1 | 2700/2500 |

### 3.1 SNOWPACK simulations

The data provided by the automatic weather stations allows us to run detailed, physics based snow-cover simulations. We apply the **SNOWPACK** model (Bartelt et al., 2002; Lehning et al., 2002; Wever et al., 2014) in a similar setup as the snow-height driven simulations in Wever et al. (2015, 2016). Because **SNOWPACK** is a one-dimensional model, we must transfer point simulation results to the slope in order to apply a ~~three-dimensional~~ two-dimensional avalanche dynamics model operating in three-dimensional terrain. The horizontal distance between release zone ~~and~~ or deposits zone and the meteorological station varied between 200 m (the nearest) and 2200 m (the farthest). More important than the linear distance is the difference in altitude. ~~The small elevation difference~~ We argue that the elevation differences between the release zones or deposits zones and the weather stations ~~,~~ (see Table 1) ~~, provides the sufficient conditions to apply snowcover models~~ are sufficiently small to provide representative snowcover simulations to estimate the initial and boundary conditions of the case studies (Vera et al., 2016; Wever et al., 2016).

To determine the initial temperature and moisture content of the snowcover requires an accurate modeling of the surface energy fluxes (sensible and latent heat exchanges, incoming short and long-wave radiation) which are influenced by the slope exposition. We account for exposition effects on surface energy fluxes in the release zones using the virtual slope concept proposed by Lehning et al. (2008), which was found to provide accurate slope simulations that correspond with wet snow avalanche activity, (Wever et al., 2016; Vera et al., 2016). We obtain snowcover layering, temperature, density and LWC in the release zones using virtual slope angles of 35° (see Table 2). The real slope angles of the release zones varied between 32° and 45°. Shortwave radiation measured

Table 2: Initial conditions derived from SNOWPACK simulations at the release for each avalanche

| Avalanche | Date | Meteostation | LWC (%) | depth (m) | density (kg m$^{-3}$) | temperature (°C) | Cohesion (Pa) | Released Volume (m$^3$) | Growth index (-) |
|---|---|---|---|---|---|---|---|---|---|
| Gruenbodeli | 23.04.2008 ≈ 14h00m | KLO3-NE | 1.45 | 0.56 | 197 | -0.3 | 100.0 | 52882 | 2.2 |
| Salezer | 23.04.2008 ≈ 15h00m | ATT2-SW | 1.89 | 0.95 | 317 | -0.1 | 150.0 | 46394 | 2.4 |
| Gatschiefer | 23.04.2008 16h00m | KLO3-N | 1.63 | 1.72 | 320 | -0.1 | 150.0 | 330544 | 1.8 |
| Braemabuhl 2013 | 18.04.2013 15h00m | WFJ2-NE | 2.97 | 1.11 | 353 | 0.0 | 150.0 | 21404 | 3.5 |
| Drusatscha | 15.04.2013 17h00m | WFJ2-W | 3.41 | 0.54 | 291 | 0.0 | 150.0 | 32730 | 2.3 |
| MO-4 Andina Chile | 15.10.2013 19h15m | CAND5-SE | 2.44 | 0.90 | 296 | -0.2 | 150.0 | 9257 | 2.1 |
| Grengiols | 26.12.2013 ≈ 13h00m | GOMS-NE | 0.00 | 1.10 | 175 | -7.4 | 100.0 | 129392 | 3.9 |
| Verbier Mont Rogneux | 13.03.2014 17h00m | ATT2-W | 3.67 | 0.60 | 317 | 0.0 | 150.0 | 55817 | 1.8 |
| Verbier Ba Combe | 13.03.2014 17h00m | ATT2-SW | 3.40 | 0.58 | 349 | 0.0 | 150.0 | 21349 | 2.1 |
| Braemabuhl verbauung | 03.04.2015 12h00m | WFJ2-NE | 1.01 | 1.10 | 285 | 0.0 | 150.0 | 6858 | 2.7 |
| Braemabuhl Wildi | 04.04.2015 ≈ 14h00m | WFJ2-NE | 1.23 | 1.10 | 245 | -1.4 | 100.0 | 45614 | 3.3 |
| CV-1 Andina Chile | 19.10.2015 17h00m | CAND5-E | 2.36 | 0.95 | 359 | -0.1 | 150.0 | 4019 | 2.2 |

at the AWS as well as snowfall amounts are re-projected onto these slopes, taking into account the exposition of the slope, (Lehning et al., 2008).

To ~~model~~ describe the snowcover at lower elevations in the transit and runout zones, we ~~use~~ used the simulated snowcover based on meteorological data measured at station in the the valley bottom. ~~This~~ In this case, flat field simulations were analyzed, as deposits zones of large avalanches are often in relatively flat terrain, compared to the release zones. The simulated snowcover information provides us with the snow temperature, snow height, density and LWC at lower elevations. In eight of the twelve case studies, the snowcover in the avalanche model can be considered as a single homogeneous layer while for the remaining case studies, the snowcover was best modeled as a two layer system consisting of old wet snow covered by dry new snow, see Table 3. The elevation dependent properties of the snowcover along the avalanche path were determined by constructing a linear gradient between the upper and lower meteorological stations. This procedure could be applied for the case studies that occurred near Davos (seven case studies) and the cases in Chile (two cases).

For the remaining case studies (Verbier Mont Rogneux, Verbier Ba Combe and Grengiols) we estimated snowcover conditions along the avalanche track by applying a negative linear gradient of one third of snowcover height per 1000 meters of altitude. This rule provides gradients of snowcover depth of 2 cm to 6 cm per 100 meters of elevation (see Table 3). This method is in agreement with the Swiss Hydrological atlas. In these special cases, the snow temperature, density and LWC were kept constant to the values estimated by the **SNOWPACK** model at the release altitude. In case of avalanches with new snow on top of the wet old snowcover, we consider the new snow amount measured at the AWS and estimate a decreasing linear gradient of new snow depth with altitude.

### 3.2 Avalanche dynamics calculations: initial and boundary conditions

We apply two different models to simulate the twelve case studies. The first is based on the thermomechanical avalanche dynamics equations presented in Section 2, see (Vera et al., 2015,

Table 3: Erosion conditions derived from the snowcover simulations for each avalanche case study. Upper and lower denotes two different erosion layers. The two layers system was used when new snow was lying over old ~~snow cover~~ snowcover and both layers were part of the studied avalanche. In case of only one layer all the fields at the second layer lower layer are set to zero.

| | LWC (%) | | Erosion depth (m) | | Erosion depth gradient (m/100m) | | density (kg/m$^3$) | | volwater (mm/m) | | temperature (°C) | | temperature gradient (°C/100m) | | erodibility (-) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avalanche | upper | lower | upper | lower | upper | lower | upper | lower | upper | lower | upper | lower | upper | lower | upper | lower |
| Gruenbodeli | 1.45 | - | 0.56 | 0.00 | 0.02 | - | 197 | - | 8.1 | - | -0.2 | - | 0.0 | - | 0.8 | - |
| Salezer | 1.89 | - | 0.95 | 0.00 | 0.03 | - | 317 | - | 18.0 | - | 0.0 | - | 0.0 | - | 0.7 | - |
| Gatschiefer | 0.00 | 1.47 | 0.55 | 0.95 | 0.03 | 0.04 | 185 | 360 | 0.0 | 14.0 | -1.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.7 |
| Braemabuhl 2013 | 2.97 | - | 1.11 | 0.00 | 0.04 | - | 353 | - | 33.0 | - | 0.0 | - | 0.0 | - | 0.6 | - |
| Drusatscha | 3.41 | - | 0.54 | 0.00 | 0.02 | - | 291 | - | 18.4 | - | 0.0 | - | 0.0 | - | 0.6 | - |
| MO-4 Andina Chile | 2.44 | - | 0.90 | 0.00 | 0.03 | - | 296 | - | 22.0 | - | 0.0 | - | 0.0 | - | 0.6 | - |
| Grengiols | 0.00 | 4.67 | 0.43 | 0.60 | 0.03 | 0.00 | 175 | 270 | 0.0 | 28.0 | -7.4 | 0.0 | 1.5 | 0.0 | 0.7 | 0.8 |
| Verbier Mont Rogneux | 3.00 | - | 0.60 | 0.00 | 0.02 | - | 317 | - | 18.0 | - | 0.0 | - | 0.0 | - | 0.6 | - |
| Verbier Ba Combe | 2.59 | - | 0.58 | 0.00 | 0.02 | - | 349 | - | 15.0 | - | 0.0 | - | 0.0 | - | 0.6 | - |
| Braemabuhl verbauung | 0.00 | 1.41 | 0.25 | 0.85 | 0.00 | 0.04 | 158 | 335 | 0.0 | 12.0 | -2.0 | 0.0 | 0.0 | 0.0 | 0.8 | 0.8 |
| Braemabuhl Wildi | 0.00 | 1.25 | 0.30 | 0.80 | 0.00 | 0.03 | 164 | 335 | 0.0 | 10.0 | -2.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.6 |
| CV-1 Andina Chile | 1.51 | - | 0.37 | 0.00 | 0.00 | - | 359 | - | 5.6 | - | -0.1 | - | 0.0 | - | 0.6 | - |

Table 4: Overview of model and model parameters used to simulate the twelve case studies.

| | VS guidelines | Thermomechanical | Comments |
|---|---|---|---|
| Reference | Salm et al. (1990) | Vera et al. (2015, 2016) | Both models in **RAMMS** |
| | Gruber and Bartelt (2007) | Buser and Bartelt (2015) | Christen et al. (2010) |
| $\mu_0$ (–) | Calibrated/guidelines | 0.55 | Reduced by lubrication |
| $\mu_w$ (–) | None | 0.12 | Constant in all simulations |
| $\xi_0$ (m s$^{-2}$) | Calibrated/guidelines | 1300 | Reduced by fluidization |
| $N_0$ (Pa) | 200 | 200 | Measured, see Bartelt et al. (2015) |
| $\alpha$ (–) | 0.00 | 0.05 - 0.07 | Depends on roughness |
| $\beta$ (1/s) | None | 1.0 | Depends on temperature |
| $R_0$ (kJ/m$^3$) | None | 2 | Constant in all simulations |
| $h_m$ (m) | None | 0.1 | Size of lubricated layer |
| $\kappa$ (–) | None | 0.6 - 0.8 | VS guidelines no entrainment |

2016); the second avalanche model follows the Swiss guidelines on avalanche calculation (Salm et al., 1990; Christen et al., 2010). The numerical model is outlined in Gruber and Bartelt (2007). Both models are implemented in the **RAMMS** software. Models and model parameters are compared in Table 4.

In the calculations, we are primarily concerned with the initial and boundary conditions, which are given by the snowcover model simulations; the release area is given by the field measurements. The fracture depth is defined by the location of the highest water accumulation within the snowcover (Wever et al., 2016) as was previously suggested by (Vera et al., 2016). Once the fracture depth is known we set the snow density, snow temperature and liquid water values as the mean values over the slab which extends from the location of the maximum liquid water to the snow surface.

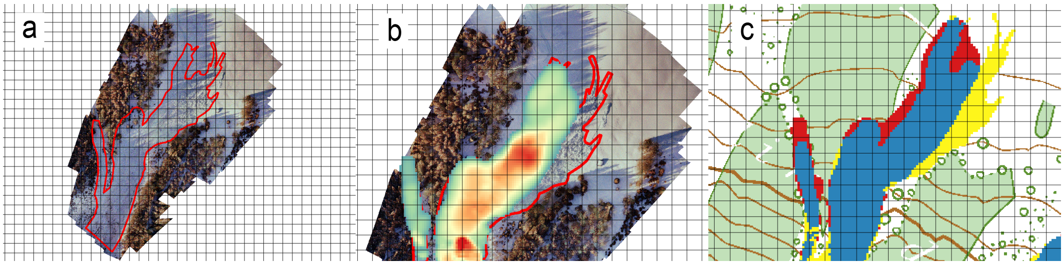
We take the values at the estimated time of avalanche release. These values are shown in Tables 2 and 3. The amount of erodible snow along the path is estimated calculating a gradient between the snowcover conditions at the release and the conditions at the valley bottom. The erosion model used is described by Christen et al. (2010); Bartelt et al. (2012a).

Once the initial and boundary conditions were found, the first set of simulations using the extended model were performed. As input parameters, the model uses the release area (measured), the snowcover initial conditions (calculated) and a set of friction and avalanche parameters. The avalanche parameters were found by Buser and Bartelt (2009); Vera et al. (2015); Buser and Bartelt (2015). These parameters were kept constant for all 12 case studies as in (Vera et al., 2016). The fluidization ~~parameter~~ parameters $\alpha$ ~~(see Bartelt et al. (2006); Vera et al. (2016)), was~~ and $\gamma$, see Bartelt et al. (2006); Vera et al. (2016), are fixed to a pre-determined ~~value~~ values based on the terrain characteristics for each avalanche path. Once ~~this parameter was fixed it was~~ these parameters are fixed they are not tuned for the remaining set of simulations.

To perform standard Voellmy-Salm snow avalanche simulations following the Swiss guidelines (Salm et al., 1990) it is necessary to include the entire avalanche mass within the release volume. The guidelines do not consider entrainment along the avalanche path and therefore erosion was not considered in the Voellmy-Salm simulations. This procedure was adopted to follow as closely as possible the Swiss guideline procedures for avalanche calculations and allows a comparison between models which consider entrainment conditions (extended model) and models which employ calibrated parameters (Voellmy-Salm). The avalanche mass of the release area was estimated from the final mass (released plus eroded) calculated using the extended model. The total mass calculated in the extended model is concentrated in the measured release area. With this approach, a higher release depth is obtained, in comparison to model calculations with entrainment. This method ensures that the total mass in both simulations is similar. The Swiss guidelines provides the user a set of friction parameters to use depending on the avalanche size and avalanche return period. Those friction parameters correspond to extreme, fast moving, dry-flowing avalanches which have longer runouts than wet ones. For the 12 case studies, the friction parameters used are the ones corresponding to the class 'Small' avalanches and return period of 10 or 30 years. This parameter combination led to the overall best fit to observations. The calculations were performed with the same terrain and grid resolution.

### 3.3 Contingency table analysis for deposition area

The results obtained with the two models are compared through a statistical contingency table analysis. We compare the area covered by the avalanche deposits calculated with both models with the deposits area measured for each case study. The terrain is divided in squared cells which




| | | Observed | | |
|---|---|---|---|---|
| | | **Yes** | **No** | **Total forecasted** |
| Forecasted | **Yes** | hits | false alarms | forecasted yes |
| | **No** | misses | correct negatives | forecasted no |
| | **Total observed** | observed yes | observed no | **TOTAL** |

Fig. 2: Method to construct the contingency table, based on measured deposits outline (a), which is then combined with the simulated deposits area (b) to identify hits (blue), false alarm (red), misses (yellow) and correct negatives (no color, map only) (c).

| | |
|---|---|
| **FAR** $= \frac{\text{false alarms}}{\text{hits} + \text{false alarms}}$ | **POD** $= \frac{\text{hits}}{\text{hits} + \text{misses}}$ |
| **HKS** $= \frac{\text{hits}}{\text{hits} + \text{misses}} - \frac{\text{false alarms}}{\text{false alarms} + \text{correct negatives}}$ | **ETS** $= \frac{\text{hits} - \text{hits}_{\text{random}}}{\text{hits} + \text{misses} + \text{false alarms} - \text{hits}_{random}}$ [1] |

[1] where

$$\text{hits}_{\text{random}} = \frac{(\text{hits} + \text{misses})(\text{hits} + \text{false alarms})}{\text{total}}$$

Table 5: Mathematical definition of the statistics scores: probability of detection (POD), false alarm rate (FAR), Equitable threat score (ETS) and Hanssen Kuijpers or true skill score skill score (HKS)

correspond with the calculation cells used in the avalanche simulations (see Fig. 2 (a) and (b)). For each cell we check whether the cell was covered by the observed avalanche deposits or not and whether the cell was covered by the avalanche simulation once the simulation stops or not. A cell will be considered as covered by the avalanche simulations only if the calculated flow height with the mass at rest is more than 20 cm corresponding approximately to two granules diameter (Bartelt and McArdell, 2009). Variations in modelled and observed deposition heights are not captured with this procedure. The correspondence of observed deposits and calculated deposits is checked using a dichotomous contingency table (see ~~Table~~ Fig 2), that split the terrain in four different classes: hits, misses, false alarm and correct negatives (see Fig. 2(c)). Computing the amount of cells for each class allows to calculate different metrics to judge how both models perform. In

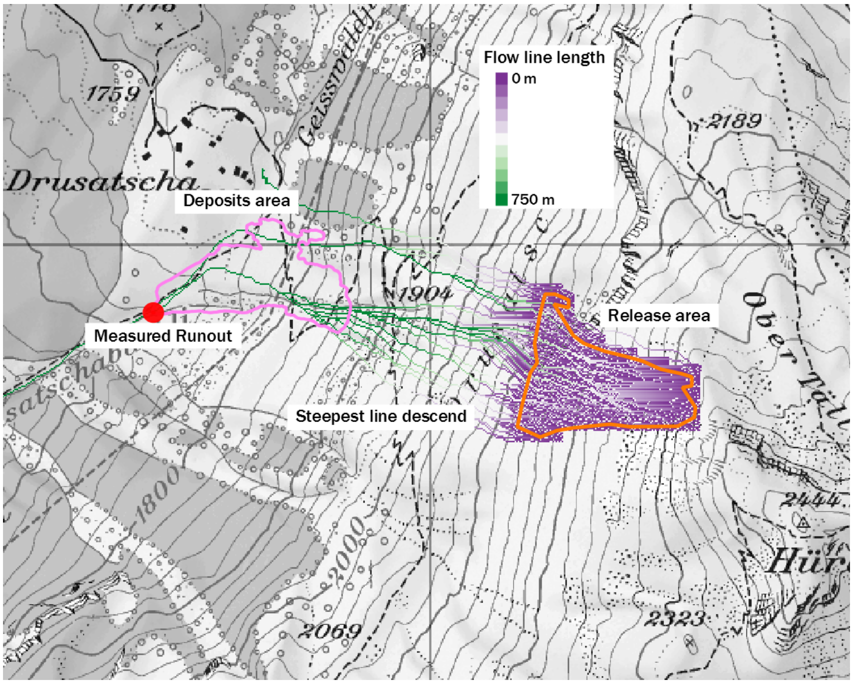



Fig. 3: Run-out distance calculation procedure. From each calculation cell at the release area the line of steepest descend is calculated. The intersection of the lowest part of the avalanche deposits with the longest calculated flowline (red dot) define the avalanche runout. The same procedure is repeated with the simulation results. The distance measured on the steepest line between the the two intersection points is defined as the runout calculation error.

this study the probability of detection (POD), false alarm rate (FAR), equitable thread score (ETS) and Hanssen-Kuipers skill score or true statistic score (HKS) (see ~~table~~ Table 5) are calculated (Woodcock, 1976). For POD, ETS and HKS a score of 1 would mean a perfect score, in the case of FAR a score of 0 would indicate the perfect score. This two-dimensional procedures avoids the problem of defining a one-dimensional measure of avalanche runout.

### 3.4 Avalanche runout

In addition to the contingency analysis study for the inundated area, runout distance are analyzed. The runout distance was calculated from the difference in meters between the maximum distance reached by the avalanche in the measurements and the avalanche simulation calculated over the line of steepest descend for each avalanche path in a DEM smoothed to a resolution of 20 m (see Fig. 3). The line of steepest ~~descend~~ descent was chosen as the longest line of steepest ~~descend~~ descent among all the possible ones departing from the depicted release area for each avalanche path. All simulations stoped when 95 percent of the total mass stopped moving (Christen et al., 2010)

### 3.5 Influence of initial conditions on avalanche runout: sensitivity study

~~To investigate how initial conditions influenced the avalanche runout and area covered by the deposits, we performed 432 simulations on the twelve avalanche tracks where we interchanged the initial and boundary conditions from the~~ In addition to using an avalanche dynamics model where snow temperature and wetness directly influence the flow rheology, we use a novel approach here to use simulated snowcover conditions to directly drive the avalanche dynamics model. We constructed a sensitivity study to (i) investigate the influence of initial snowcover conditions on the simulated avalanches and (ii) to investigate if the snowcover simulations by the SNOWPACK model for a specific case add information. We consider the 12 case studies to represent 12 ~~different initial and boundary conditions: from each of the twelve case studies we performed three different sets of simulations (3x12x12). As a sensitivity analysis we determined the difference between the observed and simulated runout as a function of the initial and eroded temperature, initial moisture content, fracture depth and snow density.~~

~~The sensitivity of the model to changes in~~ individual cases of wet snow avalanches. We construct the members of the sensitivity study by interchanging the initial conditions from the 12 case studies. This way, we ensure realistic and self-consistent simulated snowcover results which represent real wet snow avalanche cases, in contrast with when individual variables would be varied one-by-one. Furthermore, we consider that for the avalanche dynamics simulations, the snowcover conditions ~~was additionally evaluated. For this purpose, the same contingency analysis was performed for three different simulation sets constructed by varying the initial and boundary conditions for each avalanche path used in this study.~~ can be separated meaningfully in mass of the slab on the one hand (given by slab depth and snow density), and temperature and LWC on the other hand.

~~The~~ For the study, three sets of simulations were constructed as follows:

1. Twelve simulations for each avalanche path interchanging the initial and boundary conditions (fracture and erosion depth, snow temperature, density and LWC at the erosion and at the release) for the twelve different avalanches, obtaining thereby a set of 144 simulations.

2. A second set of simulations was performed by using the snow temperature and LWC that was simulated by the snowcover model for that track. However, we varied the release and erosion depths and the snow density of the twelve different case studies. This set contains another 144 simulations and is used to verify the model sensibility to changes in avalanche mass at the release and at the erosion.

3. A third set of simulations is constructed by keeping the snow depths and snow densities constant. The remaining conditions (i.e., temperature and LWC) were taken from the twelve

case studies, leading to another set of 144 simulations, to investigate the importance of snowcover properties in relation to snowpack mass.

~~In total~~ Consequently, for each of the twelve case studies we performed three different sets of simulations, resulting in a total of 432 simulations ~~were performed for the entire sensitivity analysis, thirty six for each of the twelve avalanche paths.~~ (3x12x12) where we interchanged the initial and boundary conditions from the 12 different initial and boundary conditions. For each simulation, we determined the difference between the observed and simulated runout as well as the contingency scores for the inundated area.

## 4 Results

The contingency table analysis is used to explore the following questions:

1. Is it possible to drive avalanche dynamics calculations with initial and boundary conditions derived from snowcover modeling? Does the application of thermomechanical models improve the area covered by avalanche deposits and runout distances?

2. How sensitive are the simulated deposit areas and runout distances to released mass and snowcover properties?

3. What role does the calculation grid resolution play in the simulated areas covered by the deposits and runout distances?

The results of the model runs are presented extensively in the paper supplements. The graphs in the supplement A facilitate a direct comparison between the thermomechanical approach, the standard Voellmy-Salm procedure and the actual avalanche measurements, including the location of the deposits with respect to the observed release zone. Supplement B contains the results of the model permutations. This graphical output enables a quick assessment of the model sensitivity. In the following we statistically analyze model performance.

### 4.1 Comparison between the guideline-VS and the thermomechanical model

The twelve avalanche events were simulated using the guideline-VS model (Salm et al., 1990) and the thermomechanical wet snow avalanche model presented in Section 2. Recall that the guideline friction parameters were used for wet snow avalanches and best overall fit to the observed inundation areas was found using the classification small and frequent return period of 10 to 30 years. The thermomechanical model used the fracture and entrainment depths derived from the snowcover modeling. Bulk snow temperature and moisture contents were determined by layer averaging of the fracture depth. The contingency table analysis for deposition areas and runout distances are shown in Fig. 4.

A comparison between the guideline-VS and the wet snow avalanche model reveals that the thermomechanical model obtains significantly better results than the guideline-VS model. The probability of detection (POD) in conjunction with false alarm rate (FAR) scores achieved by the thermomechanical model improve the results by more than 0.15 points (see Fig. 4). The equitable threat score (ETS) achieved by the thermomechanical model improves the guideline procedure by ~~more than 0.1~~ 0.13 points (see Fig. 4). Additionally, the Hanssen and Kuipers or true skill score (HKS) reached by the thermomechanical model improves by ~~0.19~~ 0.17 points in comparison to the HKS reached by the guideline model. Therefore, the thermomechanical model statistically outperforms the guideline procedure in all four contingency metrics. ~~The fact that the difference in ETS score between the thermomechanical model and guideline procedure is higher than the difference in HKS score shows that the HKS score is weighted toward detection, and thus POD, when the area covered by the deposit of an avalanche is small compared to calculation domain (i.e., hitting pixels with the avalanche deposits becomes a rare event). In contrast, the ETS penalizes both misses and false alarms and therefore, guideline simulations which overran the measured deposit area (see in the online Supplement) have increased FAR, and a stronger reduction in ETS scores in comparison to HKS.~~

The difference in performance between guideline-VS and thermomechanical wet snow avalanche model simulations differ per avalanche path (see Fig. 4). The guideline-VS procedure has particular difficulties with tracks containing a smooth transition between the acceleration and deposition zones. These avalanche paths have a long distance where the steepness is getting progressively flatter (i.e. Braemabuhl, Mont Rogneux, Ba Combe and Drusatcha, see in the online Supplement). In contrast, the guideline-VS model does much better on avalanche paths with a sharp transition between the acceleration and runout zones (Gruenbodeli, Salezer and Gatschiefer). In the examples where the slope angle changes smoothly the guideline calculations systematically overran the measured deposits (Braemabuhl, Wildi, Mont Rogneux, Ba Combe). Thus, the guideline-VS does achieve good scores on detection (POD) but is at the same time exhibiting a high false alarm rate (FAR).

The thermomechanical model performs equally well on both types of slope and is able to reproduce runout distances on slopes with gradual transition to the runout zone. In the case of Grengiols, the runout distance is somewhat underestimated; however, this was found to be caused by the uncertainty of the elevation of the snowfall limit. This is an important result since it indicates that the snowcover modeling must be able to accurately predict the snowline elevation.

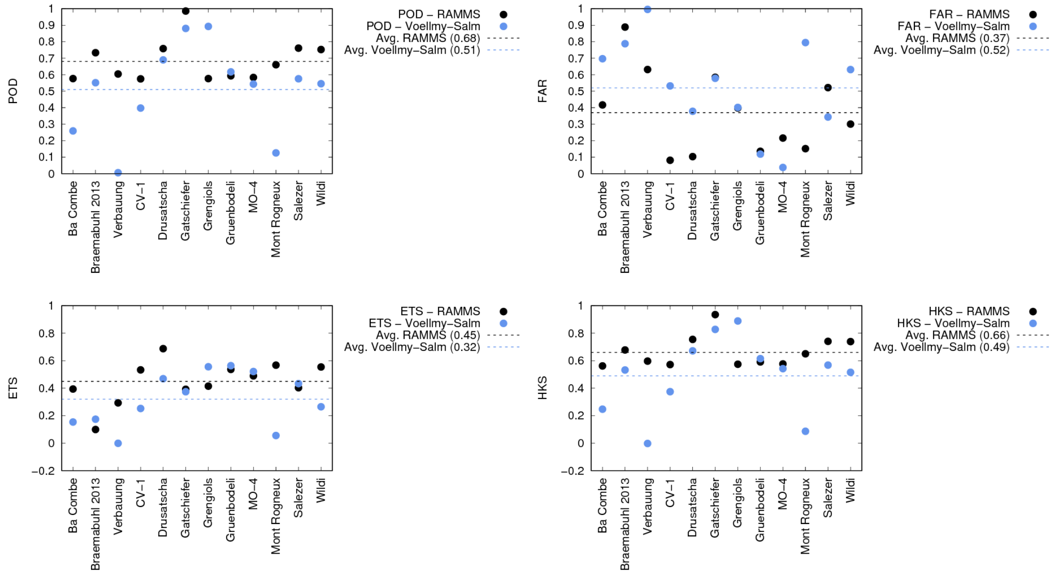



Fig. 4: Comparison of the statistical results from the thermomechanical model RAMMS (black) and the guideline-VS model (blue), for POD (a), FAR (b), ETS (c) and HKS (d).

### 4.2 Sensitivity analysis

The scores of the contingency table analysis reveal that the thermomechanical model, which utilizes the modeled initial and boundary conditions, can outperform a model based on calibrated guideline friction parameters. The primary result of the preceding section is that guideline-based avalanche dynamics models with extreme friction parameters (avalanches with return periods greater than 300 years) will have difficulty reconstructing individual case studies and that they are not easily linked to snowcover conditions. The next step is to check how sensitive the thermomechanical model is to changes in the simulated initial and boundary conditions.

#### 4.2.1 Role of initial conditions

To demonstrate the role of initial conditions, we simulated the twelve case studies using the initial conditions of all the other case studies, creating a total of 144 permutations. The initial conditions consist of fracture depth, snow density, temperature and LWC. For example, we simulated the Ba Combe case study with the initial conditions from the other eleven case studies. The simulation result of every of the permutations for each avalanche path are shown in Supplement B in the online supplement.

Fig. 5 depicts the results of the 144 simulations. In these plots, the red dots indicate the simulations performed with the **SNOWPACK** modeled initial conditions belonging to the specific avalanche path; the small black dots represent the remaining combinations of eleven simulations. The large open circle represents the average of the eleven permutations.

The first result of this sensitivity analysis is that the score difference varies more than 0.2 statistical points for every avalanche path and indicator (POD, FAR, ETS and HKS scores). This result indicates a large variability of the model with different initial conditions. The POD scores using the "'right"' initial conditions are ~~generally~~ higher than using those from the other case studies. Furthermore, the false alarm (FAR) rate is lower. The average of the four statistical indicators calculated with the real initial and boundary conditions (red line in Fig. 5) outperformed the calculations with the interchanged initial and boundary conditions for every case study. However, for particular cases, simulations with initial conditions from another avalanche path outperformed the one calculated with the real initial conditions. ~~However, the simulation with the original initial condition is among the simulations with the highest ETS or HKS scores. Also the~~ The average scores of all twelve cases is better ~~for~~ with the real initial conditions. A last important observation is that the spread of scores provided by the permutations of the initial conditions exceeds the spread of scores for all twelve simulations with the real initial conditions.

Again, for the longer avalanche paths with a smooth transition to the runout zone (Gatschiefer, Drusatcha, Grengiols, Verbier Mont Rogneux and Braemabuhl), the scores varied up to 0.5 points in comparison to avalanche paths where the transition is marked by an abrupt change in slope angle (MO-4 and CV-1 and Gruenbodeli). Thus, long avalanche tracks with a smooth transition to the runout zone ~~, are more sensitive to changes in initial conditions and benefit~~ benefit the most from a correct initialization using **SNOWPACK** simulations.

### 4.2.2 Role of snowcover mass and density

The initial conditions include both mass/density and temperature/water content. To quantify the relative importance of initial mass versus initial snowpack properties, we performed another set of 144 simulations where only the mass (both the fracture mass and entrainment depths) varied. The results of the contingency table analysis are depicted in Fig. 6. The results are similar to the first sensitivity analysis where the entire set of initial and boundary conditions were varied. This suggests that the selection of the initial and boundary conditions for mass is more important than the ones for temperature/LWC. For wet snow avalanches, this implies that the layers where meltwater accumulates in the release zone must be identified accurately as this defines the height of the fracture slab and therefore the release mass. A ~~small variation~~ change in the fracture depth ~~would~~ of 10cm can lead to a large variability in the predicted avalanche runout. This is a problematic result because it indicates the critical role of fracture depth as an input parameter in avalanche simulations.

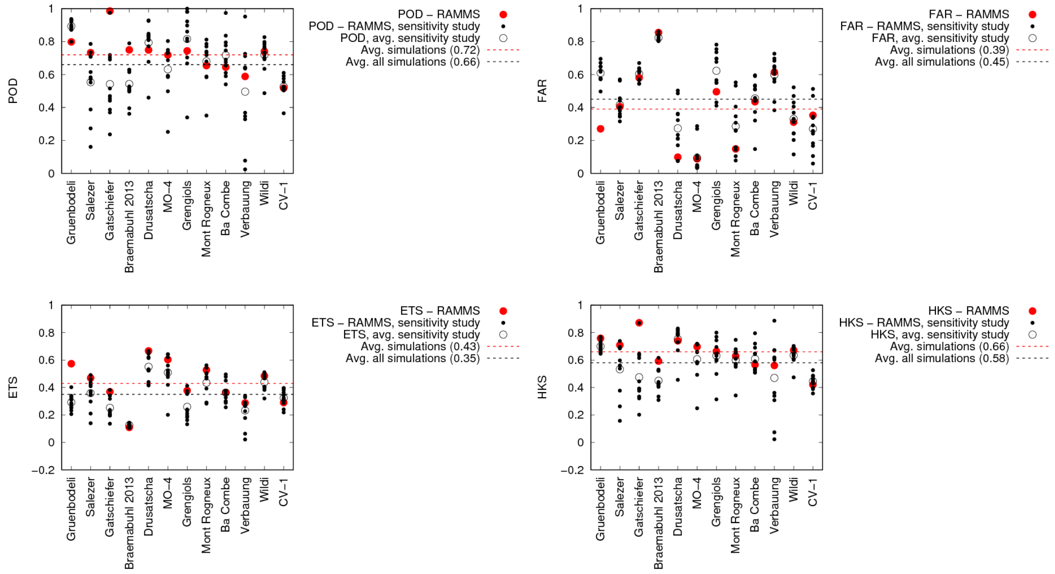



Fig. 5: Sensitivity study simulating every avalanche path with the twelve different initial and boundary conditions using the thermomechanical model RAMMS. The red dot denotes the simulation performed with the initial and boundary conditions calculated for the corresponding avalanche path. The open black circle denotes the average of the eleven permutations (filled black dots). In this plot for every avalanche path fracture and erosion depth, temperature, density and LWC at the release and along the avalanche path (erosion) are varied.

The role of mass entrainment is difficult to identify in the statistical scores because we considered only warm/moist snowcovers. Moreover, the permuations did not include dry, cold snowcovers. This result suggests that the snow quality (temperature, moisture) is more important than the snow amount.

#### 4.2.3 Role of snowcover temperature and water content

Fig. 7 displays the results of the other set of 144 thermomechanical model simulations where the temperature and LWC in the release and entrainment zones were permuted. The mass (release and eroded) was defined by the snowcover simulations driven by the meteorological data for each case study. ~~We find the~~ The statistical results are less sensitive to changes in temperature and LWC than to mass. This is due to the fact that only wet snow avalanches were considered and the temperature range did not vary outside the wet snow regime. ~~Variations are primarily due to variations in LWC.~~ This too, is a reasonable result because moisture contents in the twelve case studies varied only between 0% and 5%, see Table 3. Although the variations are less pronounced than those caused by mass changes, Fig. 7 illustrates that correctly specifying initial snow temperature and LWC also contributes positively to the model performance. The ~~variation was strongest~~ strong variation on long

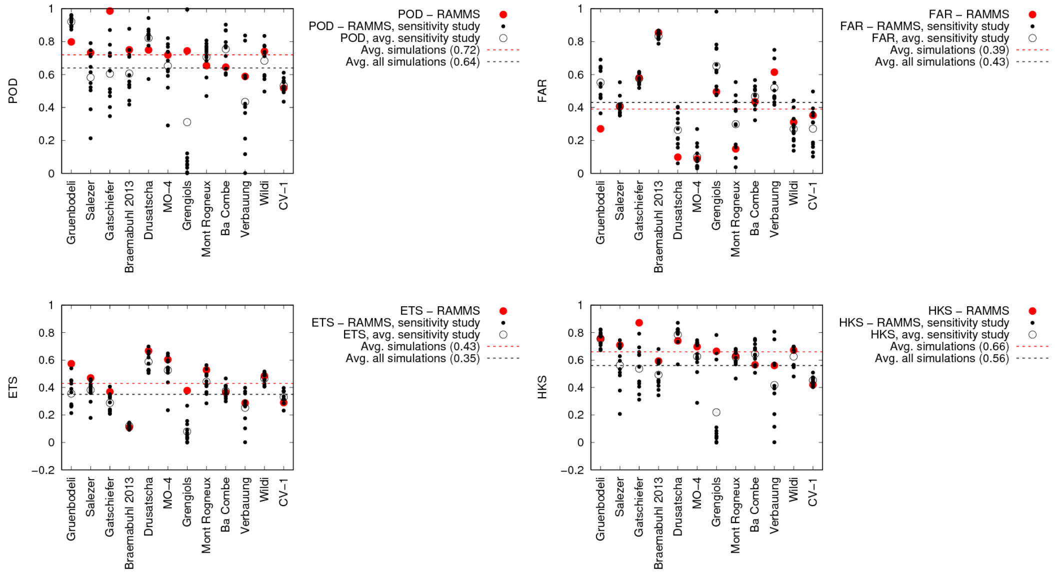



Fig. 6: Sensitivity of the thermomechanical model RAMMS to permutations of avalanche mass (fracture depth and density). For every avalanche path twelve different fracture depths, released densities, erosion depths and eroded densities are permuted, keeping the LWC and snow temperature constant. Markers and colors as in Fig. 5.

avalanche tracks with a smooth transition to runout zone demonstrates, once again~~indicating that this path geometry is especially sensitive to any changes in the initial~~, that path geometry dominates over changes in snowcover boundary conditions.

### 4.3 Sensitivity to calculation grid size

Contingency tables scores for the thermomechanical model can also depend on the selected grid resolution. This would imply that the constant set of friction parameters of the wet snow model is bounded to a particular cell size. We subsequently repeated the simulations using three different grid sizes: 3x3 m, 5x5 m and 10x10 m. The influence on the contingency scores is depicted in Figs. 8 and 9 for 10 m and 5 m respectively.

A similar analysis was performed by (Bühler et al., 2011); however without a statistical score and only on a limited number of case studies. The qualitative results of that study indicate that a ~~courser resolution smooths out~~ coarser resolution smooths the terrain, causing the wet model simulations to overflow the observed deposit areas. Due to overflowing, the POD score increases by almost 0.1 statistical points in average in comparison with the 3 m resolution simulations. The coarser simulations are highly penalized in the FAR false alarm rate indicator, showing a drop of 0.2 statistical points on average in comparison with the finer resolution. The statistical scores (ETS and

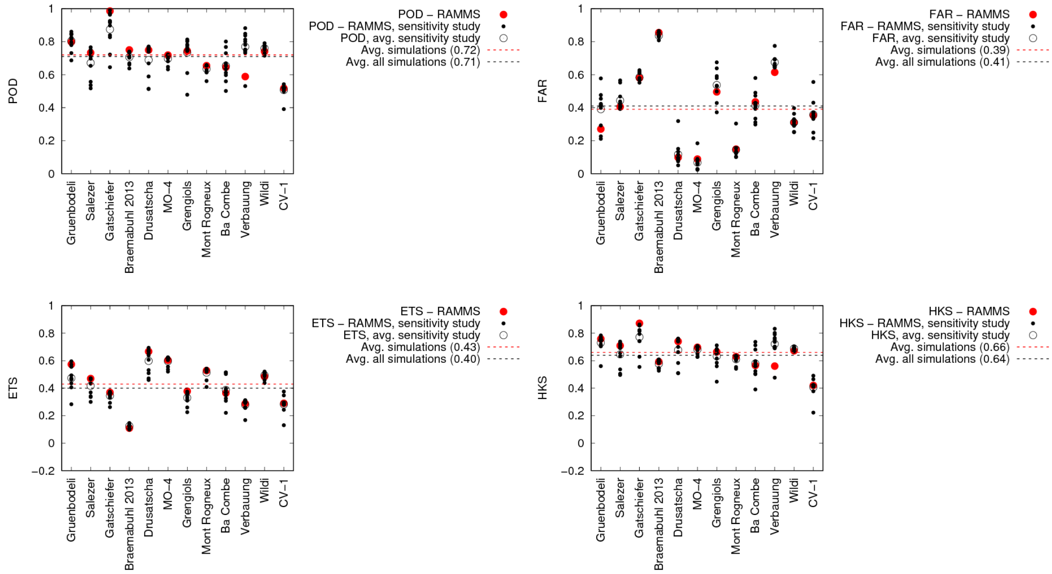



Fig. 7: Sensitivity of the thermomechanical model to different snow temperature and LWC. For every avalanche path twelve different snow temperature and LWC in the release and erosion zones are varied, keeping the release and eroded depth and density constant. Markers and colors as in Fig. 5.

HKS) were positively influenced by the increase in hit rate, but this was compensated by the even larger increase in false alarms. The ETS score is severely penalized, dropping the statistical score by 0.15 points for the coarser simulations (10 m) in comparison to finer simulations (3 m). Even though the HKS score is more weighted to the number of hits, it likewise decreased, but by a smaller amount. The increase in false alarms was so large that it mostly compensated the improvement obtained by an increase in the number of hits.

The same analysis was repeated using 5 m resolution. In this case, the results do not differ greatly from the results obtained with a 3 m resolution. The 5 m resolution overall statistics (see Fig. 9) are close to or even equal (in the case of the HKS score, see Fig. 5), to the results obtained by the 3 m resolution simulations. Nevertheless, the 5 m meter resolution simulations obtained higher POD score than the 3 m resolution but also a higher FAR. This pattern was already observed in the comparison between 3 m and 10 m; however, in this case the difference is much lower. In the other two statistical indicators ETS and HKS even more similar results are obtained. The ETS score (see Fig. 9) is slightly lower for the 5 m resolution than for the 3 m. However both obtained the same score in the HKS indicator. The results obtained in the ETS and HKS indicators show the same tendency observed in the comparison between 3 m and 10 m. Coarser resolutions lead to overflowing and obtaining more hits but also more false alarms, which penalize the overall score.

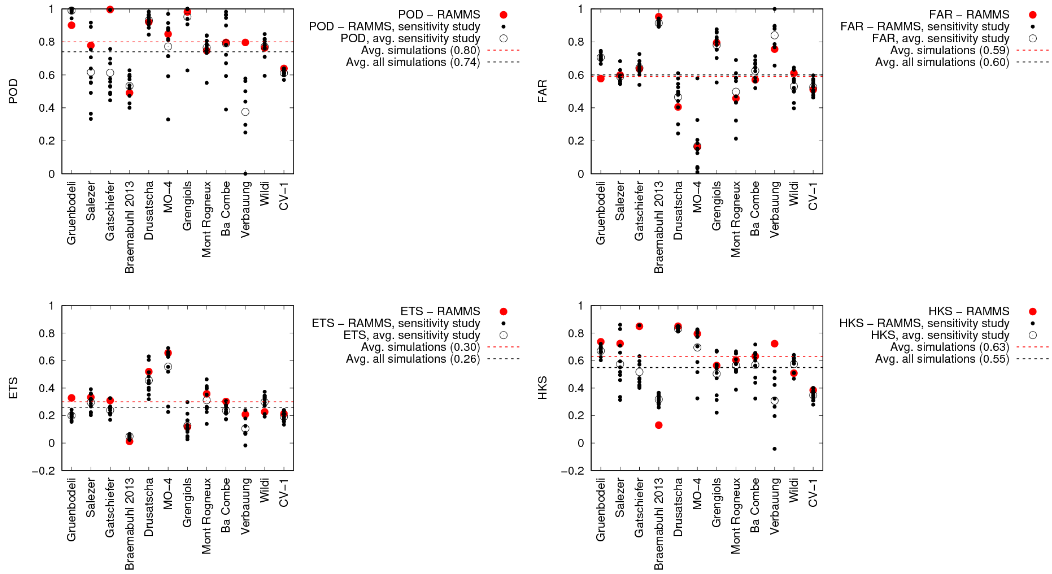



Fig. 8: Sensitivity study simulating every avalanche path with the twelve different initial and boundary conditions, but with a simulation resolution (grid size) of 10 m for the 144 simulations (compare to Fig. 5 for 3 m resolution. Markers and colors as in Fig. 5.

Nevertheless, in the case of 3 m and 5 m, it is necessary to compare avalanche path by avalanche path and to check which resolution better suits a particular avalanche path. Narrow steep gullies with pronounced topographic features (Ba Combe, MO-4 and CV-1) require higher resolution than open slopes (Drusatscha, Mont Rogneux, Wildi and Gatschiefer).

~~A secondary result in this analysis, is that independent of the grid resolution, there was a large variability of the model results by varying the initial and boundary conditions. The variability found for 3 m, 5 m and 10 m cell size was similar for all case studies and for all statistical indicators.~~

## 4.4 Runout analysis study

A commonly used measure for avalanche size is the runout distance. Fig. 10 shows the difference in simulated and measured runout distance for each studied avalanche for different grid cell sizes using the thermomechanical model RAMMS as well as the guidelines-VS model. The absolute error in runout distance calculated by the thermomechanical model is about three times smaller than those predicted by the guidelines-VS model. The difference between both models was larger on paths where the transition to the deposition zone was smoother (Drusatscha, Braemabuhl, Mont Rogneux, Ba Combe, Gatschiefer). On the paths where this transition is more pronounced, the calculated runout distances are closer (e.g., Gruenbodeli, MO-4, CV-1, see Fig. 10).

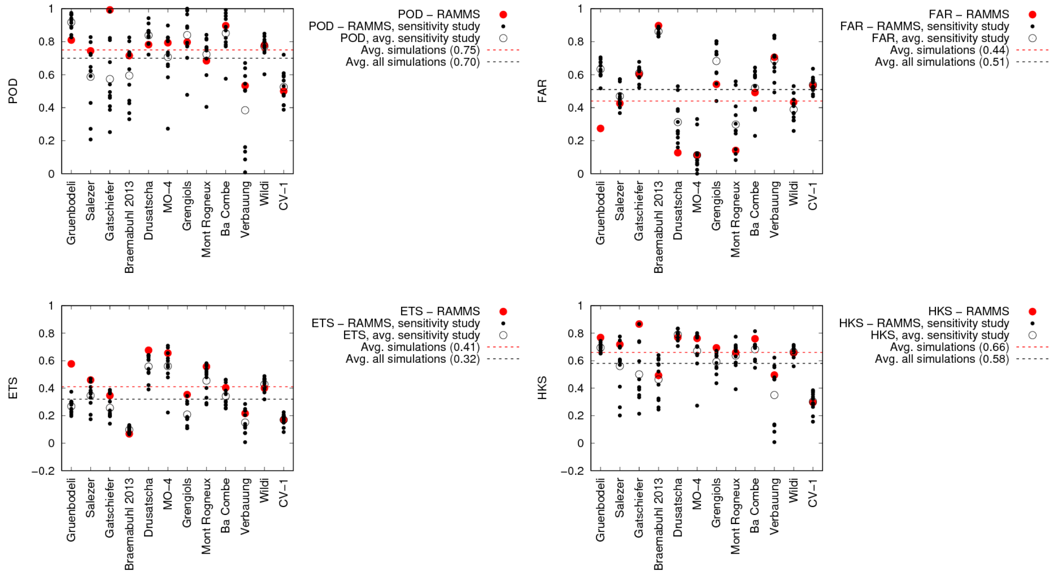



Fig. 9: Sensitivity study simulating every avalanche path with the twelve different initial and boundary conditions, but with a simulation resolution (grid size) of 5 m for the 144 simulations (compare to Fig. 5 for 3 m resolution. Markers and colors as in Fig. 5.

The analysis was repeated using two coarser grid resolutions 10 m and 5 m cell size for the thermomechanical model (see Fig. 10). In the case of 10 m resolution, the model tends to overrun measured runout distances. The average error between simulated and measured runout increases from around 49 m with 3 m resolution to 72 m with 10 m resolution. The difference between 3 m and 5 m resolution is much smaller and the 5 m resolution calculations slightly outperform the 3 m ones in terms of runout distance. On the other hand, the 3 m resolution simulations show on average higher ETS score and equal HKS score, compared to 5 m simulations (~~not shown~~see Section 4.3).

We repeated the sensitivity study for runout distance with three sets of 144 simulations interchanging the initial and boundary conditions as described in the previous section (see Fig. 11). The results obtained performing the sensitivity analysis confirmed the results achieved in the previous contingency analysis. The thermomechanical model is sensitive to changes in the initial and boundary conditions. Those changes are more important on avalanche paths where the transition to the runout is smooth. On those paths, changes in the initial and boundary conditions lead to deviations of hundreds of meters on runouts calculations, Gatschiefer, Drusatscha, Mont Rogneux, Ba Combe, Fig. 11.

~~As was shown in the contingency analysis, the~~ The runout calculations were more sensitive to changes in mass than in changes in snowcover conditions (temperature and LWC). Varying the mass in the release and erosion doubles the absolute error obtained by varying only snow temperature and LWC~~(see Fig. 11).~~.

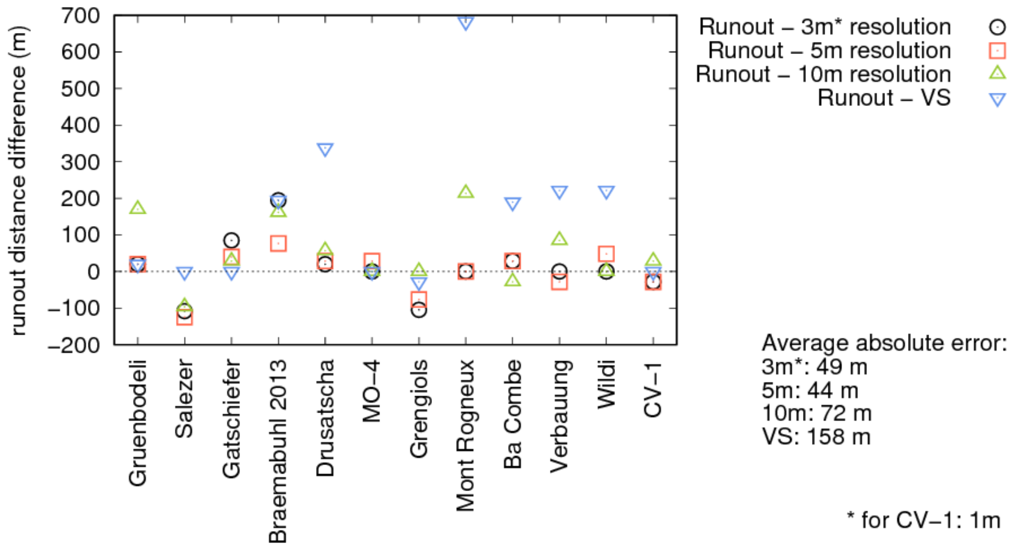



Fig. 10: Runout error plot comparing thermomechanical wet snow model calculations (black dots) with guideline-VS runout calculations (blue triangles), as well as runout calculations with 5 m and 10 m model resolution with the thermomechanical model (red squares and green triangles, respectively). The legend shows the absolute average simulation error for each set of simulations. It was necessary to simulate the CV-1 case with a 1m grid resolution to better account for a vertical wall.

## 5 Discussion

Our analysis is limited to evaluating deposition areas and runout distances for the twelve case studies. Other important avalanche variables, such as speed, dynamic flow heights and impact pressures are not considered in the analysis, although they are crucial in many aspects of assessing avalanche risks. Thus, we are considering only one primary component of the avalanche flow problem: calculating the area covered by the avalanche deposits. We circumvent the lack of flow data by considering well-documented case avalanche case studies in a single flow regime (wet) with return periods of approximately 10 to 30 years. An advantage of this approach is that we consider more than one track geometry, allowing us to draw conclusions about the application of snowcover models and avalanche dynamics calculations in different terrain. This is important because our analysis reveals that the interplay between track geometry and mass are the decisive components in the estimation of runout and inundated area.

The starting mass was specified by performing snowcover simulations to determine the fracture

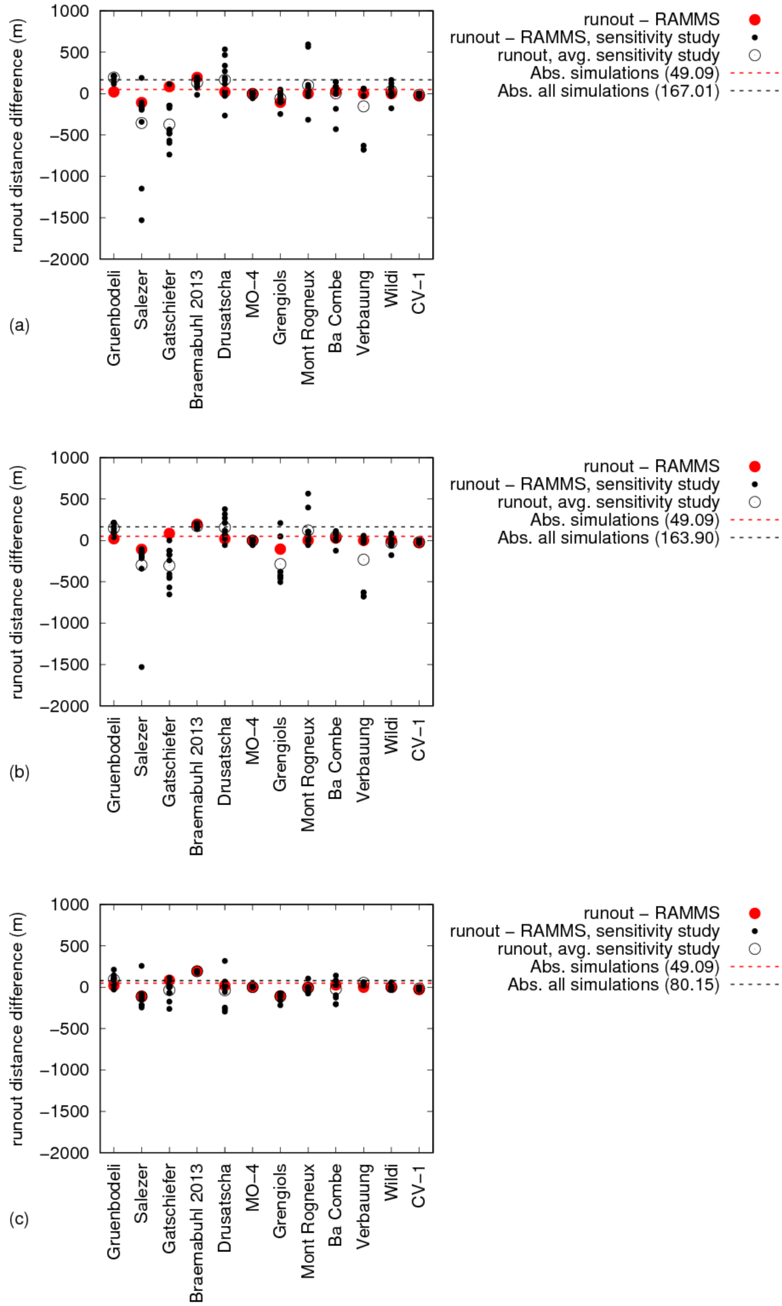



Fig. 11: Difference between simulated and measured runout distance for the wet snow model simulations with the corresponding initial conditions (red dots) and permutations (black dots). The average of the eleven permutations is depicted as a black open circle. (a) varying both snow mass (fracture depth and density) and snow properties (temperature and LWC), (b) varying snow mass only and (c) varying snow properties only. The red and black lines show the average absolute error in meters of the whole set of simulations (sensitivity and real simulations) to the runout distance measured in the field.

depth, density, temperature and water content of the release zone. The snowcover simulations were driven by measured meteorological data from stations near the release zone. The spatial extent of the release was known from observations and/or measurements. Having accurate information where the avalanche released contributes much to the goodness of the statistical scores. Knowing the location of the release zone and a DEM of the avalanche track predetermines the flow path of the avalanche in the simulations, making a contingency table analysis useful. The model has one parameter $\alpha$ (Buser and Bartelt, 2009), which depends on the avalanche path and still has to be chosen by the avalanche expert. Therefore the application will demand experience in terrain and modeling of avalanches by the avalanche expert, even though the range of $\alpha$ is well-constrained (Vera et al., 2016) .

An advantage of the contingency table analysis is that it can be used to identify tracks where there will be a large variability in runout depending on the initial conditions. Our analysis of the simulations revealed a large variability in predicted runout for tracks with flat terraces and gradual slope transitions to the runout zone. Here, we showed that the results are very sensitive to the specification of mass in the release and entrainment zones. On these tracks, an underestimation of fracture depth of only 10 cm could lead to significant runout shortening and underestimation of the affected area. However, the initial and boundary conditions estimated from snowcover modeling have demonstrated a good accuracy in the overall results, the red dots on Figs. 5, 6 and 7 show on average better statistical scores than the black dots calculated with the variations. This result suggests statistically that initial conditions derived from snowcover modeling improve randomly chosen initial conditions derived from a set of wet snow avalanche days. Once again, although the coupling between the snowcover modeling and avalanche dynamics calculations can be automatized, the sensitivity analysis suggests that a mistake in the mass estimation can lead to entirely wrong results. We emphasize that we come to this conclusion even though we restricted our attention to a single avalanche flow regime. Nonetheless, the coupling of snowcover models and avalanche simulations could provide avalanche services with more information to make a risk assessment. Using avalanche dynamics models in this way differs from traditional avalanche calculations, which are based on extreme conditions, with no link to particular snowcover or meteorological conditions.

The general thermomechanical avalanche dynamics model RAMMS performs better than the guideline-VS model in all statistical scores, HKS, ETS, POD and FAR (see Fig. 4). The guideline procedures are designed to model extreme, dry flowing avalanches, not particular avalanche events. However, the guideline model achieved in some cases high contingency table scores, despite the application on non extreme, wet snow avalanches. The guideline-VS model was forced using friction coefficients calibrated by (Salm et al., 1990). It was necessary to use the friction coefficients corresponding to smaller avalanche sizes in order to achieve a good correspondence between measurements and simulations. For all case studies, the friction coefficients chosen correspond to size class 'Small' and a return period of 10 to 30 years. The guideline-VS model had to be manipulated by an expert user to get the best results. For example, the general model was first applied to determine the mass-balance of the event, which was then used to establish the initial conditions (i.e., released plus eroded mass) of the guideline-VS model. Another disadvantage of the guideline model is that first a calibration of the friction parameters is required to obtain reasonable contingency table scores. Both steps are not required in the general model applications, because the friction parameters are determined as a known function of snowcover conditions. ~~Moreover, the connection between friction and initial starting mass for the guidelines-VS model were derived from the wet snow model calculations. The guideline-VS model really cannot exploit the automated weather measurements, and additional procedures are required to make the guidelines calculations.~~

Because we considered only wet snow avalanches, the range of snow temperature was rather narrow and close to zero. The water content varied between 1% and 5%, which is a typical range of bulk LWC for slopes (Heilig et al., 2015). The vertical liquid water distribution typically exhibited a thin layer with high LWC located near layer boundaries (capillary barriers), which supports the assumption in the avalanche model that the liquid water is concentrated at the sliding surface. The results of the snowcover simulations were visually inspected to determine the avalanche fracture depth (following Wever et al. (2016)). This depth could be verified by the observations of the actual release zone. The bulk LWC of the slab above the ~~maximum~~ depth of the maximum local LWC was used to initialize the simulations. In general, the statistical scores of the contingency table analysis did not change much as a function of the water content. However, changing water content in some cases led to a large difference in simulated inundation area and runout distance. These cases are associated with terrain characteristics and its influence on the rate of meltwater production as well as the LWC of the eroded snow. For example, the Grengiols and Mont Rogneux avalanche case studies stopped on a flat zone when the initial liquid water was reduced below the simulated **SNOWPACK** value. This indicates that underestimated LWC can lead to spurious runout shortening. In general, however, variations of mass (i.e., fracture and erosion depths together with snow density) produced larger variations in the final simulation results (see Fig. 5, 6 and 7). The mass variations in the sensitivity analysis were broad, see Table 1. Therefore, using this set of case studies with only wet snow avalanche cases, the model is more sensitive to changes in avalanche mass than in snowcover conditions (LWC and snow temperature).

The statistical scores of the contingency table analysis are dependent on the grid resolution of the avalanche dynamics calculations. The 10 m resolution appears to be far too coarse for the avalanche sizes of the case study examples. The contingency scores of the 3 m and 5 m resolutions are similar. However, the 3 m runout calculations show a trend to slightly shorter runout distances. The statistical scores of the 3 m resolution are overall better than the 5 m resolution because the 3 m scores were not penalized by excess runout and therefore obtained fewer false alarms. The 5 m resolution clearly achieved the best results for open slopes with gradual transition zones. A 3 m resolution might still be necessary when the track contains narrow gullies, bare ground or shallow snowcovers where terrain features, including the presence of blocky scree, can play an important role. Deposition patterns of the smaller events could clearly be better represented by the finer 3 m resolution.

## 6 Conclusions

We used the physics based snowcover model **SNOWPACK** to set the initial conditions for avalanche dynamics calculations. We restricted our attention to avalanches in one flow regime (wet) where the depth and spatial extent of the avalanche release area was known. We used a contingency table analysis to statistically evaluate how well avalanche dynamics models can predict deposition area and runout distances. Although we can demonstrate that physics based models improve the statistical scores, we note that on certain track geometries the results of the avalanche dynamics calculations are extremely sensitive to the specification of the correct starting conditions, particularly fracture and entrainment depths. These tracks contain flat track segments below the release zone and gradual transition zones leading towards the avalanche runout zone. In these cases, underestimating fracture heights and entrainment depths can lead to significant underprediction of avalanche runout distances. The problem appears not to be with the quality of the avalanche dynamics simulations, but illustrates that for these cases it is crucial that numerical snowcover models accurately predict the state of the snowpack from data measured from automatic weather stations.

The model chain could be applied in regions where considerable experience and knowledge of local snowcover variability and avalanche history exist. As these conditions change from year to year, a complete cadaster of documented events is still invaluable. There are cases where these conditions are fulfilled, see Vera et al. (2016). In these situations the model chain can support decisions on a deterministic basis and provide decision makers with a valuable source of information about current avalanche risks.

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