Answers to reviewer on paper:
"Cold-to-warm flow regime transition in snow avalanches"

Anselm Köhler et al.

September 18, 2018

1 Editors comments to the Authors by Guillaume Chambon

Thank you for your submission to TC/TCD. As you may know, papers accepted for TCD appear immediately on the web for comment and review. Before publication in TCD, all papers undergo a rapid access review undertaken by the editor and/or reviewer with the aim of providing initial quality control. It is not a full review and the key concerns are fit to the journal remit, basic quality issues and sufficient significance, originality and/or novelty to warrant publication. The criteria for this evaluation can be found at `http://www.the-cryosphere.net/review/ms_evaluation_criteria.html`. Grades are from 1-4 (excellent-poor).

Originality (Novelty): 2.

   The study is based on methods and datasets that have already been published in several recent papers. However, the analysis proposed here goes one step beyond, focusing on avalanches that show a transition from a cold to warm flow regime, and looking for relations between the characteristics of this transition and snow cover properties. Particularly interesting is the correlation found between the degree of transition (partial or complete) and the altitude of the $-1\,°C$ isotherm in surface snow, suggesting that the transition is mainly driven by entrainment of warm snow by the avalanche.

   Thanks for the given value of our publication, however, we would like to point out that only parts of the data have been published before and most of the applied methods are new.

Scientific Quality (Rigour): 2

   The study makes clever use of a combination of advanced monitoring and modelling methods (GEODAR, snowpack modelling) to derive important and novel insight on the physics of avalanches. In that respect the paper is remarkable. I would nevertheless recommend that the authors consider expanding upon the description and analyses of their results, in order to provide better support to their conclusions. Hence, while the physical description of the transition is essentially based on two examples, I would suggest they give more information on how the features observed on these examples can be generalized, and on the variability observed among the different avalanches.

E.g., are complete cold-to-warm transitions systematically as abrupt as for the example shown in the paper?

   Yes, we have added this observation to section 3.2.

Along the same line, the precise definition and extraction method of path lengths P_c, P_w and P_t, would need to be explained in more details.

   We have reworked the data section which describes the extraction and terrain mapping method also based on the comment of reviewer 2.

For complete transitions, is it always possible to measure a difference between P_c and P_t? Is the stopping signature of the cold front always present?

   Yes, by definition is the cold stopping signature needed otherwise we can not be sure that its a cold to warm transition or a warm shear to warm plug transition. Following that, P_c is always farther than the transition point.

For partial transitions, how is P_w defined in cases where several warm fronts are visible (case of the example shown in the paper)?

   The case of the example is quite unique, but therefor enables to study the formation of a warm tail in an insulated manner. However, much more usual is the tail above. Sometimes we can identify two warm tails, but these are each in one of the two couloirs. In this case we define it as the farthest of the two.

I do not consider these amendments as necessary at this stage, and I will send to paper to referees in its current version, but I feel that they would contribute to render the study more convincing and sound.

Significance (Impact): 1.

The issue of cold to warm (or dry to wet) transitions in avalanches is emerging and of high importance, particularly in the context of climate change. Although more and more evidences show that this transition frequently plays an important role for large avalanches that travel large distances, it remains poorly documented and only seldom accounted for in models. In that respect, the paper provides important constraints to guide future developments of avalanche models.

Presentation Quality: 3.

I recommend that, in the revision phase, the authors consider improving the presentation of the introduction, with the objective to render the paper more self-contained. Important elements from previous studies, which are essential for proper understanding of the previous paper, would need to be recalled in more details, and the terminology would need to be made clearer. A few examples below:

- What do the authors call flow regime? How are these regimes characterized on GEODAR data? The information given at the beginning of section 3 could be usefully recalled earlier.
  We have expanded the discussion of flow regimes in the introduction, and partly merged from the beginning of section 3.

- What is called a powder snow avalanche in the paper? The fact that these avalanches involve different regimes, including a dense core, would need to be explained more clearly.
  In fact, we refer to the powder snow avalanche described by Sovilla, 2015 and Issler, 2003 with different layers and compoments. However, our data (together with Koehler 2018) shows that there are not only cold parts but also warm flow regimes involved. New to the definition is that this is the case for most of the powder snow avalanches in VdlS.

- What is the avalanche flowing length measured on radar data?
  We have added a few sentences in the methodology section to explain better how to read the MTI plots.

The clarity of the writing would also need to improved in some sections, and notation inconsistencies need to be corrected ($R_{c,w,t}$ in lieu of $P_{c,w,t}$)

During the review process, we have reworked several parts as well as the mentioned inconsitency with the notation.

2 Anonymous Referee #1

The paper by Köhler et al presents detailed measurements obtained from radar techniques (the GEODAR, already presented in a number of previous papers, and the pulse-Doppler system), conducted at Valle de la Sionne avalanche test site, Switzerland. The authors pay attention to the cold-to-warm transition during flow propagation, by considering in parallel the temperature calculated from the snow cover model SNOWPACK. The introduction provides some general ideas on the problem of wet-snow avalanche and more particularly on the cold-to-warm transition problem with some relevant recently published papers. Section 2 presents a brief description of the two radar techniques used and the snow cover reconstruction with SNOWPACK, as well as the data sets. Section 3 describes the results by distinguishing between complete and partial warm-to-cold transitions. It is first based on one example for each transition and two key graphs (Figs. 5 and 6) including all the avalanche events considered are then presented and shortly discussed. Section 4 is a more extended discussion on the results. The limitations of the study are discussed too. Finally, section 5 concludes the manuscript by synthesizing the main results and discussing future works to be done.

2.1 General comment:

The present paper relies on radar techniques that are advanced in situ measurements methods to "look inside the avalanches", following a number of recent studies (about GEODAR in particular). By coupling those radar measurements with snow cover reconstruction (the temperature in particular) and making use of the rough assumption that the temperature of the flowing snow is equal to the snow cover temperature, the authors are able to highlight a relation between the degree of cold-to-warm transition (partial versus complete) and the altitude where the snow cover temperature is $-1\,°C$. Though $-1\,°C$ has been previously identified as a threshold temperature controlling the transition between nearly no granulation and efficient snow granulation (see the controlled experiments done by Steinkogler et al, 2015), it may appear as an arbitrary threshold.

I enjoyed the reading of the paper. The result shown on Fig. 5 is quite remarkable. The topic addressed in the manuscript is timely. I believe that the manuscript can deserve publication if the authors make an effort to revise some points. The success of Fig. 6 is somewhat counter-balanced by the result shown on Fig. 6. My main concern on the scientific content is that a sensitivity analysis to the choice of some thresholds (thickness of $0.5\,m$ for the snow cover taken into account, temperature threshold of $-1\,°C$) is missing. Including such a sensitivity analysis to changing those thresholds is needed in order to reinforce the arguments provided by the authors on the physics of the cold-to-warm transition. How the plots shown on Fig. 5 and 6 would be changed by choosing other values of those thresholds?

> We have done a quick sensitivity analysis before, and also written about the results in the discussion section. The main outcome is that the found relation just shifts for different temperatures and averaging depth.
> We do not strictly propose that a linear relation between H_s and the transition index is the "right answer" - we just show that there is a trend that makes sense and in the words of the second reviewer, we do not aim to provide a profound relation but rather "... (ii) to quantify in a simple way how the degree of transition from a dry-snow flow regime to a wet-snow flow regime depends on the snow- cover temperature along the avalanche path.", "They find a clear positive correlation between F_t and H_s.".
> A detailed sensitivity study (changing 50cm and $-1\,°C$ threshold) would not change anything about this trend and would not change the general message which we want to transport.

I would have a request on the organization of the paper, in addition. The discussion section (section 4) is not well-organized. I invite the authors to make it much more readable. A couple of points

that are direct interpretations of key plots shown on Figs. 5 and 6 should be discussed in more detail and moved to section 3.3. The discussion section could be split into two sub-sections: one for a general discussion on the main results and one about the limitations of the methods used.

Thanks for the suggestions. Accordingly, we split the discussion into discussion of results and limitations of methodology.

Please find below a detailed list of major to more minor comments on the manuscript.

2.2 List of major/minor points:

Sec. 1 - Introduction
- page 1, line 22: [..., whereas dense flow regimes, especially warm regimes, can be diverted or even stopped.]. This sentence is somewhat reductive. I agree that rapid dry- and cold-snow avalanches are difficult to divert and stop. But some flow regimes of wet-snow avalanches can pose serious problems too. Their interaction with protection structures is sometimes very complex, due to nearly unpredictable flow trajectories around avalanche dams (see some examples in Johannesson et al., 2009; European Handbook, chapter 8). Could you please qualify your statement.

Yes, sure. As this is just a teaser sentence, we softened the statement.

- p. 2, lines 9-10: [when liquid water is still expected to be absent.]. I would remove this statement given the fact that it is now well-established that localized melting can occur at ambient temperatures a few degrees below the freezing point (Dash et al, RMP 2006; Turnbull, PRL 2011).

Removed the statement as suggested.

- p. 2, end of line 10: the existence of that quasi-liquid layer in flowing snow has two consequences. It can increase snow cohesion on the one side (and thus increase the size of aggregates) but it may also lubricate the contacts between snow aggregates on the other side (thus enhance flow mobility). Maybe the second effect could be shortly discussed, in addition.

We have added a sentence about lubrication and slush flows.

- p. 2, lines 20-21: [A partial transition affects only the tail of the flowing avalanche and the final run-out is still cold-dominated.]. This sentence suggests that the transition does not occur at the front but mostly at the tail. Could it be that such a scenario with the cold-to-warm transition occurring at the front does exist?

We have reformulated the sentence, stating that partial transition means that warm and cold regimes separate due to different velocities and thus, the warm regime becomes visible often only at the tail. In our opinion, a transition may also occur at the front if for example the lower layers are warmer then the upper layers; but there is no way to resolve that with GEODAR.

- p. 3, lines 13-14: why this arbitrary value of 0.5 m? The statement [Despite the crudeness of this measure, we assume that...] needs clarification. Please could you justify? Maybe you could explicitly refer to the paper section which addresses in detail the assumptions made.

We have connected this statement with the justification of the 0.5 m assumption in section 2.2.

- p. 3, lines 20-21: [Finally, the discussion (sec. 4) brings together both result parts and the study is finished by a conclusion (sec. 5).]. This sentence is quite easy: I guess you could propose a more precise sentence, more relevant to the content of your paper in order to announce both discussion and conclusion sections.

Yes, we have reformulated the sentences to introduce the content.

Sec. 2 - Methods and data
   - p. 4, line 15-16: maybe you could give (at least) one relevant reference already published for each system, the older system and the newer system.

Ok.

- Fig. 1, caption, line 3 (p. 5): shown (not show)

Ok.

- p. 6, lines 12-23: this part justifies your assumptions made (in particular the 0.5 m). Please refer to this part at p. 3, line 13, in the introduction (see a previous comment).

Ok.

- p. 8, Table 1: could you please provide an order of magnitude of the error/uncertainty on P_c and P_w? And thus F_t?

We state an uncertainty for P_c and P_w in the data section 2.3 already. We have added a sentence on the error in F_t where we define it in section 3.3. The error is in the order of 0.05 to 0.1.

- p. 9, lines 10-13: is there any uncertainty on this threshold of $-1\,°C$ between warm and cold regimes? Temperature is certainly a very important control parameter but other factors may come into play. Maybe you could discuss this a bit (see another comment below, on Fig. 6).

Sure, there will be an uncertainty on the $-1\,°C$ threshold. However, the data in this paper can not be used to validate or test this threshold and we simply take it from the literature (see introduction). We think that much more difficult to handle is the assumption that the flowing snow temperature is assumed to be similar to the resting snow cover temperature. This assumption is probably one of the reasons explaining the scatter in Fig. 6. We have added a paragraph about that.

Sec.3 - Results
   - p. 12, lines 3-12: this is a very interesting observation, providing a quantitative proof of a mechanism known from the field experience gained by some snow avalanche experts. Under a context of climate change / global warming, we may expect more events with rain occurring at high altitude on the snow cover during winter. Your measurements are relevant to this problem. Maybe you could add a short word on this point here.

Yes, there is some work done by C. Mitterer et al. about the snow cover weakening due to melting in spring time and they successfully relate the beginning of a wet avalanche period to the liquid water content (LWC). That such increase in LWC can come from rain is just an interesting observation but a bit off-topic to the rest of the content.
Actually this paper is practically related to the climate change problematic. Transitional avalanche are exactly what we expect to happen more in future. This can be also independent of rain. Transition will happen more in future just because we expect the snow cover to increase in temperature. A final paragraph in the conclusion states that.

- p. 12, lines 21-24: [... This discrepancy corroborates the turbulent character of both surges.]. Could you please explain better what you mean here? Do the differences stem from different positions of the devices and/or assumptions made with respect to main flow direction? As such, very turbulent flows, with significant velocities in all (3D) directions can produce different results depending on the technique used. This part needs more clarification.

> No, both devices are mounted at the same location. Only the Doppler radar measures velocity directly and it's the full velocity distribution of the complete frontal zone. Instead, GEODAR measures only the front approach velocity. Large differences between the approach velocity (GEODAR) and the Doppler velocity distribution are usually found in the intermittent regime of powder snow avalanches, where large mesoscale structures can have velocities up to 60% larger than the front. Since these structures are measured by the Doppler radar, the measured velocities are generally bigger. Characteristic for the intermittent regime is surging, which originates from a non-uniform velocity field, see Koehler 2016 and Fischer 2016.

- p. 13, Eq. (5): could you please give an uncertainty on F_t? (back to a previous comment on uncertainties on P_w and P_c). And report this uncertainty on Fig. 5.

> We added a paragraph on the uncertainty of F_t right after the definition in equation 5. Given that $P_{w,c}$ can have an error of 100 m, we find F_t to have an error of up to 0.1.

- Fig. 5: it is nice to see this correlation between H_s and your F_t. Would be nice too to study the sensitivity of the plot to changing the threshold of $-1\,°C$. Would that plot be improved or deteriorated by choosing a different temperature threshold (below or above $-1\,°C$)?

> No, the plot works exactly the same, just H_s is shifted. We have tested that by choosing different temperature thresholds. But we find that $-1\,°C$ is a reasonable choice: The limit towards $F_t = 1$ (pure warm avalanches) is in the release area and not above or below. Partial and complete transitions are split by the H_s:H_t 1:1-line (Figure 6). We have added a paragraph in the discussion of the methodology.

- p. 14 - 15. That you use the linear fit to extrapolate and obtain the value of 860 m a.s.l. for F_t=-1 is questionable to me. Because it does concern the arrest conditions of the avalanche, I guess the effect of local topography coupled with the snow (flowing/deposited and entrained) properties is crucial. I would suggest that either you dont extrapolate or your provide more critical discussion on that result.

> Well, we do not extrapolate explicitly. We just discuss the linear relation and state already that it does not work towards F_t=-1. However, we highlighted the limited validity towards F_t=-1 more clearly.

- p. 15, lines 3-6, and Fig. 6: I may interpret this plot showing H_s versus H_t as a proof that (i) the $-1\,°C$ threshold may a bit arbitrary and (ii) other factors come into play. Those points need more critical discussion. Maybe some arguments given in the discussion should be already developed here (see another comment thereafter).

> This is correct. We do discuss all this in the long discussion section. For example, we state that our choice of temperature threshold of $-1\,°C$ splits the partial and complete transitions. However, the main point taken from this plot is that we need to differentiate between superficial and deep layer entrainment.

Sec.4 - Discussion

- p. 16, lines 10-11: that the flow regime in the run-out zone can be estimated when H_s is known relies on the linear fit proposed for the relation between F_t and H_s. You could be more precise here, and add at the same time that this will need further investigation: linear fit or other relation? range of F_t for which the linear fit is valid? asymptotic behaviors when F_t tends towards -1 or +1?. See also a previous comment.

> We added a paragraph which explicitly includes the limitations and the necessity of further investigations. This paragraph is similar to what the second reviewer D. Issler suggested with the three bullet points.

- a general comment: this section is difficult to read because there are too many ideas. I would propose to put some points (in particular: entrainment at the surface versus deeper in the snow cover, effect of the topography, front dynamics) earlier in Sec. 3 and maybe extend the discussion on those points in Sec. 3, because they are direct and important interpretations of the plots shown on Figs. 5 and 6. Also, the remaining points (not transferred to sec. 3) could be a sub-section 4.1 and the discussion on the limitations of the method (starting from line 26, p. 17) could be a sub-section 4.2.

> We have split the discussion into results and limitations.

Sec. 5 - conclusions
   - p. 18, line 26: the flow regime influences not only the pressure on structures but also the flow mobility (run-out: velocity and volume). Please add those points.

> Thanks, we have added flow mobility.

- p. 18, line 32: please remove "robust relation" but (for instance) use "correlation" instead or keep "relation" only. I agree that this result is very nice but this result will need further validation.

> Removed robust.

- p. 19, lines 3-6: how those values of 300 m and 500 m depend on some (arbitrary) choices you made? A sensitivity analysis (of plots on Fig. 5 and Fig. 6) to changing the threshold values for the temperature ($-1\,°C$ here) and the snow cover thickness taken into account ($0.5\,m$) is missing in your study.

> Sure, these values are found with our assumptions of $0.5\,m$ surface snow and $-1\,°C$ threshold temperature. Other factors like flow volume, path geometry, older deposits ... are not taken into account, but undoubtedly important. Any future study needs to investigate those factors in order to find a universal relation. We do not believe that a sensitivity study of the above mentioned values brings any more insights, rather than shifting the relation. We have added that these values are found by taking the chosen values for the threshold temperature and the depth.

3   D. Issler (Referee #2)

3.1   Content of the paper

Over a period of some three decades, our capability of numerically simulating the evolution of the snow cover in some detail in 3D has developed to a level where these tools can be used in diverse applications with some confidence (notwithstanding major residual problems). Greatly developed and diversified experimental techniques – all of them installed at the Valle de la Sionne test site in Switzerland – have given us an unprecedented, detailed view of the processes inside flowing avalanches. One of the most conspicuous of these new instruments is GEODAR, a phase-array-based radar system that eventually will allow high-resolution 3D mapping of entire avalanches through time. Finally, thanks to IR imaging, the role of the snow temperature in the snow cover and the flowing avalanche has become a major focal point of research in avalanche science, mostly due to work at SLF in Switzerland.

In this paper, the authors combine these three major elements: snow-cover simulation, 18 avalanche measurements with GEODAR and Doppler radar, as well as previously gained insight into the critical role of snow temperatures near melting on the flow regime of avalanches. The main objectives are (i) to verify the effect of snow-cover temperature by comparing a rather large sample of measured avalanches and (ii) to quantify in a simple way how the degree of transition from a dry-snow flow regime to a wet-snow flow regime depends on the snow-cover temperature along the avalanche path.

The measurements with GEODAR and Doppler radar allow distinction between different flow regimes, as recently shown in a different paper by some of the same authors. Moreover, they can distinguish "complete" from "partial" transitions and locate a representative transition point. From the run-out distances of the warm and cold parts of the flow, they construct a transition index F_t and relate it, for each event, to the reconstructed altitude H_s where the mean temperature of the top layers of the snow cover reached $-1\,°\mathrm{C}$. They find a clear positive correlation between F_t and H_s . Similarly, warm avalanches (undergoing a full transition) are shown to make the transition to the warm-snow flow regime above NO: BELOW the altitude H_s , whereas that point is below NO: ABOVE H_s for all cold-snow avalanches (with partial transition only).

> Thank you for summarizing the paper in such good words. We even allowed us to copy some sentences into the discussion and conclusion.

3.2   General comments

The transition index proposed by the authors is a clever attempt to (semi-)quantitatively capture an aspect of the flow-regime transition process with a minimum number of observable quantities. In order to link it to the thermal regime of the flow, the transition altitude, H_t , is invoked and statistically compared to the altitude H_s below which the upper snow cover is warm. The authors seem to be aware of the difficulties and limitations of this approach, but it might be useful to spell them out more explicitly. From my point of view, the following points are particularly important:

- The transition index will probably be most useful for avalanches with drop heights of 500 m or more. For smaller avalanches, H_s tends to be either above the release area or below the run-out area.

- While H_s can be determined wherever and whenever there is enough meteorological data for running snow-cover simulations, finding H_t for a given event requires either detailed investigation of the avalanche deposits or measurements with a GEODAR or advanced Doppler radar.

- For use as a predictive tool, e.g. for road closures or evacuations, a plot like Fig. 6, containing many events, would be necessary. Probably, such copious and detailed data is available only for a handful of avalanche paths worldwide.

  We adopted your suggestion to highlight these limitations with bullet points, and placed the list at the beginning of the discussion to bring these important points directly to the reader.

That being said, I agree, however, that the transition index and the correlation between H_s and H_t are a meaningful way of demonstrating the relevance of the thermal regime for the flow of avalanches.

The method for determining the uncertainty in the snow temperatures $\bar{T}_{2,3}$ remains unclear to me. The way I read the text, they calculate the standard deviations as

$$\sigma_T = [\sum_1^N (T_i - \bar{T})^2/(N-1)]^{1/2} \,,$$

with the sum extending over the computational layers used by SNOWPACK in the top $0.5\,\mathrm{m}$ of the snow cover. If this is indeed what they mean, I cannot see how this should be connected to the uncertainty of H_s – that uncertainty is more directly connected to the question whether a linear extrapolation of snow pack temperatures is admissible. As a consequence, I cannot assess whether the authors approach for determining the consequent uncertainty in H_s is sound or too optimistic. The way they do it according to Fig. 1 assumes that the deviations of T_2 and T_3 from their means $\bar{T}_2$ and $\bar{T}_2$ are tightly and positively correlated. If this is not the case, the uncertainty in H_s will be much larger. This would, however, have considerable importance for Figs. 5 and 6 and for the firmness of conclusions that can be drawn from them. These issues have also been commented upon by the other reviewer and need to be addressed carefully by the authors.

  Yes, that's what we did. And in our opinion this is one of the few suitable and possible approaches how we can estimate an uncertainty of the snow cover temperature. We mostly think of daily variation of the temperature which propagates into the snow cover slowly (warming as soon as the sun comes out). Such warming and in particular the timing may not be captured by the flat field measurements and their simulations, but the spread of layer temperatures may help to get a feeling of the resulting uncertainty or spread of possible values.
  Since it is not a standard deviation or error estimate – as you clearly pointed out – we changed the name to temperature variability.
  Given the fact that the "error" is the variability of the snow temperatures in the top 50cm of the snow cover, we think that the question of correlated or anti-correlated error between both weather stations comes down to fluctuations of the SNOWPACK model result. Therefore, one can expect that the variations rather go into the same direction for both weather stations. The linear extrapolation of the snow temperatures is in fact motivated by the work of Steinkogler et al. (2014, crst). They find a close to linear temperature distribution with 4 points along the VDLS avalanche path (taken from Alpine3D simulations). Here, we did use Alpine3D for all avalanches to check the linearity, and as we state, the examples in Figure 1 are the ones with the largest deviation from linear.

The title of the paper is more general than its content in that dynamical aspects are more or less completely left out. However, the GEODAR data offer a unique opportunity to quantify some aspects of the dynamics: Figures 3 and 4 suggest that a major component of the avalanche first moves at a nearly constant speed, then decelerates over a period of 5 - 10 s, and then continues again at nearly constant speed. From the curvature of the streaks, it should be relatively straightforward to extract the deceleration, and since the location is also known fairly precisely, the retarding accelerations before, during and after the cold-to-warm flow-regime transition can be determined.

This is a rather remarkable phenomenon with far-reaching consequences for modeling the flow. I do not understand why the authors hardly mention this, and I strongly encourage them to dedicate a subsection or a few paragraphs to an at least preliminary analysis.

Yes, you are completely right: It is a pity that we left out those dynamic aspects. However, an analysis like this can easily fill a paper itself: Yes, GEODAR suggests to show all these features directly, but the problem is more subtle and needs a lot of care!

Are we sure, that the snow is the same before/after the transition, but just a bit warmer? Where exactly are the plug flow regime parts in the avalanche, do they have a down-ward or side-way direction? Similarly, are the features at the same lateral position or do they belong to other features of the avalanche?

To answer those questions precisely, one needs a very complete reported dataset – For both examples we do not even have a video because of cloudy weather and night. In this respect, we will not dynamically investigate the dataset here, but we are planing to find out scientifically sound methods to do that in future.

3.3   Minor points

P1, L4,5: The sentence "The intake of . . . regime transition."   sounds strange and undecided. It is well established by everyday experience and experiments that the rheological properties of (granular) snow change significantly with temperature near the freezing point. Please find a more precise and informative wording.

Changed the sentence to point out the importance of warm snow entrainment on cold to warm flow regime transitions.

P1, L8: ". . . the farthest deposit consists of cold snow."

Ok.

P1, L23: "on the flow regime" Earlier references to this phenomenon are
Gauer, P., Lied, K. and Kristensen, K. (2008). On avalanche measurements at the Norwegian full-scale test-site Ryggfonn. Cold Reg. Sci. Technol. 51, 138- 155.

Sovilla, B., Kern, M., Schaer, M. (2010). Slow drag in wet avalanche flow. J. Glaciol. 56 (198), 587-592.

Thanks for the literature suggestion. We have added Gauer (2008), but keep Sovilla (2016) as it compares the pressure for different flow regimes rather than solely analyzing wet snow avalanches.

P1, L76 – 86: The logical flow of this section would be improved by moving this paragraph on observations between lines 55 and 56. To make a clear connection to what follows, in L56 one could say ". . . is now also recognized in modeling."

We are sorry, but we can not identify the paragraph you are suggesting to move. There are no line numbers larger than 24 on P1.

P2, L1: In my view, calling the velocity-independent part of the impact pressure on obstacles hydrostatic is an unfortunate choice. Hydrostatic pressure is the pressure exerted by a fluid at rest, and the term "pressure" is commonly reserved for the isotropic part of the total stress. In the present case, there is no isotropy. Furthermore, the pressure drops significantly (but not to 0) once the avalanche has come to rest. The reason for the height dependence of the normal stress at impact is that the frictional forces between snow particles are proportional to the slope-normal stress, which is essentially of hydrostatic origin. It might be useful to borrow expressions from granular-flow mechanics and replace "dynamic" by "grain-inertia induced", "hydrostatic" by "quasi-static granular" or something similar.

Thank you for the suggested expressions. We adopted grain-inertia induced pressure and quasi-static gravitational contribution. Both terms are used in Sovilla (2016) which is the relevant literature for the sentence.

P2, L14: "a halt"

Ok.

P2, L18: "...and parts of which undergo a transition to a warm-wet regime"

Ok.

P2, L20: "full" $\Rightarrow$ "entire"

Ok.

P2, L21-22: "...all the avalanching snow becomes warm and the final runout is determined by the dynamical properties of the warm flow regime."

Ok.

P2, L30: "more slowly"

Ok.

P2, L32: Some pictures and descriptions can be found, e.g., on the webpages `http://snf.ngi.no/breitzug.040113.html` and `http://snf.ngi.no/breitzug.050212.html`.

These two links are very interesting and indeed describe events with complete transition. We would like to include them in the paper, but we think, their content should be uploaded to a data repository as websites can change too quickly. We suggest for example the European repository `zenodo.org`. Zenodo offers a DOI and so-called communities for the content which make linking very easy.

P3, L2: "lof of attention"

Ok.

P5, Fig. 1: It seems that this figure will occupy most of an entire page, thus there is no need to squeeze things to the point where they become unintelligible. A good solution might be to give the upper panels a common main heading "Avalanche VdlS #17-3030" and each of them a subheading such as "Snowcover temperature from Alpine3D" and "Snow-temperature profiles along centerline" or similar, and analogously for the lower two panels. It took me a long time to (probably) understand the intended meaning of "$\bar{T}$ of profiles $\bar{h}$ 0.5 m depth".

Thanks for the feedback, indeed this figure contains a lot of information. We have improved the organization with headings, clearer legend and caption.

P6, L7: I do not think you mean to say that temperature profiles cannot be measured automatically, but I cannot guess what you mean to say.

Changed accordingly to mean that temperature profiles are not measured automatically.

P6, L19: "... the typical volume of large avalanches in VdlS, $(0.5 - 1) \cdot 10^6 \, m^3$, by the typical affected are of ..."

Ok.

P6, L30: "... crosses the threshold ..."

Ok.

P6, Eq. (2): $H_b \Rightarrow H_3$

Ok.

P7, L1-2: What kind of "standard deviation" is meant? What kind of "law of error propagation" do you apply? From the right panels of Fig. 1 it appears that you assume fluctuations of $\bar{T}_2$ and $\bar{T}_3$ (whatever may be their origin) to be maximally correlated. If one assumed them to be maximally anti-correlated, the grey areas would become much wider at $-1\,°$C.

As said above, we use the temperature fluctuations or variations found in the simulated layers of the top 50 cm. This is used to get a range of possible value for the H_s, as it is one way we can estimate any uncertainty.
The question if the fluctuations are correlated or anti-correlated is complicated and hard to answer. We can only argue that since they are fluctuations, their origin is likely to be the same on both stations and thus they would correlate. The question can also be expanded in the direction of the reliability of SNOWPACK – we hardly have a "proof" that the simulation setup is correct for snow temperatures (it is often calibrated with the total snow depth so that accumulation and melting is correct on the scale of the season). We clarified the definition of the temperature uncertainty in the new version of the paper.

P7, L4: "are" $\Rightarrow$ "is"

Ok.

P7, L7: "... domain is sliced into ..."

Ok.

P7, L12 ff.: This is an important passage, please describe this in somewhat more detail.

We hope to have clarified this paragraph together with the caption of Figure 1 and the figure itself.

P7, L13: "temperature $\bar{T}$"

Ok.

P7, L17: "at the station VDS2. The event #13-3019 ..."

Ok.

P7, L19-20: "... reflect the pattern of warm and cold temperatures reasonably well"

Ok.

P7, L25: "an approximate" ⇒ " a minimum"

Ok.

P7, L28: "...(VDS3) first became operational ..."

Ok.

P8, Table 1: The asterisk in "(McElwaine* et al., 2017)" should be removed in the table legend. Also on P19, L25. the column GEODAR timestamp is difficult to read. Please use ISO notation YYYY-mm-ddTHH:MM, with the letter T separating date and time.

Changed the citation style. We would like to stay with the GEODAR timestamp, as this is the notation used in the data repository, and we need the additional seconds to uniquely identify the data sets.

P8, L2: "such as photographs and data from the flow ..."

Ok.

P8, L2: I have never encountered the notion "terrain registration procedure", and a search in Google does not immediately turn up useful results. Please explain what you mean or use an established notion.

We simplified the sentence. One could use "geo-referencing scheme", but even that is just a word for a bunch of techniques. To explain what we did, we cite Koehler (2016) which covers the process in detail.

P8, L3: "thought of as a transfer"

Ok.

P8, L8: Scatterbrains like me have already forgotten that this abbreviation was defined and last used only four pages ago...

We reformulated the sentence to indicate that MTI plot is a product of the GEODAR data and link with Fig. 2.

P8, L9: The term starving-stopping mechanism was not introduced literally before, but the readers will probably guess that you mean the same mechanism as referred to on P2, L12.

We changed the word order to make the guessing easier.

P9, L5-6: "...in the photographs in Fig. 2."

Ok.

P9, L16: "themselves"

Ok.

P9, L18: "extent"

Ok.

P9, L19: Too sloppy language – a flow regime is not an area or a deposit. "with the same colors"

Added: regions of the flow regimes.

P9, L21: "sort of lateral resolution" – please formulate this more precisely and in non-colloquial English.

We removed this sentence, as it is more confusing than helpful.

P9, L22: "When the most distal deposits are cold, . . . "

Ok.

P9, L23-25: Do you think that starvation is necessary in this case, or could it be enough that the front picks up warm snow and experiences higher friction? Then it would be possible for the tail to run up on the body and front. Do you mean to say that it is (theoretically?) obvious that flows in the warm regime are slower than those in the cold regime, or do you refer to GEODAR measurements? It might be best to remove this sentence. If you keep it, you may want to write something like "The flow velocity differs markedly between the cold and warm flow regimes."

Actually starvation is a good word, if for example the runout of the avalanche in the cold regime is reached by the intermittent region. In this case, mesoscale structures starve by depositing material with time. In our opinion, a lack of light snow available to entrain is what causes a starving in the more dilute part of the flow (which may have a limited interaction with the ground). However, if the furthest reaching part of the cold avalanche is a denser flow, there may be the intake of warmer snow that changes the flow regime. Concerning the velocity, you are right and we have removed the lines.

P10, Fig. 2: The insets lack axis labels.

Ok.

P11, Fig. 3: The plots from the Doppler radar on the right-hand side raise a question at closer examination: The length of the range gates is 25 m in the line of sight according to information given in Sec. 2. This may correspond to about 30 m along the flow direction. At a dominant velocity of approx. 30 m/s, the front should take about 1 s to cross the range gate, which is compatible with the plots. However, between t = 12.5 s and 15 s, a bi-modal velocity distribution with dominant velocities diminishing from 10 to 1 m/s in the first surge and from 20 to 15 m/s in the second.

We have a problem with this question which seems to be not finished, probably? We are not sure what the point of the reviewer was, but maybe it is important to note that due to the missing lateral resolution of the Doppler radar it may appear that surges co-exist or overtake each other which may also lead to the second surge that appears to be a bi-modal velocity distribution but in reality is a consequence of the overlapping of lateral avalanche features.

P11, L22,26: "farthest"

Ok.

P11, L1: "farthest"

Ok.

P11, L10-11: Suddenly, there seem to be different warm flow regimes. Do you perhaps mean different parts of the avalanche that are in the warm flow regime?

This is indeed confusing. We have changed flow regime to singular.

P12, L7: "decline "

Ok.

P12, L8-9: "...changed rather gradually ..." - the dominant velocity inside the range gate diminishes at a rate of up to 0.8 g, akin to an emergency stop with a car! I cannot see velocities as high as 30 m/s in the second surge in Fig. 3 except right when it enters range gate 18. "..., the velocity distribution ranges from ... to ..."

We have removed the word gradually. And reformulated the complete passage to include that we see a rapid deceleration along a single range gate for each surge, but also a deceleration between the range gates for surge 2 and 3 whereas the first front continues through all three range gates.

P12, L15: "from the left-hand side"

Ok.

P12, L16: "influenced" ⇒ "wetted"

Ok.

P12, L17: Strange sentence - how can an "altitude H_s " ... "visually summarize" a "snow cover"???

P12, L22: "discrepancy" ⇒ "difference"

Ok.

P12, L29: "farthest"

Ok.

P13, L7: Should one perhaps mention explicitly that this transition point is not a material point but more akin to a shock front?

Yes, to mention explicitly that no material is travelling uphill is a good idea as the MTI plot are often quite confusing to read. We have added a sentence.

P13, L8: An alternative explanation would probably be that material flowing into the range gate later is significantly slower and therefore stops more easily. In order to decide this (rather relevant) question about piling up, one would have to approximately reconstruct the flow of avalanche parcels across the range gate, adjusting the longitudinal profile of velocity so as to reproduce the recorded intensity distribution in the velocity-time plot.

Thanks for bringing our thoughts to this possible interpretation. We have added that, but also mentioned that a decision is difficult to make. As you mention, to decide between both interpretations needs a lot of effort, and this is exactly the same for many of the "dynamical aspects put right under the readers nose".

P13, L14 and throughout rest of the text: It is never mentioned that F_t is used to multiply some other physically relevant quantity. Therefore, it should be called a transition index rather than a transition factor.

Yes, we have though about that too, however, we changed it throughout the paper.

P14,15: Figures 5 and 6 are somewhat large in this manuscript. Shrinking them by about 50% so that they can be placed side by side on a single page might still be sufficient.

Yes sure, to our knowledge the final layout is in two columns so that the figures can be placed in a single cumn each. Changed the figure size to half page width in the draft.

P14, L3-4: "...have transition factors F_t = -0.18 (...) and F_t = +0.31 (#13-3019)."

Ok.

P14, L6: To be pedantic, one ought to say something like "..., and the set of values is well distributed over this range".

Ok.

P15, Fig. 6: "Altitude of transition, H_t , against altitude of the $-1\,°\mathrm{C}$ line, H_s ." "happen" $\Rightarrow$ "occurs", "characterizes"

Ok.

P15, L1-2: If one thinks about the dynamics of avalanches and the topography of Vallée de la Sionne, it is obvious why the naive extrapolation fails, but it would probably be helpful to some readers if this was explained.

We have added a sentence describing roughly the avalanche path at the beginning of the method section.

P16, L1: "1700" $\Rightarrow$ "1800"???

Yes, we can say that and it fits with the next paragraph where we find the $-1\,°\mathrm{C}$ line above 1800.

P16, L9: "superficial" $\Rightarrow$ "surficial"

Ok.

P16, L10: Do you mean to say that the concept of H_s can be applied only to Valle de la Sionne? What is then the value of your approach ?

Well, we hope not, but we can not test it yet. We have included explicitly the unknown path dependency into the beginning of the discussion section.

P16, L16: "...of deeper and therefore warmer layers

    Ok.

P16, L20: "results in" ⇒ "undergoes"

    Ok.

P16, L27: "structures" ⇒ "texture", "show that" "can produce completely warm-wet deposits"

    Ok.

P16, L31: "higher" ⇒ "more"

    Ok.

P17, L5: "altitude at the end"

    Ok.

P17, L5: "gently inclined runout area"

    Ok.

P17, L12-13: "...able to hold back mass from ..." - This can easily be (mis-)read as you suggesting that tension forces are exerted on the front by the tail.

    Thanks for pointing out this sentence. We have clarified it.

P17, L15: "more importantly"

    Ok.

P17, L27: "may play a role in"

    Ok.

P17, L27: "with regard to"

    Suggestion not found

P17, L34-35: This assumption does not really affect what you have done because you have not really considered the rheology and mechanics of flowing snow. This will, however, become important when one tries to take this approach from an empirical method tied to a specific site to a general one, applicable to any avalanche path.

    Right, that is the beauty of an empirical approach that many factors are included. However, we left the sentence and pointed the reader that this becomes important when generalizing the results.

P18, L15: "relatively gentle"

P18, L19: "As an example,"

P18, L23: "common in large"

P18, L24: "occurs", ". . . of snow grains causes . . ."

P18, L28: "unexpectedly long"

P19, L3: "almost all large"

P19, L7: ". . . as a first step in developing a method for predicting the. . ."

P19, L22: ". . . mitigation procedures be adapted. . ."

3.4   Recommendation

This paper contains a number of novel aspects, in particular the combination of several advanced experimental techniques in avalanche dynamics with snow-cover modeling. The topic of thermal effects in avalanche dynamics has recently attracted much interest, thus the paper is undoubtedly timely. The concepts discussed here may also help guiding future modeling efforts.

The data presented in this paper is unique due to the GEODAR. As far as this can be judged from the outside, the data analysis and the snow cover simulations appear to be sound.

The authors havepresumably deliberatelyadopted a phenomenological approach and not tried to interpret their data through semi-quantitative or quantitative models. I personally think that a simple physical analysis, e.g. an estimate of the different components of the energy balances of the considered avalanche events along their paths, would be highly interesting and add value to the paper. Such an analysis might give some indications as to the predictive power of the transition index for avalanches in the Valle de la Sionne and how it might be used as a predictive tool in other avalanche paths. I do not, however, insist on this point.

We agree that the analysis could be extended. However, the described avalanches are all very different and, in our opinion, any more indepth analysis would require to deal with each one individually rather than describing all with a common method. We will work on exactly that in future projects and thus build on the results shown here.

As mentioned under "General comments", I think it is a real pity that the authors do not present at least a preliminary analysis of the dynamical aspects that the GEODAR images put right under the readers noses. Adding such an analysis would significantly increase the value of this paper.

> We agree that the GEODAR data together with the Doppler radar data include many details and dynamical aspects on each avalanche. However, even very simple questions require a detailed knowledge of each event. The work definitively continues in interpreting the data in the mentioned details.

Contrary to Reviewer #1, I do not have objections against the organization of the paper. I find the presentation to be logical and (except for some details mentioned above) easy to understand. The figures are informative and well executed; some minor modifications have been indicated above. However, the writing style, grammar and spelling definitely need attention to the details.

All aspects considered, I recommend the paper for publication in The Cryosphere after minor corrections (and the mentioned additions).

Cold-to-warm flow regime transition in snow avalanches

Köhler Anselm[1,2], Fischer Jan-Thomas[2], Scandroglio Riccardo[1], Bavay Mathias[1], McElwaine Jim[3], and Sovilla Betty[1]

[1]WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[2]Austrian Research Centre for Forests (BFW), Innsbruck, Austria
[3]Department of Earth Sciences, Durham University, Durham, UK

Correspondence to: Anselm Köhler, anselm.koehler@slf.ch

Abstract. Large avalanches usually encounter different snow conditions along their track. When they release as slab avalanches comprising cold snow, they can subsequently develop into powder snow avalanches entraining snow as they move down the mountain. Typically, this entrained snow will be cold ($\overline{T} < -1\,°\mathrm{C}$) at high elevations near the surface, but warm ($\overline{T} > -1\,°\mathrm{C}$) at lower elevations or deeper in the snow pack. The intake of ~~thermal energy in the form of~~ warm snow is believed to be of major importance to increase the temperature of the snow composition in the avalanche and eventually cause a flow regime transition. Measurements of flow regime transitions are performed at the Vallée de la Sionne avalanche test site in Switzerland using two different radar systems. The data are then combined with snow temperatures calculated with the snow cover model SNOWPACK. We define transitions as *complete*, when the deposit at runout is characterized only by warm snow, or as *partial*, if there is a warm flow regime but the ~~furthest~~ farthest deposit is characterized by cold snow. We introduce a transition ~~factor~~ index F_t, based on the runout of cold and warm flow regimes, as a measure to quantify the transition type. Finally, we parameterize the snow cover temperature along the avalanche track by the altitude H_s, which represents the point where the average temperature of the uppermost $0.5\,\mathrm{m}$ changes from cold to warm. We find that F_t is related to the snow cover properties, *i.e.* approximately proportional to H_s. Thus, the flow regime in the runout area and the type of transition can be predicted by knowing the snow cover temperature distribution. We find, that, if H_s is more than $500\,\mathrm{m}$ above the valley floor for the path geometry of Vallée de la Sionne, entrainment of warm surface snow leads to a complete flow regime transition and the runout area is reached by only warm flow regimes. Such knowledge is of great importance since the impact pressure and the effectiveness of protection measures are greatly dependent on the flow regime.

1 Introduction

For avalanche practitioners dealing with situations where they need to judge the avalanche hazard for infrastructure, flow regime transitions can cause large uncertainties. Which flow regime reaches the valley bottom is of great interest from two perspectives. Firstly, the usefulness of permanent protection measures like avalanche dams depends strongly on the flow regime (Jóhannesson et al., 2009). Indeed, deflecting and catching dams are relatively ineffective against the highly fluidized intermittent frontal regime of powder snow avalanches, whereas dense flow regimes, especially warm regimes, can more easily be diverted or even stopped. Secondly, the force generated by an avalanche on a structure in the path depends strongly on flow regime

1

(Sovilla et al., 2016). The dynamic (Gauer et al., 2008b). A velocity dependent grain-inertia induced pressure is dominant in cold-dry flow regimes, whereas ~~the hydrostatic~~ a flow depth dependent quasi-static gravitational contribution is dominant in warm-wet flow regimes (Sovilla et al., 2016).

Recent studies identified the snow temperature as a key parameter causing the agglomeration of snow (Steinkogler et al., 2014) and a change of the flow dynamics by altering the velocity and the effective friction (Naaim et al., 2013; Gauer and Kristensen, 2016), as well as the stopping dynamics (Köhler et al., 2018). A temperature value of $-1\,°C$ is proposed by a study on snow granulation (Steinkogler et al., 2015a), where they observed a significant change from millimetre sized grains to the formation of decimetre sized granules above this temperature. We emphasize the temperature of the snow by calling avalanches warm and cold rather than wet and dry, since the flow behaviour changes already at a threshold of $-1\,°C$~~, when liquid water is still expected to be absent~~. That this transition occurs below $0\,°C$ is presumably due to the existence of a quasi-liquid layer even at sub-zero temperatures ~~(Dash et al., 2006), which~~ (Dash et al., 2006; Turnbull, 2011). Liquid water may cause the cohesion of snow to increase by formation of granules, but may also lubricate the contacts between snow aggregates and result in slush flows.

The avalanche flow regime – a region inside the avalanche where the same physical processes are dominant – can be deduced from radar signatures of flow processes by use of the radar GEODAR (Köhler et al., 2018). Cold flow regimes are identified by the starving mechanism in which the avalanche loses mass from the tail until finally the front comes to halt. We call cold regimes those flow regimes which contain cold snow $(< -1\,°C)$, and are either the cold dense regime or the dilute frontal region of powder snow avalanches called intermittent regime. In contrast, warm flow regimes are identified by either abrupt stopping or a backward propagating shock; either a large flowing part stops instantaneously or the front comes to ~~an~~ a halt and incoming material piles up. We call warm regimes those flow regimes which occur for warm snow temperatures $(> -1\,°C)$, and are either the warm shear regime or the warm plug regime. Köhler et al. (2018) differentiated flow regimes comprising cold and warm snow further in detail. However, relevant for the discussion here is that the majority of large avalanches shows transitions between cold and warm flow regimes. These transitions and the relation with snow cover properties are the focus of this paper.

This study deals exclusively with avalanches that start in a cold-dry regime and ~~later have regions in~~ parts of which untergo a transition to a warm-wet regime, that is, those avalanches exhibit a cold-to-warm flow regime transition. We define these transitions as *partial transition* or *complete transition*, depending on whether only parts, or the ~~full~~ entire avalanche, transforms. A partial transition ~~affects only~~ becomes often visible at the tail of the flowing avalanche as cold and warm flow regimes separate due to different velocities and the final runout is still cold-dominated. With a complete transition, all the snow ~~transforms into warm regimes~~ becomes warm and the final runout is ~~warm-dominated~~ determined by the dynamical properties of the warm flow regime.

Large avalanches composed mostly of cold snow are powder snow avalanches and have been described by many authors ~~(Sovilla et al., 2015; Issler, 2003; Schweizer et al., 2015)~~ (Sovilla et al., 2015; Issler, 2003). They usually release as a slab containing cold snow, and the runout area is reached by fast flowing cold snow. In addition to the typical structure of a suspension cloud, a frontal intermittent region and a ~~dense~~ cold dense core and tail, GEODAR images reveal often warm flow regimes in

the tail and indicate that a partial transition happened (Köhler et al., 2018). Issler (2003) introduced the nomenclature "mixed powder snow avalanche" to describe the occurrence of dilute and dense flow regimes together in one avalanche event. The definition applies mostly for cold dense and dilute regimes, but Issler (2003) reported of damp deposits which are not covered by dust of the dilute regimes and thus had been flowing later and ~~slower~~more slowly.

5 Warm-dominated avalanches release similarly to cold-dominated ones, but transform completely somewhere along the path. In this case, the runout is dominated by warm regimes. Literature on this type of avalanche is hard to find, since to our knowledge such a transition is rarely recognized and the events are rather described as wet avalanches. There are some measurements with radar and picture in Gauer et al. (2008a) indicating a complete transition, but have been interpreted as a secondary wet slab released by the primary dry–cold avalanche. An example of an avalanche with a complete transition re-

10 leased spontaneously near the village of Moos in Passeiertal, Italy, on the 6th of February 2014. A video of this avalanche drew a lot of attention, because most of the avalanche travelled along a road in front of houses with people on their balconies (www.youtube.com/watch?v=f5waSw2mMfY). The avalanche released on the south-east facing slopes below the summit of Scheibkopf ($2816\,\mathrm{m\,a.s.l.}$) after a major snow storm and developed a large powder cloud and thus contained cold snow. At around $15\,\mathrm{s}$ after the start of the video, the powder cloud began to decay so that the cold parts stopped at approximately

15 $1700\,\mathrm{m\,a.s.l.}$. A dense flow continued and flowed over a cliff into a shallow valley, where finally a slow-moving plug flow developed. The avalanche transformed completely from a cold powder snow avalanche into a warm flow, which finally flowed slowly along the road.

The present study tries to answer the question of how the *degree* of transition relates to the snow cover properties along the avalanche track. To quantitatively describe the *degree* of transition as a continuum between partial and complete, we define the

20 transition ~~factor~~ index F_t, which is a function of the path length of warm and cold flow regimes.

We then explore the relationship with snow cover characteristics, focusing on the snow temperature $\overline{T}$ averaged over the uppermost $0.5\,\mathrm{m}$ of the snow cover. This depth is expected to be frequently entrained into the avalanche, though of course there may be more or less entrainment. ~~Despite the crudeness of this measure, we assume~~ This assumption is backed up by field observations on typical entrainment depths and underpinned in section 2.2. We find that $\overline{T}$ is a representative indicator for

25 the thermal energy intake due to entrainment and we will show that it can be used to give a good prediction of the transition ~~factor~~index.

The study starts by introducing the test site and sensor equipment (sec. 2.1), the method to derive the snow cover temperatures by simulations with the numerical model SNOWPACK (sec. 2.2), and a short description of the avalanche data (sec. 2.3). The following results section is divided in two parts. Firstly, we detail the kinematic and dynamic characteristics of partial and

30 complete transitions by means of two different radar systems (sec. 3.1 and 3.2). Secondly, we present the analysis of the degree of transition with the snow cover temperatures (sec. 3.3). Finally, the discussion (sec. 4) ~~brings together both result parts and the study is finished by a conclusion (sec. 5).~~ is divided into two sections which brings results into wider context and points out limitations of our methodology.

2 Methods and data

2.1 Test site and radar sensors

The full-scale avalanche test site Vallée de la Sionne (VdlS) is situated in the west of Switzerland. The east-facing avalanche path extends from high altitudes at $2700\,\mathrm{m}$ a.s.l. to intermediate altitudes with a total drop-height of $1300\,\mathrm{m}$. The VdlS
5 avalanche track can be roughly characterized with a $40°$ steep release area above $2300\,\mathrm{m}$ a.s.l., followed by a flatter section which leads into two $35°$ steep couloirs between $1800\,\mathrm{m}$ a.s.l. and $2100\,\mathrm{m}$ a.s.l. with the runout area starting below and continuing into the valley floor at $1400\,\mathrm{m}$ a.s.l.. Especially in the early and late season, there can be minimal snow in the lower part of the slope but still sufficient snow for avalanches in the release areas at higher elevations.

The test site is equipped with multiple sensor systems at different locations. On a $20\,\mathrm{m}$ high pylon near the start of the
10 runout area, sensors give high-resolution vertical profiles of flow velocity, flow height, density as well as impact pressure (Sovilla et al., 2013). Upward-looking flow profiling radars and seismic sensors are situated in two locations along the flow path. Data are also collected over the entire slope by two complementary radar systems: the GEODAR (Ash et al., 2010) allows tracking of avalanche features with high spatial and temporal resolution, and the pulse-Doppler system (Schreiber et al., 2001) complements this with complete velocity distributions of the avalanche flow. An automatic seismic trigger enables
15 measurement of even spontaneous avalanches.

GEODAR is a high-resolution frequency modulated continuous wave radar and was first installed in winter season 2009/10 (Ash et al., 2014). The system has been continually improved and currently has a range resolution of $0.75\,\mathrm{m}$ at $110\,\mathrm{Hz}$ over the entire slope (Köhler et al., 2018). GEODAR is able to resolve internal flow structures below the powder cloud. By means of feature tracking, comparison with other data and qualitative interpretations, new and very detailed insights into processes
20 during an avalanche descent have been gained (Vriend et al., 2013; Köhler et al., 2016, 2018). The data processing, feature extraction and terrain registration are done here with the same methods as described in these three publications. An approach velocity $v_a(t)$ of the avalanche front towards the radar is calculated by the derivative of the range-time trajectory $r(t)$, which is corrected for the angle between terrain and the radar beam θ (Köhler et al., 2016)

$$v_a(t) = \frac{\dot{r}(t)}{\cos\theta}\,. \tag{1}$$

25 The processed GEODAR data are usually shown as range-time plots with the colour representing the intensity of the moving-target identification (MTI) filter (*e.g.* left panels of Fig. 2). This filter suppresses static targets and background clutter and highlights moving structures. Often the front and tail give the clearest signature from light to dark colours and vice versa. Inbetween, the avalanche signature is usually dark coloured with line and streak patterns (Köhler et al., 2018). The distance between front and the tail along the range axis is the avalanches flowing length, which in general increases between release
30 area and the fastest parts reaching the valley floor.

The other radar, a pulse-Doppler radar, was permanently installed at Vallée de la Sionne for the winter season 2009/10 and upgraded in 2016/17. The older system provided a spatial resolution of $R_g = 50\,\mathrm{m}$ (Schreiber et al., 2001) and the newer system gives $R_g = 25\,\mathrm{m}$ (Fischer et al., 2016). This resolution is referred to a range gate extent (R_g), and the Doppler mea-

surements provide an intensity distribution of velocities over time $I_k(t, v)$ of the flowing material within each range gate R_k with a running number k (*e.g.* Fig. 3 and 4). The peak of this distribution describes the velocity of maximum intensity and gives the velocity at which most of the material is travelling (Gauer et al., 2007; Fischer et al., 2014). The data can also be transformed into a range-time representation (Fischer et al., 2016), which is very similar to GEODAR intensity-range plots but

5   represents the mean velocity in each range gate k at each time as

$$\overline{v}_k(t) = \frac{\int v \, I_k(t, v) \, dv}{\int I_k(t, v) \, dv} \tag{2}$$

(middle panels in Figure 2). This can then be converted from a discrete function of range to a continuous function using finite volume interpolation methods.

2.2   Snow cover reconstruction

10   The test site Vallée de la Sionne is equipped with three weather stations. The bottom station VDS3 (indicated with subscript $_3$) at elevation $H_3 = 1680 \, \text{m a.s.l.}$ is representative for the runout area. The top weather station VDS2 (subscript $_2$) at elevation $H_2 = 2390 \, \text{m a.s.l.}$ gives a good approximation for the release area even though it is situated $3 \, \text{km}$ to the north of the avalanche path. Both weather stations are installed in flat fields sheltered from winds to most-accurately represent the undisturbed snow height. Both weather stations measure air temperature, humidity, wind speed, snow height, radiation and snow surface temperature,

15   which are the complete set of parameters necessary to simulate the desired snow cover profiles. A third station VDS1 is situated directly on the ridge above the release area and measures especially wind speed and therefore wind loading.

The meteorological data have been prepared with the library `meteoIO` (Bavay and Egger, 2014), *i.e.* missing values have been interpolated and temperature and snow height data have been filtered. Corrections according to Huwald et al. (2009) were necessary for the air temperature, as unventilated temperature sensors are used and these usually overestimate the temperature

20   for situations with low wind speed but strong radiation. Special attention has been given also to the snow height data at the VDS3 station, since for low snow heights the measurements were biased by vegetation so that the values had to be manually reset to $0 \, \text{m}$.

To obtain snow temperature profiles, the snow cover has to be modelled as these ~~can not be~~ are not measured automatically. ~~.~~ The snow cover at the location of the meteo stations has been reconstructed with the numerical energy balance model

25   `SNOWPACK` (Lehning et al., 2002) to obtain vertical snow profiles as a function of time. We have applied the simulation setup for the operational simulations of the Intercantonal Measurement and Information System (IMIS), the high alpine weather station network in Switzerland (Schmucki et al., 2014).

In this publication, we explore how the temperature of the snow cover entering an avalanche determines the degree of a cold-to-warm transition. There is no common approach to reduce the temperature profile of the snow cover to a single

30   representative value. Naaim et al. (2013) used the average snow temperature in the full path without differentiating between release and runout area. This approach is very broad, but suitable for situations where it is necessary to compare a large number of avalanche events. In a detailed study, Steinkogler et al. (2014) averaged over an estimated entrainment depth. This is most accurate but requires very detailed entrainment data, and therefore is only suited for studies with a few avalanches. Köhler et al.

(2018) approximated this depth by assuming that the uppermost $0.5\,\mathrm{m}$ of snow was entrained. Sovilla et al. (2006) showed that significant entrainment occurs along the full avalanche path. If we divide the ~~usual total volume of~~ typical volume of large avalanches in VdlS of $(0.5\text{--}1) \times 10^6\,\mathrm{m}^3$ by the ~~approximately~~ typical affected area of $(1\text{--}2) \times 10^6\,\mathrm{m}^2$ (Dufour et al., 2000; Steinkogler et al., 2014), the average entrainment depth of $\overline{h} = 0.5\,\mathrm{m}$ appears to be a reasonable assumption. The approach with a constant averaging depth can be regarded as a trade-off between accuracy and practicability for analysing many avalanche events, even though large avalanches can usually dig much deeper into the snow cover (Gauer and Issler, 2004; Sovilla et al., 2006).

Thus, we average the simulated snow temperature

$$\overline{T} = \sum_i \frac{h_i T_i}{\overline{h}} \tag{3}$$

from the layers i with thickness h_i and layer temperature T_i in the uppermost $\overline{h} = 0.5\,\mathrm{m}$ of the simulated snow cover. With `SNOWPACK` simulations we compute $\overline{T}$ only at the location of VDS2 and VDS3 (squares in right panel of Fig. 1), but are interested in the snow cover temperatures along the entire avalanche path.

We parameterize $\overline{T}$ along the avalanche path with the altitude H_s of the $-1\,^\circ\mathrm{C}$ line. H_s represents the altitude where $\overline{T}$ ~~changes~~ crosses the threshold from above to below $-1\,^\circ\mathrm{C}$, similar to the zero-degree level in meteorology. ~~We~~ Motivated by the work of Steinkogler et al. (2014), we estimate H_s with a linear relation between the altitude of the weather stations H_2 and H_3 and the average temperatures $\overline{T}_2$ and $\overline{T}_3$ of the uppermost $0.5\,\mathrm{m}$ of the snow cover by

$$H_s = H_{\underline{b}3} + (H_2 - H_3)\frac{-1 - \overline{T}_3}{\overline{T}_2 - \overline{T}_3}\,. \tag{4}$$

The elevation uncertainty $\triangle H_s$ is estimated with the ~~standard deviation~~ temperature variation of the uppermost $0.5\,\mathrm{m}$ snow temperature $\triangle \overline{T}_{2;3}$ at both weather stations ~~with the law of error propagation.~~. In fact, $\triangle \overline{T}_{2;3}$ is the standard deviation of the simulated layer temperatures in the uppermost $0.5\,\mathrm{m}$ of the snow pack. The right panels of Figure 1 show graphically the linear interpolation of $\overline{T}_{2;3}$, and H_s and $\triangle H_s$ is found at the intercept of the grey area with the dashed line at temperature $-1\,^\circ\mathrm{C}$. $\triangle H_s$ is not the uncertainty of H_s, but give rather a spread of possible values.

Our parameterization of the snow cover temperatures in the avalanche path and the temperature gradient ~~are~~ is in fact only dependent on altitude. To check the validity of ~~this strong assumption (~~these strong assumptions (flat field simulations, linear elevation gradient, see Eq. 4), we have additionally performed `Alpine3D` simulations to compare the results (Lehning et al., 2006). `Alpine3D` performs physically-based spatial interpolations of all the meteorological input data over a domain, *i.e.* the area of the VDLS test site. This domain is ~~slit~~ sliced into grid cells with resolution of $25\,\mathrm{m}$ x $25\,\mathrm{m}$ and for each cell a `SNOWPACK` simulation is performed (Schlögl et al., 2016). While our single `SNOWPACK` simulations are calculated for flat fields, `Alpine3D` simulates the snow cover at each cell with their local slope and aspect. The `Alpine3D` output are grids of a parameter like the $0.5\,\mathrm{m}$ snow temperature $\overline{T}$ for every simulation step, and a full `SNOWPACK` output can be generated at any point of interest.

Results of ~~both numerical~~ `Alpine3D` and `SNOWPACK` simulations for two example avalanches are shown in Figure 1. The left panels show the spatial distribution of the ~~temperature~~ temperature $\overline{T}$ over the catchment of VdlS from `Alpine3D`. The

right panels display ~~a vertical transect~~ the vertical profiles of layer temperatures T_i along the line of steepest descent from the ~~middle of the release area~~release area. These profiles are generated by the `Alpine3D`simulations as full outputs at points of interest. Additionally in the right panels are the data of `SNOWPACK`simulations for both weather stations denoted with white squares, together with a graphical representation of the interpolation in Eq. 4 which give $H_s$at the intercept with the temperature

5 threshold of $-1\,°C$ (black square). ~~These two example avalanches~~

The two example in Figure 1 have the largest deviation between Eq. 4 and the `Alpine3D` simulations in our data sets. The #17-3030 event (top) occurred in spring-time when the flat fields receive more sun than the eastern aspects and thus show higher temperature for $\overline{T}_2$ at ~~VDS2 station . The~~the station VDS2. The event #13-3019 ~~event~~corresponds to a rain event and the right panel shows isothermal $0\,°C$ snow in the runout area but very cold snow in the release area. However, if compared with

10 the gridded $\overline{T}$ of `Alpine3D` output in the left panels, both H_s estimates (grey areas) reflect ~~reasonably well the~~ the pattern of warm and cold ~~temperature pattern~~temperatures reasonably well. Thus, we expect a deviation from equation 4 for situations like spring-time with strong radiation influence, and H_s will be less accurate if large regions are isothermal. In particular, rain-on-snow events may be overlooked as the water ingress is difficult to measure and to capture with `SNOWPACK` (Würzer et al., 2017).

15 ## 2.3 Data set

In this study, we selected avalanche events from Vallée de la Sionne that ~~fulfil~~fulfill three criteria: 1) they were large enough to pass the measurement pylon at range $655\,m$ near the start of the runout area. This criterion implies ~~an approximate~~ a minimum drop height of $1000\,m$. 2) The avalanche stopped where it was visible to GEODAR, that is before the counter-slope. 3) A cold-to-warm transition as described by Köhler et al. (2018) occurred somewhere in the avalanche.

20 Since the lower weather station (VDS3) ~~was first employed~~ first became operational in the winter season 2012/13, we selected large avalanche events from then until the season 2016/17. From totally measured 130 avalanche events, 18 avalanches ~~fullfil~~fulfill these criteria and were selected. Two of them are compared in detail in Figure 2. The selected avalanches cover the full variability between partial (Sec. 3.1) and complete flow regime transitions (Sec. 3.2). Noteworthy is that avalanches with a complete transition are relatively rare in our data set. There was a three-day period at the beginning of February 2013 when

25 three out of the four of these avalanches occurred. Avalanches with a partial transition could occur all winter from December to March. The avalanche and snow cover data used in this publication are summarized in Table 1.

A release location $[X_0, Y_0, Z_0]$ was assigned to each avalanche event by the use of additional data from the VdlS test site ~~as pictures and the~~ such as photographs and data from flow profiling radars (Köhler et al., 2018). We ~~used a terrain registration procedure to~~ map the radar range R onto the line of steepest descent from the release location (*i.e.* green line in Fig. 2). ~~This~~

30 Such a procedure can be thought of as a transfer function between radar range R, real world coordinates $[X, Y, Z]$ and the path length P (Köhler et al., 2016). The path length P is the projected ground parallel distance from the release point $P_0 = 0\,m$. Whereas the radar range R is the line-of-sight distance, and is generally smaller than P. Since we often do not know precisely the release coordinates, the highest point of the most likely release area was used, giving an uncertainty of $50\,m$ to $100\,m$ in path length P.

Table 1. Summary of the avalanche events with the extracted path lengths P, the transition ~~factor~~ index $F_t = \frac{P_w - P_c}{\max(P_c, P_w)}$ and altitude of transition H_t, as well as the snowpack conditions H_s and mean temperatures at both meteo stations $\overline{T}_{2;3}$. Data of avalanche events indicated with a * in front of the row can be received from the GEODAR repository ~~(McElwaine* et al., 2017)~~(McElwaine et al., 2017).

SLF-Nr	GEODAR timestamp	P_c [m]	P_w [m]	F_t	H_t [m a.s.l.]	H_s [m a.s.l.]	$\overline{T}_2$ [°C]	$\overline{T}_3$ [°C]
*#13-3003	2012-12-04-04-46-05	1980	1770	-0.11	1820	1719 ± 30	-4.4 ± 0.2	-0.8 ± 0.1
*#13-3019	2013-02-01-17-14-50	1630	2370	0.31	1730	1989 ± 74	-2.3 ± 0.6	0.0 ± 0.0
*#13-3020	2013-02-01-20-18-46	1990	2580	0.23	1660	2003 ± 44	-2.2 ± 0.3	0.0 ± 0.0
*#13-3021	2013-02-02-05-27-31	1560	2230	0.30	1700	1953 ± 26	-2.6 ± 0.2	0.0 ± 0.0
*#13-3024	2013-02-05-23-31-53	2080	1630	-0.22	1770	1506 ± 146	-8.1 ± 1.1	-2.4 ± 1.1
*#14-0012	2014-02-13-19-21-32	2460	1630	-0.34	1770	1325 ± 73	-4.3 ± 0.6	-2.1 ± 0.3
*#15-0009	2015-01-29-05-18-08	1980	1580	-0.20	1810	1627 ± 82	-5.3 ± 0.3	-1.3 ± 0.5
*#15-0013	2015-01-30-02-12-22	2640	1680	-0.36	1810	1200 ± 221	-7.2 ± 0.4	-3.5 ± 0.8
*#15-0016	2015-02-03-10-20-16	2310	1200	-0.48	1870	1281 ± 191	-9.9 ± 0.8	-4.2 ± 1.2
*#15-0020	2015-02-03-12-04-39	2560	1860	-0.27	1770	1585 ± 71	-8.6 ± 0.5	-1.9 ± 0.7
#16-3017	2016-01-18-10-40-14	2640	1370	-0.48	1970	1556 ± 16	-10.4 ± 1.0	-2.4 ± 0.3
#16-3032	2016-02-09-18-31-25	1430	1430	0.00	1960	1858 ± 50	-3.4 ± 0.5	-0.2 ± 0.1
#17-3014	2017-01-13-02-47-38	1760	1560	-0.11	1790	1470 ± 45	-4.5 ± 0.3	-1.8 ± 0.2
#17-3027	2017-03-02-12-22-03	1590	1820	0.13	1820	1979 ± 121	-2.1 ± 0.7	-0.2 ± 0.1
#17-3028	2017-03-06-15-48-07	1990	1530	-0.23	1850	1798 ± 72	-4.0 ± 0.7	-0.4 ± 0.3
#17-3030	2017-03-06-22-05-22	2600	2140	-0.18	1750	1416 ± 77	-5.8 ± 0.5	-2.3 ± 0.4
#17-3033	2017-03-08-11-04-22	2130	2130	0.00	1730	1786 ± 35	-4.4 ± 0.5	-0.4 ± 0.1
#17-3036	2017-03-08-11-25-24	2090	1930	-0.08	1690	1786 ± 35	-4.4 ± 0.5	-0.4 ± 0.1
Moos avalanche, 6 Feb. 2014		1600	2900	0.45	1700	> 2000	–	–

From the ~~GEODAR MTI plots~~ MTI plots of the GEODAR data (left in Fig. 2), we extracted manually the following ranges and calculated the corresponding path lengths:

- P_c: Path length of front containing cold snow, primarily identified by a ~~starving stopping~~ stopping with the starving mechanism.

5

- P_w: Path length of front containing warm snow, primarily identified by a backward propagating shock or abrupt stopping.

- P_t: Path length until the point of transition between a cold front and a warm front. For avalanches with a complete transition P_t was relatively precise. For partial transitions P_t could be identified only as soon as the warm front separated from the rest of the flow (Fig. 2) and this gave rise to an uncertainty of ± 50 m in path length.

The coloured dots in Figure 2 show the features in the MTI images to which the three points ~~P_c, P_w and P_t~~ R_C, R_W and R_T

10 belong for two example avalanches. The transfer function between radar range R and path length P is roughly given by the labels in ~~pictures~~ the photographs in Figure 2.

3 Results

~~Avalanche examples for a partial (top) and a complete (bottom) cold-to-warm transition. The avalanches are visualized by means of GEODAR data (left), mean Doppler velocities $\overline{v}_k(t)$ (middle) and geo-referenced pictures of the deposits (right). Flow features extracted from GEODAR are highlighted in the other panels. The warm regimes are identified by typical coarse-grained and rough deposits (purple and magenta), while the fine-grained and smooth cold deposits can only be sketched (blue). The path along the steepest descent is drawn in green. The cold and warm runout distances and the transition point are indicated with coloured dots.~~

This section starts with a qualitative characterisation of both cold-to-warm flow regime transition types by means of GEODAR and pulse-Doppler data. Then we relate the degree of transition of all 18 avalanches with the snow cover data. Here, we do not differentiate in detail the flow regimes classified by Köhler et al. (2018), but simply consider cold and warm flow regimes only. We call cold regimes those flow regimes which contain cold snow ($< -1\,°C$), *i.e.* the cold dense regime and intermittent regime. And we call warm regimes those flow regimes which occur for warm snow temperatures ($> -1\,°C$), *i.e.* the warm shear regime and warm plug regime. Warm and cold regimes differ clearly in their MTI stopping signatures. We refer to Köhler et al. (2018) for a detailed description of stopping signatures in the GEODAR signal and the differentiation between cold and warm *flow regimes*.

Note, we can not validate the temperature threshold for snow granulation of $-1\,°C$ with our data. We focus on snow temperature as driving factor, other influences like liquid water content or salt content in maritime snow are neglected. Furthermore, as we use snow cover simulations to examine the temperature of the flowing avalanche, we explicitly assume that the temperatures of the flow and the snow cover is the same. This is clearly an assumption, which depends for example on the entrainment rate, but it is the best we can do.

Figure 2 gives an overview of how cold-to-warm transitions manifest ~~themself~~ themselves in an MTI image, in the mean velocity from Doppler radar and in a picture of the deposit structures. In the pictures, it is feasible to clearly define the deposits of the warm flow regimes (purple and magenta), while the lateral ~~extend~~ extent of the cold regimes (blue) can only be sketched. The outlines around regions of the flow regimes can also be extracted from the GEODAR and Doppler data (annotated with the same colors). Due to a smaller opening angle of the Doppler radar antenna, features on the far-right side of the track are not captured (dashed)~~, but this gives a sort of lateral resolution~~.

When the ~~deposits which reached the furthest runout distance~~ most distal deposits are cold, a partial transition ~~happend~~ happened higher up in the avalanche path and deposits of warm snow can be identified (#17-3030, top panels). In contrast, a complete transition happens when an initially cold avalanche starves and transforms into a warm avalanche (#13-3019, bottom panels). ~~Obviously, the velocity of both flow regime types is different.~~ While cold regimes are rather quick, warm flow regimes separate in range and time as they are much slower (Fig. 2). The timing when the avalanche reaches the ~~furthest~~ farthest runout distance is therefore different. The avalanche with complete transition (#13-3019) reaches the ~~furthest~~ farthest runout around $350\,s$ later than the avalanche with partial transition (#17-3030).

3.1 Example of a partial transition

The upper panel of Figure 2 shows avalanche #17-3030 as an example of a partial transition. This avalanche originated from the right hand side of the release area and followed the right couloir. The snow consisted of mainly freshly fallen cold snow and was for most of the avalanche track colder than $-1\,°C$ (upper panels of Fig. 1). The $-1\,°C$ line was estimated at $H_s = (1416 \pm 77)\,m\,a.s.l.$ ($\approx 200\,m$ range) ~~,~~ and thus close to the valley floor~~and the furthest runout~~. Avalanche #17-3030 was a typical powder snow avalanche for the Vallée de la Sionne path, with an intermittent regime at the front and followed by a slow moving dense tail (Sovilla et al., 2015). The geo-referenced picture on the top-right of Figure 2 was taken after $1.5\,days$ with intense snow fall. Still, the rough deposition patterns of the warm flow regimes can be easily identified, whereas the fine-grained deposits from the cold flow regimes were hidden under the new snow cover.

The GEODAR data are complemented by velocity data captured by the Doppler radar (top-middle in Fig. 2), which shows the mean velocity $\overline{V}(R,t)$ in a range-time plot, *i.e.* the expected value of the velocity distribution for every time t and range R (Eq. 2). Unfortunately, the start of the Doppler radar was delayed by $10\,s$, thus most of the front is missing, but the regions inside the avalanche where fast and slower flow regimes prevail can be clearly identified. Several fast surges are visible, and were characterized by a velocity of up to $30\,m\,s^{-1}$. These surges belonged to the cold regimes which can be identified on the basis of their starving stopping signatures. The ~~furthest~~ farthest point reached by the avalanche was the runout of the cold front at $R_C = 150\,m$ range (blue dot, Fig. 2, top), which corresponds to $P_c = 2600\,m$ path length. This avalanche had a cold-dominated runout.

Two slowly flowing tails followed after the front had passed and were characterized by a homogeneous velocity of $2\,m\,s^{-1}$ to $5\,m\,s^{-1}$. Both tails show the characteristic abrupt stopping signatures of warm snow. The transition into the magenta tail becomes visible in the MTI plot at the end of the steep couloir at a range $R_T = 950\,m$ (blue/magenta dot). Interestingly, the avalanche's flowing length started to increase already at a range of $1300\,m$, which suggests that a transition towards the warm and slower ~~regimes~~ regime may have started higher up. However, the warm tail continued to flow for another $250\,s$ until it finally stopped at $R_W = 550\,m$ range, corresponding to $P_w = 2140\,m$ path length. A warm tail like this one is characteristic for most of the powder snow avalanches observed in VdlS. Sometimes, an avalanche can have two of them flowing in both couloirs at the same time. In this case, the warm runout is defined by the tail which went farthest.

The tail at $400\,m$ to $600\,m$ range (outlined in dark purple, Fig. 2) is an unusual feature which we only observe in this data set. However, it enables an excellent opportunity to detail the formation of such a warm tail. It originated from entrainment of warm snow in the 20 degree slope of the runout area. Interestingly, the upper boundary of the entrainment corresponds to a rain limit at $1600\,m\,a.s.l.$ a few days before the avalanche. The liquid water ingress may have caused a weakening of the snow cover.

Figure 3 gives a detail of the transition leading towards this warm tail. In the right panels, the velocity distributions of the corresponding range gates R_{16}, R_{17} and R_{18} from the Doppler radar are shown. Three surges are visible in these range gates with high velocities at their fronts that ~~declines~~ decline towards their tails. ~~The Doppler data show that the velocity changed during the transition rather gradually from fast to slow.~~ For the first two fronts, the velocity distribution ~~stretches between~~

ranges from $10\,\text{m s}^{-1}$ to $30\,\text{m s}^{-1}$. The lower signal intensity at smaller velocities indicates that most of the snow moves fast. By comparison, the approach velocity of the front v_a extracted from the GEODAR data is around $25\,\text{m s}^{-1}$. The Doppler data show that the velocity during the transition changed rather rapidly from fast to slow inside one range gate. Along the three range gates, the first front continues with similar velocity distribution, but the second and third surge diminish. The third front

5 in R_{18} already contains low velocities at its beginning, possibly corresponding to the formation of the warm tail. The terminal velocity (later than $30\,\text{s}$) of the warm tail is characterised by a narrow velocity distribution as expected for a plug-flow regime in all three range gates.

3.2 Example of a complete transition

The lower panels of Figure 2 show the GEODAR data, Doppler data and a picture of avalanche #13-3019 as an example of

10 a complete cold-to-warm transition. The avalanche descended from the left hand side and followed the left couloir. The snow cover was ~~influenced~~ wetted by rain up to around $2000\,\text{m a.s.l.}$. The temperature pattern was highly dependent on the aspect (bottom left of Fig. 1), but the altitude $H_s = (1989 \pm 74)\,\text{m a.s.l.}$ ($\approx 1400\,\text{m range}$) ~~visually~~ summarizes the simulated snow cover reasonably well. Avalanche #13-3019 would normally be classified as a warm-wet event, since the deposit showed the typical rough and coarse-grained surface and levées could be identified. But the GEODAR data reveal that a complete flow

15 regime transition occurred at $R_T = 950\,\text{m}$ (magenta/blue dot, bottom left in Fig. 2).

Above the transition at R_T, two major surges can be identified with high velocities. The approach velocity v_a measured with GEODAR was $30\,\text{m s}^{-1}$ to $35\,\text{m s}^{-1}$, while the Doppler data showed ~~mean~~ material velocities of $50\,\text{m s}^{-1}$ to $60\,\text{m s}^{-1}$ ~~. This discrepancy corroborates~~ (Gauer et al., 2007). Such a velocity difference is usually found in the intermittent regime of the frontal region in powder snow avalanches (Sovilla et al., 2018), and corroborates on the turbulent character of both surges

20 ~~(Gauer et al., 2007)~~(Köhler et al., 2016). The first surge continued for another $100\,\text{m}$ after the transition point R_T, and finally starved at $R_C = 840\,\text{m}$ range (blue dot, Fig. 2, bottom), corresponding to $P_c = 1630\,\text{m}$ path length. Note, all avalanches with complete transition in the data set show for the cold front the starving stopping signature. The starving front is a primarily indicator for cold regimes, so that we clearly exclude any other flow regime transition such as warm shear to warm plug transition (Köhler et al., 2018). Therefore the path length of the cold regimes is always farther than the transition point.

25 Below the transition, the avalanche quickly decelerated and revealed the MTI signature of a warm plug regime – the parallel streaks are interpreted as the signature of large granules riding on a fairly stable surface of the flow due to a homogeneous velocity field (Köhler et al., 2018). The mean velocity decreased after the transition to around $3\,\text{m s}^{-1}$ to $5\,\text{m s}^{-1}$ and was very homogeneous in the full body of the avalanche (bottom-middle in Fig. 2). The warm flow regime continued to flow for another $300\,\text{s}$ before reaching the ~~furthest~~ farthest runout at $R_W = 200\,\text{m}$ range (magenta dot) and $P_w = 2370\,\text{m}$ path length.

30 This avalanche thus had a warm-dominated runout.

Figure 4 shows a zoom of the transition region as an MTI image (left) and distributions of the Doppler velocity in three range gates (right). In R_{18}, the front of the first surge showed low intensity for small velocities, but a broad spectrum of velocities between $20\,\text{m s}^{-1}$ to $70\,\text{m s}^{-1}$. The second surge was in general slower, and showed large intensities in a narrow and slow velocity band. The MTI image indicates that streak signatures (black) crossed the second surge and suggests that

11

the low velocities belonged originally to the first front. The duration of the high velocity region in each surge was rather short with $5\,\mathrm{s}$, compared to fully developed powder snow avalanches where this region can last up to $40\,\mathrm{s}$ (Steinkogler et al., 2014). However, the velocity distribution after the transition was narrow with the centre at low and constant velocity indicating a plug flow. Interestingly, the velocity distribution in the plug regime showed very little intensity for velocities between zero and

5   $2\text{–}3\,\mathrm{m\,s^{-1}}$, which indicated a very coherent movement of the avalanche (Fig. 4, Doppler data R_{17} and R_{18} at t $>50\,\mathrm{s}$).

The flow regime transition happened rather quickly in this avalanche ~~, occuring~~ as well as in the other avalanches with complete transition in our data set. The transition occurs within around $100\,\mathrm{m}$ travelled distance and over a period of less than $15\,\mathrm{s}$. Furthermore, the location of the transition seemed to have traveled uphill ($\dot{R}_T(t) > 0$) as the black lines in the left of Fig. 4 indicate. Note, no material is traveling upwards at the transition point, but the shock front of the deceleration is moving. This

10   may be caused by a piling up of incoming fast material on top of the ~~mass of~~ already decelerated material. Or, an alternative explanation could be that material flowing into the range gate later is already slower and therefore stops more easily at higher locations. However, a complicated model-based dynamic interpretation of the MTI plot and the Doppler data would be needed to decide between both possible interpretations.

As in avalanche #17-3030, the flowing length started to increase at a range of $1500\,\mathrm{m}$ (bottom-left Fig. 2), indicating a

15   separation of fast and slow material in direction of the flow. Faster and possibly cold material may have been concentrated towards the front, while slower and maybe warm material segregated towards the tail.

3.3   Snow cover influence on transition type

To differentiate between avalanches with partial and complete transitions, we quantify the degree of transition by defining the transition ~~factor~~ index

20
$$F_t = \frac{P_W - P_C}{\max(P_C, P_W)} \tag{5}$$

as the difference between the path length from cold (P_c) and warm (P_w) flow regimes divided by the total path length reached by the avalanche. For avalanches with a partial transition (*e.g.* Sec. 3.1), the transition ~~factor~~ index is negative and the runout is dominated by cold regimes. For events with $F_t \approx 0$ the cold regime and the warm regimes reach the same runout. For a positive transition ~~factor~~index, the runout is dominated by warm regimes, corresponding to avalanches with a complete transition (*e.g.*

25   Sec. 3.2). A value of ± 0.5 means that the dominant regime reaches twice as far as the other regime. The limits of F_t to both sides, *i.e.* $F_t = -1$ and $F_t = 1$, correspond to avalanche types made of purely cold regimes and purely warm regimes, respectively. The avalanches from the examples in Figure 2 have ~~a transition factor~~ transition indices of $F_t = -0.18$ (#17-3030) and $F_t = 0.31$ ~~for avalanche~~ (#13-3019). Note, we do not give an uncertainty of the transition index F_t explicitly in Table 1. However, an uncertainty of $50\,\mathrm{m}$ to $100\,\mathrm{m}$ in the path lengths P_c and P_w propagate into the transition index F_t as an uncertainty

30   of ± 0.05 to 0.1.

The transition ~~factor~~ index F_t together with the altitude H_s for all avalanches are shown in Figure 5. The 18 analysed avalanches cover F_t in the range between -0.5 and 0.4, and ~~all events are~~ the set of values is well distributed over this range. A linear regression gives $H_s(F_t) = (895 \pm 149) \cdot F_t + (1760 \pm 39)$ with a correlation coefficient of $r = 0.85$. For pure warm

avalanches ($F_t = 1$), the regression gives H_s at $2660\,\mathrm{m\,a.s.l.}$, which corresponds to the altitude of the release area. For pure cold avalanches ($F_t = -1$), the regression would give H_s at $860\,\mathrm{m\,a.s.l.}$ which is far below the runout area of Vallée de la Sionne at $1400\,\mathrm{m\,a.s.l.}$ ~~This may indicate~~ However, we do not think that the extrapolation towards purely cold avalanches ($F_t = -1$) has ~~limited~~ any validity in this setting.

5   Figure 6 compares the altitude H_s against the altitude H_t, that is where the snow cover changes from $-1\,°\mathrm{C}$ against where the transition occurs. We find the altitudes of the transitions H_t scatter on both sides of the 1:1-line (blue dashed); in other words, the transition can happen above or below the H_s-line. Furthermore, H_t can be up to $500\,\mathrm{m}$ in elevation away from H_s. The majority of the avalanches perform the transition above the H_s-line, *i.e.* avalanches with a partial transition (blue symbols). For these events we find that H_s lies below ~~$1700\,\mathrm{m\,a.s.l.}$~~ $1800\,\mathrm{m\,a.s.l.}$ and thus in the runout area. And for a few of them, the

10   H_s-line is even below the valley floor (below $1450\,\mathrm{m\,a.s.l.}$), which in turn means that it can practically not be reached and that entrainment of surface snow can not cause a partial transition.

The remaining avalanches perform the transition below the H_s, *i.e.* these events express either a complete transition and the warm regimes are dominant in the runout (red symbols), or cold and warm regimes reach similar runouts (white symbols). For these events we find that H_s is consequently higher than $1800\,\mathrm{m\,a.s.l.}$ which corresponds approximately to the altitude of the

15   middle of the avalanche path so that the entrainment of surface snow increases the avalanche temperature.

4   Discussion

4.1   Discussion of results

We find a continuous degree of transition between partial and complete flow regime transitions (Fig. 5). This continuous degree can be related to the altitude H_s, the altitude where the average modelled temperature of the ~~superficial~~ surficial snow layer

20   changes from below to above $-1\,°\mathrm{C}$. This means that, ~~for the VdlS avalanche path,~~ the flow regime type in the runout area — but not the runout distance itself — can be estimated when H_s is known.

This (semi-)quantitative attempt to capture an aspect of the flow regime transitions with a minimum number of observable quantities need further investigations to find out if the proposed linear fit or other relations are valid. Even if the linear fit appears to work at least for a certain range of F_t values, one still needs to find answers to the asymptotic behaviors when

25   F_t tends towards -1 or 1. Similar, we can not test the path dependency of our results since all our data are from the VdlS avalanche path. However, we think that at least the following three limitations are important to bear in mind for the discussion of the results.

– The transition index will probably be most useful for avalanches with drop heights of more than $500\,\mathrm{m}$. For smaller avalanches, H_s tends to be either above the release area or below the run-out area.

30   – While H_s can be determined wherever and whenever there is enough meteorological data for running snow-cover simulations, finding H_t for a given event requires either detailed investigation of the avalanche deposits or measurements with a GEODAR or Doppler radar.

Avalanches with a cold-dominated runout occur in Vallée de la Sionne when H_s is up to $300\,\mathrm{m}$ in elevation above the valley floor. The nomenclature of UNESCO (1981) would classify such an avalanche as "C1G7", with the code 7 meaning the

5   deposit consists of a mix of cold-dry and warm-wet snow. We find that the point H_t where the transition becomes visible lies exclusively above H_s for cold-dominated avalanches. Thus the transition cannot be caused by snow erosion from the surface, but entrainment of deeper ~~buried~~ and therefore warmer layer of the snow cover must be accounted for. Since the surface (*i.e.* new snow) is cold, a powder snow avalanche maintains its dynamics from surface entrainment, but later flowing parts like the denser core may eventually dig deeper into the snow cover, erode the warmer snow layers and develop a warm tail even above

10   H_s.

We observe that nearly every large powder snow avalanches in Vallée de la Sionne ~~results in~~ undergoes a partial transition. This suggests that large purely cold-dry powder snow avalanches are very rare. In all GEODAR data acquired over the last 7 years (140 in total with 20 powder snow avalanches), only one large powder snow avalanche (#15-0017, Köhler et al. (2016)) without a clear partial transition can be found. This avalanche was released shortly after avalanche #15-0016 ($F_t = -0.48$)

15   which had entrained and removed most of the snow in the track. Purely cold-dry avalanches do exist, but perhaps, only as long as they stay small and thus entrain only layers of cold snow close to the surface.

Warm-dominated avalanches are usually classified as wet avalanches, since such a description is mostly based on the deposit ~~structures~~texture. Our data show ~~,~~that initially cold-dry avalanches can ~~lead to complete~~ produce completely warm-wet deposits ($F_t > 0$). A special nomenclature for those avalanches does not exist or is not used consistently, even though the UNESCO

20   avalanche classification scheme allows for different wetness classes in the release and runout areas. An avalanche with a complete transition could be denoted as "C1G2" (UNESCO, 1981). The results in Figure 5 indicate that such avalanches occurred in VdlS when H_s is ~~higher~~ more than $500\,\mathrm{m}$ in altitude above the valley floor. We find that H_t, the point where the transition is initiated, is consequently $200\,\mathrm{m}$ to $300\,\mathrm{m}$ below H_s (Fig. 6). This indicates that entrainment of warm snow from the surface is most likely the cause for the transition, but also that a previously developed cold flow regime may be able to

25   overflow a surface of warm snow for about this distance. As soon as the transition towards warm regimes begins, it happens instantaneously and not gradually, *i.e.* in only $100\,\mathrm{m}$ and $15\,\mathrm{s}$ (Fig. 4).

Interestingly, the actual altitude of the transition H_t differs for events with partial and complete transitions (Fig. 6). All partial transitions in cold–dominated avalanches occurred in the elevation band between 1750 and $1850\,\mathrm{m\,a.s.l.}$, which corresponds to the altitude ~~of~~ at the end of the steep couloir. Complete transitions could occur even at lower elevations down to around

30   $1650\,\mathrm{m\,a.s.l.}$, which correspond to the ~~gentle~~ gently inclined runout area and even the altitude of the pylon. We think that the above mentioned change in the terrain does not necessarily cause the transition, but gentle terrain may favour the warm and presumably slower flowing snow to separate from fast cold regimes in flow direction. Such a separation can be observed at higher elevations where the flowing length starts to increase and the avalanche extends in range in the MTI plots (Fig. 2). This lengthening occurs most often above H_t and may indicate an earlier start of the transition and a separation of slower and faster

35   flowing regions.

Both transition types are relevant for the dynamics at the avalanche front and especially during deposition in the runout area. For partial transitions, the relevance is indirect as the runout is still cold-dominated, but the slow warm tail ~~is able to hold back mass~~ keeps mass away from the front and reduces the size of the cold flow regimes. For complete transitions the relevance is obvious, as the runout is warm-dominated even though a cold avalanche released. The time-scale when a warm-dominated avalanche reaches the runout is delayed by several hundreds of seconds due to slower velocities of the warm flow regimes (Figure 2). More ~~important~~importantly, the pressure exerted on structures in the runout depends strongly on the flow regime, and in general is a function of velocity, density and flow height together with a geometry factor (Sovilla et al., 2016). Cold–dominated flow regimes have a dominant velocity squared contribution and the hydrostatic term vanishes due to small densities. In contrast for warm flow regimes, the dynamic term can be neglected due to smaller velocities, but the large density increases the importance of the hydrostatic pressure contribution. Sovilla et al. (2016) presented an example which deviates from the cold or warm pressure scheme and both — dynamic and hydrostatic — contributions are found to be important. We can imagine that avalanches with a complete transition may generate similar high pressures during the transition process as result of remnant high velocities together with an increase in density. Such an argument seems to be different for avalanches with a partial transition. As mentioned above, the warm tail results most likely from deep entrainment by the dense core where the velocities are slower than at the front, so that the dynamic pressure contribution probably stays small.

Another important topic is the extent to which frictional heating due to dissipation processes during the avalanche descent may play a role ~~for~~ in flow regime transitions (Vera Valero et al., 2015). Frictional heating compared to a temperature increase due to entrainment was recently investigated experimentally on two medium sized purely cold avalanches by Steinkogler et al. (2015b). They concluded that frictional heating depends mainly on the effective height drop, but the contribution due to entrainment was found to be more variable and dependent on the erosion depth and snow temperature. Here, we cannot differentiate between both heating mechanisms on the basis of our data set. In fact, we include the frictional heating of the flowing snow as it affects P_w and P_c indirectly. However, the relation in Figure 5 indicates that indeed snow erosion and the temperature of the eroded snow have an important effect on the flow dynamics.

4.2 Limitations of methodology

Two limitations in regard to temperature exist in our methods. Throughout the whole study, we have assumed that the flowing snow temperature is similar to the snow cover temperature. This is a vague and untested assumption, and the effect depends possibly on the entrainment rate and the temperature difference between the flowing snow and the snow cover. This assumption does not affect the correlation between H_s and F_t observed in the data. However, it would be an important factor for a generalization of the presented empirical approach. Furthermore, the history of avalanche activity in the avalanche path can significantly alter the snow cover by entrainment and deposition (Steinkogler et al., 2014). The SNOWPACK model can account for this with ~~reinitialisation~~ reinitialization of the snow cover. But this can be only done for artificial avalanches where precise mass-balance measurements are available. Our approach disregards this fact. However, we are interested in the surface layers consisting of the recent new snow precipitation. The simulation of these new top layers is more dependent on the meteorological data than on the older snow layer underneath.

Also questionable appears the estimation of H_s by linear interpolation between two weather stations. We imply that the snow temperature changes only due to an altitude gradient, and this altitude gradient is found to be in the range of $100\,\mathrm{m\,°C^{-1}}$ to $400\,\mathrm{m\,°C^{-1}}$. The estimate of H_s could be improved with detailed analysis performed with distributed snow cover models like `Alpine3D`. Such analysis has been done by Steinkogler et al. (2014), but their result show small deviation from linear along the Vallée de la Sionne avalanche path. However, we wanted to use a simple parameterization for H_s. "Simple" means that H_s can be estimated from different data sources, *e.g.* field observations or regional snow reports, since for many avalanche paths and past events much less information about the snow cover characteristics is generally available.

The presented method is based on the temperature threshold of $-1\,°\mathrm{C}$ with respect to the uppermost $0.5\,\mathrm{m}$ of the snow cover. To validate this $-1\,°\mathrm{C}$ temperature threshold is not the scope of this study, but we have tested our method also for $-2\,°\mathrm{C}$ and $-0.5\,°\mathrm{C}$. The effect is a shift in the H_s altitude, *e.g.* in Figures 5 and 6. Our results indicate that $-1\,°\mathrm{C}$ is a reasonable value. For $-2\,°\mathrm{C}$ the partial (blue) and complete transitions (red) are not split anymore by the 1:1-line in Figure 6. And for $-0.5\,°\mathrm{C}$, the regression in Figure 5 predicts for pure warm avalanches ($F_t = 1$) only a H_s altitude of $2150\,\mathrm{m\,a.s.l.}$, which is clearly below the release areas so that regions with cold flow regimes are expected.

Another difficulty is how to generalize our results to other avalanche tracks since we have only investigated a single slope. We expect a path dependence of the correlation between snow cover and the transition index F_t. Vallée de la Sionne is known to be a relatively gentle avalanche path so that avalanches normally stop naturally in the runout area. But for steeper paths, *i.e.* $40°$ from top to bottom, we expect that more often both flow regimes may reach the valley floor. Our analysis should be extended to take into account other variables, such as volume or mass estimates and path geometry. To directly extend our method to other avalanche paths, regional snow and avalanche reports as well as path length estimation from world-wide available digital terrain models, may already be sufficiently accurate. As an example, the Moos avalanche from the introduction fits into the relation found for VdlS (star in Fig. 5 and 6), but noteworthy to say, the geometry of this avalanche path in terms of altitudes, slope and path length, is very similar to the VdlS.

5 Conclusions

GEODAR measurements have shown that flow regime transitions are common in large snow avalanches. One of these transitions occur between cold and warm snow when agglomeration of snow grains causes larger granules to form. In first order, this happens as soon as the flowing snow temperature changes from below to above $-1\,°\mathrm{C}$. Such a flow regime transition is very important for the dynamics of the avalanching snow, as the flow regime influences the flow mobility and the pressure exerted on structures in the path. However, we want to stress that the runout distance itself does not depend on the flow regime as cold and warm avalanches can reach unexpectedly long runouts.

We find two types of cold-to-warm flow regime transitions depending on whether parts or the complete avalanche changes the flow regime. A partial flow regime transition can occur at the tail and depends on the entrainment of deeply buried warm snow layers by the avalanche's dense core. In contrast, a complete flow regime transition can occur at the front due to the entrainment of warm snow at the surface. We find a continuous degree of transition between both types and a relation

between this and the snow cover temperature along the avalanche track. More specifically, the transition ~~factor~~ index F_t is linearly related to the altitude H_s where the average snow cover temperature in the uppermost $0.5\,\mathrm{m}$ changes between warm and cold at a threshold of $-1\,°\mathrm{C}$.

At Vallée de la Sionne, almost ~~every~~ all large powder snow avalanches exhibit a transition. ~~When~~ Given the choosen assumption of threshold temperature of $-1\,°\mathrm{C}$ measured in the uppermost $0.5\,\mathrm{m}$, we find when H_s is found no higher than $300\,\mathrm{m}$ above the valley floor, a partial transition ($F_t < 0$) is observed and results in a warm tail. For complete transitions ($F_t > 0$), the altitude H_s is located more than $500\,\mathrm{m}$ above the valley floor and results in only warm flow regimes in the runout area.

This work can be regarded as a ~~step towards the possibility to predict~~ first step in developing a method for predicting the dominant flow regime in the runout area — but not the runout length — based on knowledge of the snow cover temperature along the path. It is worth mentioning that meteorological and snow cover data from the release area are not representative for the avalanche dynamics in the runout area. Therefore, any hazard and risk evaluation should be made with additional information. Knowing the flow regime in the runout area may improve risk assessment, for example, the effectiveness of a dam may be evaluated in real-time. Nevertheless, the presented approach is strongly dependent on the track geometry and this requires care in adapting our results to other avalanche paths.

Compared to the complexity of temperature influence on avalanche dynamics, our presented method is rather simple. Effects such as frictional heating, temperature difference between entrained and flowing snow, entrainment depth and mixing and separation of snow at differently temperatures are important factors, and to identify their significance on the flow dynamics is a challenging task. We are convinced that future measurement procedures with laser-scans for mass balance, infrared radiation thermography in combination with temperature measurement during the passage of an avalanche, and manual or simulated snow profiles will be very useful to further understand the interplay between these factors. Finally, investigating flow regime transitions in greater detail may become important in respect to climate change. Less snow cover at lower altitudes, strong temperature gradients and quickly varying weather systems may lead to a snow cover situation favouring transitions in avalanches. Warm flow regimes may reach runout areas more frequently and thus require that hazard mitigation procedures ~~are~~ be adapted accordingly.

References

Ash, M., Brennan, P. V., Chetty, K., McElwaine, J. N., and Keylock, C. J.: FMCW Radar Imaging of Avalanche-like Snow Movements, in: Proceedings of the 2010 IEEE Radar Conf., pp. 102–107, IEEE, Arlington, Va., https://doi.org/10.1109/RADAR.2010.5494643, 2010.

Ash, M., Brennan, P. V., Keylock, C. J., Vriend, N. M., McElwaine, J. N., and Sovilla, B.: Two-Dimensional Radar Imaging of Flowing Avalanches, Cold Reg. Sci. Tech., 102, 41–51, https://doi.org/10.1016/j.coldregions.2014.02.004, 2014.

Bavay, M. and Egger, T.: MeteoIO 2.4.2: a preprocessing library for meteorological data, Geosci. Model Dev., 7, 3135–3151, https://doi.org/10.5194/gmd-7-3135-2014, 2014.

Dash, J. G., Rempel, A. W., and Wettlaufer, J. S.: The physics of premelted ice and its geophysical consequences, Rev. Mod. Phys., 78, 695–741, https://doi.org/10.1103/RevModPhys.78.695, 2006.

Dufour, F., Gruber, U., Bartelt, P., and Ammann, W.: Overview of the 1999 measurements at the SLF test site Vallée de la Sionne, in: International Snow Science Workshop, Big Sky–Montana, US, pp. 527–534, 2000.

Fischer, J.-T., Fromm, R., Gauer, P., and Sovilla, B.: Evaluation of probabilistic snow avalanche simulation ensembles with Doppler radar observations, Cold Reg. Sci. Tech., 97, 151–158, https://doi.org/10.1016/j.coldregions.2013.09.011, 2014.

Fischer, J.-T., Köhler, A., Kofler, A., Sovilla, B., and McElwaine, J.: Front and internal velocity distribution in powder snow avalanches, International Snow Science Workshop, Breckenridge, Colorado, 2016.

Gauer, P. and Issler, D.: Possible erosion mechanisms in snow avalanches, Ann. Glaciol., 38, 384–392, https://doi.org/10.3189/172756404781815068, 2004.

Gauer, P. and Kristensen, K.: Four decades of observations from NGI's full-scale avalanche test site Ryggfonn – Summary of experimental results, Cold Reg. Sci. Tech., 125, 162 – 176, https://doi.org/10.1016/j.coldregions.2016.02.009, 2016.

Gauer, P., Kern, M., Krister Kristensen and, Karstein Lied and, L. R., and Schreiber, H.: On pulsed Doppler radar measurements of avalanches and their implication to avalanche dynamics, Cold Reg. Sci. Tech., pp. 55–71, https://doi.org/10.1016/j.coldregions.2007.03.009, 2007.

Gauer, P., Issler, D., Lied, K., Kristensen, K., and Sandersen, F.: On snow avalanche flow regimes: Inferences from observations and measurements, International Snow Science Workshop, Whistler, Canada, pp. 717–723, 2008a.

Gauer, P., Lied, K., and Kristensen, K.: On avalanche measurements at the Norwegian full-scale test-site Ryggfonn, Cold Reg. Sci. Tech., 51, 138 – 155, https://doi.org/10.1016/j.coldregions.XXXXX, 2008b.

Huwald, H., Higgins, C. W., Boldi, M.-O., Bou-Zeid, E., Lehning, M., and Parlange, M. B.: Albedo effect on radiative errors in air temperature measurements, Water Resour. Res., 45, https://doi.org/10.1029/2008WR007600, w08431, 2009.

Issler, D.: Experimental Information on the Dynamics of Dry-Snow Avalanches, in: Dynamic Response of Granular and Porous Materials under Large and Catastrophic Deformations, edited by Hutter, K. and Kirchner, N., pp. 109–160, Springer, https://doi.org/10.1007/978-3-540-36565-5_4, 2003.

Jóhannesson, T., Gauer, P., Issler, P., Lied, K., Hákonardóttir, K. M., et al.: The design of avalanche protection dams: recent practical and theoretical developments, in: No. EUR 23339 in Climate Change and Natural Hazard Research Series 2, 978-92-79-08885-8, European Commission, 2009.

Köhler, A., McElwaine, J. N., Sovilla, B., Ash, M., and Brennan, P. V.: The dynamics of surges in the 3 February 2015 avalanches in Vallée de la Sionne, J. Geophys. Res., 121, 2192–2210, https://doi.org/10.1002/2016JF003887, 2016.

Köhler, A., McElwaine, J. N., and Sovilla, B.: GEODAR Data and the Flow Regimes of Snow Avalanches, J. Geophys. Res., 123, https://doi.org/10.1002/2017JF004375, 2018.

Lehning, M., Bartelt, P., Brown, B., and Fierz, C.: A physical SNOWPACK model for the Swiss avalanche warning Part III: meteorological forcing, thin layer formation and evaluation, Cold Reg. Sci. Tech., 35, 169–184, https://doi.org/10.1016/S0165-232X(02)00072-1, 2002.

Lehning, M., Völksch, I., Gustafsson, D., Nguyen, T. A., Stähli, M., and Zappa, M.: ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology, Hydrol. Process., 20, 2111–2128, https://doi.org/10.1002/hyp.6204, 2006.

5   McElwaine*, J. N., Köhler*, A., Sovilla, B., Ash, M., , and Brennan, P. V.: GEODAR data of snow avalanches at Vallée de la Sionne: Seasons 2010/11, 2011/12, 2012/13 & 2014/15 [Data set], Zenodo, https://doi.org/10.5281/zenodo.1042108, *equally contributing authors, 2017.

Naaim, M., Durand, Y., Eckert, N., and Chambon, G.: Dense avalanche friction coefficients: influence of physical properties of snow, J. Glaciol., 59, 771–782, https://doi.org/10.3189/2013JoG12J205, 2013.

Schlögl, S., Marty, C., Bavay, M., and Lehning, M.: Sensitivity of Alpine3D modeled snow cover to modifications in DEM resolution, station
10   coverage and meteorological input quantities, Environ. Model. Softw., 83, 387 – 396, https://doi.org/10.1016/j.envsoft.2016.02.017, 2016.

Schmucki, E., Marty, C., Fierz, C., and Lehning, M.: Evaluation of modelled snow depth and snow water equivalent at three contrasting sites in Switzerland using SNOWPACK simulations driven by different meteorological data input, Cold Reg. Sci. Tech., 99, 27 – 37, https://doi.org/10.1016/j.coldregions.2013.12.004, 2014.

Schreiber, H., Randeu, W. L., Schaffhauser, H., and Rammer, L.: Avalanche dynamics measurement by pulsed Doppler radar, Ann. Glaciol.,
15   32, 275–280, https://doi.org/10.3189/172756401781819021, 2001.

Schweizer, J., Bartelt, P., and van Herwijnen, A.: Snow Avalanches - Chapter 12, in: Snow and Ice-Related Hazards, Risks and Disasters, edited by Shroder, J. F., Haeberli, W., and Whiteman, C., pp. 395 – 436, Academic Press, Boston, https://doi.org/10.1016/B978-0-12-394849-6.00012-3, 2015.

Sovilla, B., Burlando, P., and Bartelt, P.: Field experiments and numerical modeling of mass entrainment in snow avalanches, J. Geophys.
20   Res., 111, F03007, https://doi.org/10.1029/2005JF000391, 2006.

Sovilla, B., McElwaine, J., Steinkogler, W., Hiller, M., Dufour, F., Suriñach, E., Guillen, C. P., Fischer, J.-T., Thibert, E., and Baroudi, D.: The full-scale avalanche dynamics test site Vallée de la Sionne, International Snow Science Workshop, Grenoble–Chamonix, France, pp. 1350–1357, 2013.

Sovilla, B., McElwaine, J. N., and Louge, M. Y.: The structure of powder snow avalanches, C. R. Phys., 16, 97–104,
25   https://doi.org/10.1016/j.crhy.2014.11.005, 2015.

Sovilla, B., Faug, T., Köhler, A., Baroudi, D., Fischer, J.-T., and Thibert, E.: Gravitational wet avalanche pressure on pylon-like structures, Cold Reg. Sci. Tech., 126, 66–75, https://doi.org/10.1016/j.coldregions.2016.03.002, 2016.

Sovilla, B., , McElwaine, J. N., and Köhler, A.: The intermittency region of powder snow avalanches, J. Geophys. Res., https://doi.org/10.1002/2018JF00xxxx, 2018.

30   Steinkogler, W., Sovilla, B., and Lehning, M.: Influence of snow cover properties on avalanche dynamics, Cold Reg. Sci. Tech., 97, 121–131, https://doi.org/10.1016/j.coldregions.2013.10.002, 2014.

Steinkogler, W., Gaume, J., Löwe, H., Sovilla, B., and Lehning, M.: Granulation of snow: From tumbler experiments to discrete element simulations, J. Geophys. Res., 120, 1107–1126, https://doi.org/10.1002/2014JF003294, 2015a.

Steinkogler, W., Sovilla, B., and Lehning, M.: Thermal energy in dry snow avalanches, Cryosphere, 9, 1819–1830, https://doi.org/10.5194/tc-
35   9-1819-2015, 2015b.

Turnbull, B.: Scaling Laws for Melting Ice Avalanches, Phys. Rev. Lett., 107, 258 001, https://doi.org/10.1103/PhysRevLett.107.258001, 2011.

UNESCO: Avalanche atlas: Illustrated international avalanche classification, Tech. rep., International Commission on Snow and Ice, UNESCO, Paris, http://unesdoc.unesco.org/Ulis/cgi-bin/ulis.pl?catno=48004&gp=1&lin=1&ll=1, 1981.

Vera Valero, C., Wikstroem Jones, K., Bühler, Y., and Bartelt, P.: Release temperature, snow-cover entrainment and the thermal flow regime of snow avalanches, J. Glaciol., 61, 173–184, https://doi.org/10.3189/2015JoG14J117, 2015.

5 Vriend, N. M., McElwaine, J. N., Sovilla, B., Keylock, C. J., Ash, M., and Brennan, P. V.: High-resolution Radar Measurements of Snow Avalanches, Geophys. Res. Lett., 40, 727–731, https://doi.org/10.1002/grl.50134, 2013.

Würzer, S., Wever, N., Juras, R., Lehning, M., and Jonas, T.: Modelling liquid water transport in snow under rain-on-snow conditions - considering preferential flow, Hydrol. Earth Syst. Sci., 21, 1741–1756, https://doi.org/10.5194/hess-21-1741-2017, 2017.
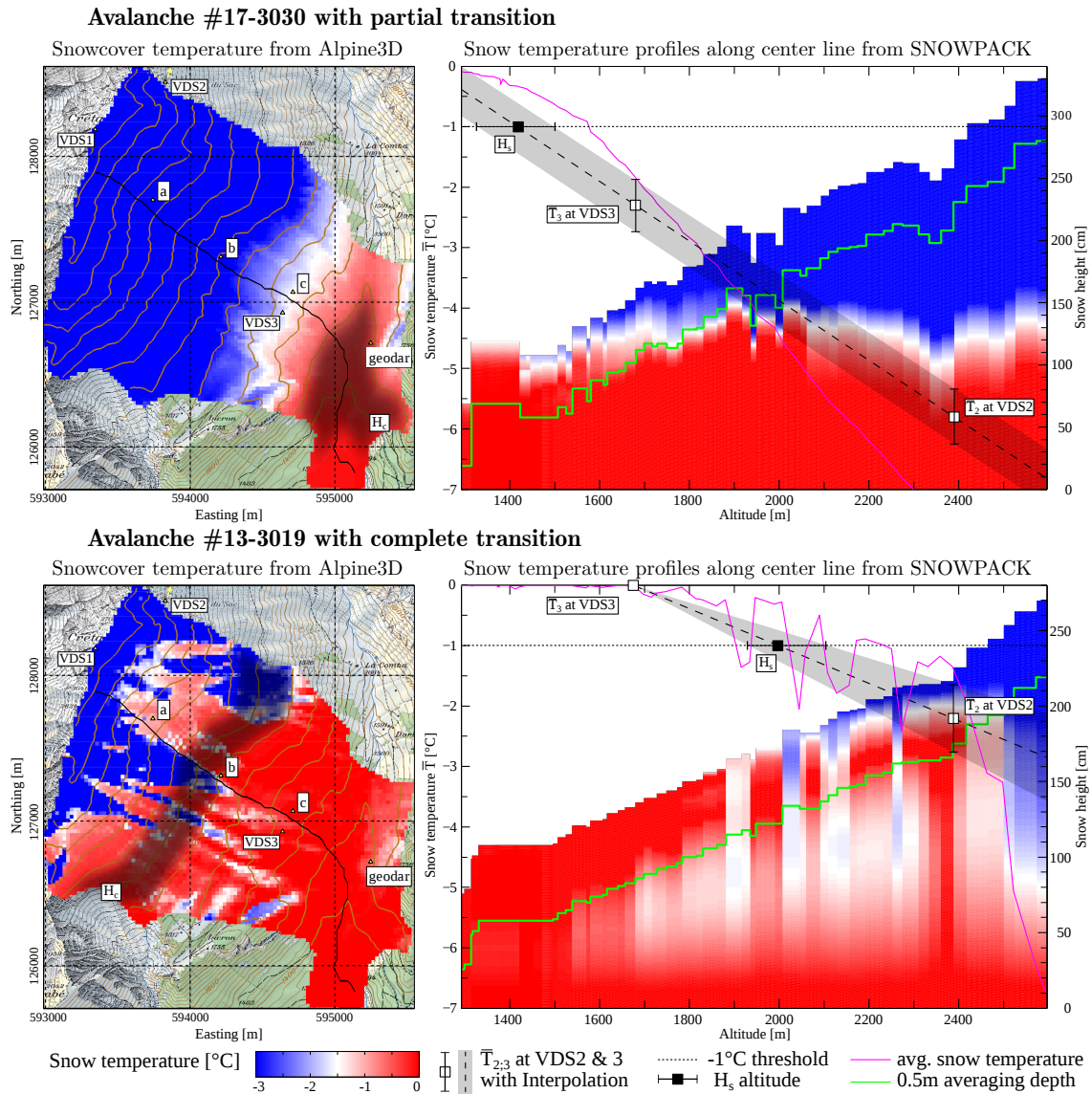
Figure 1. Snow cover simulations for avalanche #17-3030 with partial transition (top) and #13-3019 with complete transition (bottom). The left panels show the averaged temperatures $\overline{T}$ values of the uppermost 0.5 m snow cover from `Alpine3D` gridded over the VdlS catchment. The area overlay in grey denotes $H_s \pm \triangle H_s$. For reference, the location of the pylon (c) and profiling radars (a, b) are show shown. The black line indicates right panels show the snow temperature profiles along the path of steepest descent where the vertical temperature transect (black line in the right left panels are evaluated). The purple curve indicate indicates the average temperature $\overline{T}$ of the top 0.5 m of each vertical profile. $\overline{T}$ at the top and bottom weather station are shown with white squares together with the standard deviation as error temperature variations. H_s is calculated using linear interpolation between the weather stations and is as the intercept of grey area with $-1\,°C$ and shown with black squares.
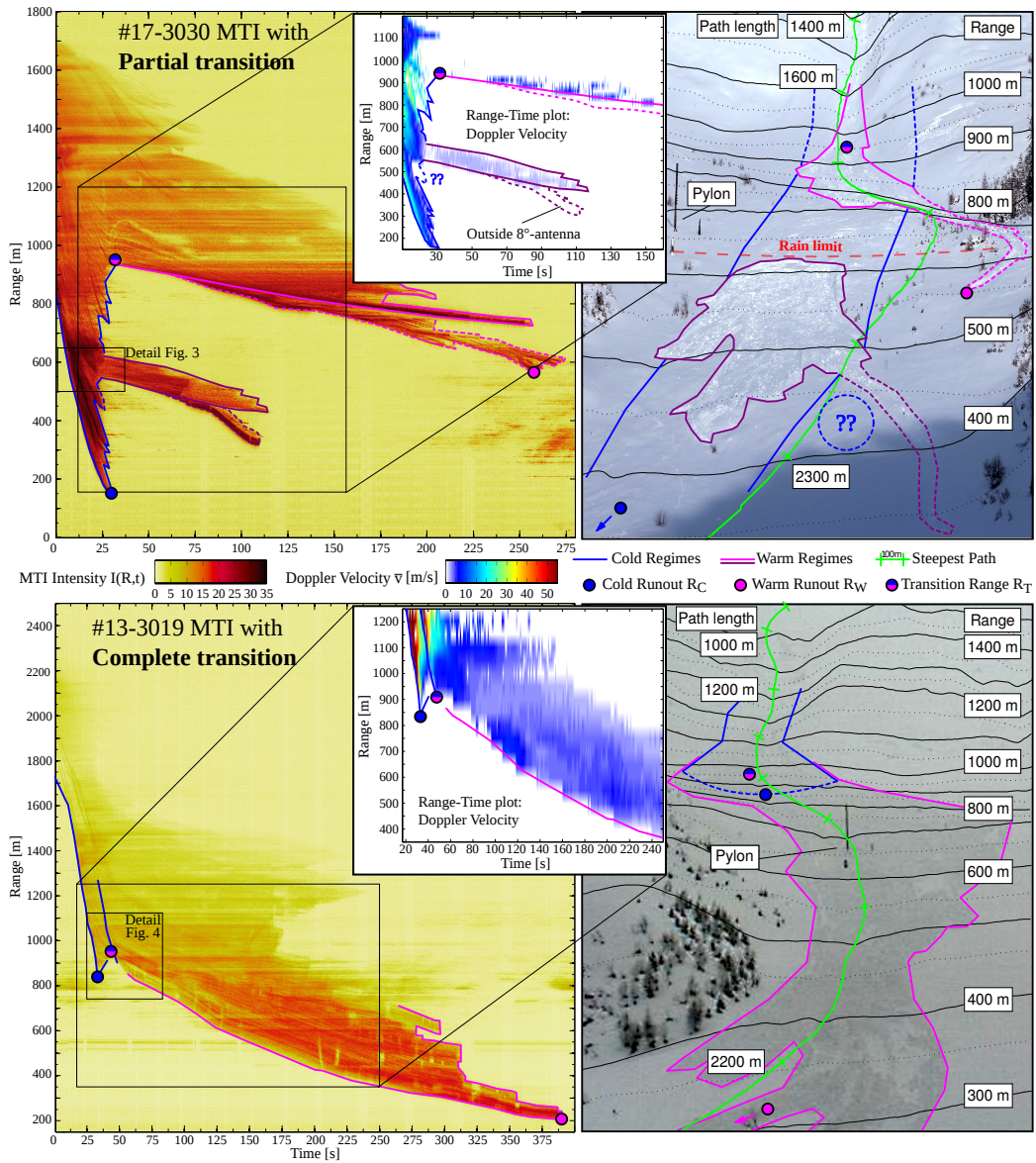
Figure 2. Avalanche examples for a partial (top) and a complete (bottom) cold-to-warm transition. The avalanches are visualized by means of GEODAR data (left), mean Doppler velocities $\overline{v}_k(t)$ (middle) and geo-referenced pictures of the deposits (right). Flow features extracted from GEODAR are highlighted in the other panels. The warm regimes are identified by typical coarse-grained and rough deposits (purple and magenta), while the fine-grained and smooth cold deposits can only be sketched (blue). The path along the steepest descent is drawn in green. The cold and warm runout distances and the transition point are indicated with coloured dots.
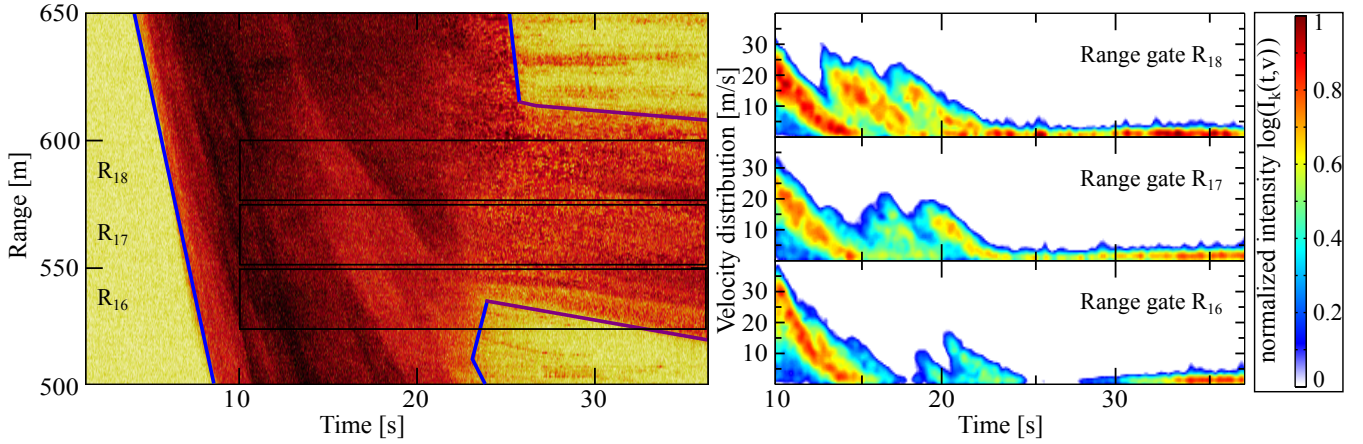
Figure 3. Detail of a partial transition from avalanche #17-3030 from the top panels of Figure 2. Left: Zoomed MTI plot with location of Doppler range gates. Right panels: Doppler velocity distribution in the ranges gates R_{16} (525–550 m), R_{17} (550–575 m) and R_{18} (575–600 m).
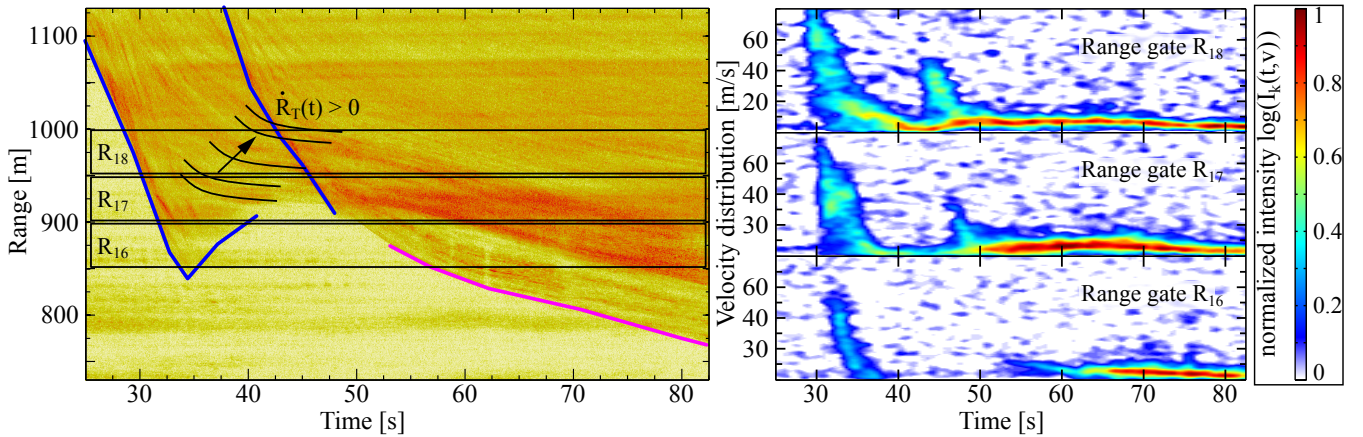

Figure 4. Detail of complete transition from bottom panels of Figure 2. Left: MTI with location of Doppler range gates. The location of transition R_T is not fixed, but moves upward with time $\dot{R}_T(t) > 0$. Right panels: Doppler velocity distribution in range gates R_{16} (850–900 m), R_{17} (900–950 m) and R_{18} (950–1000 m).
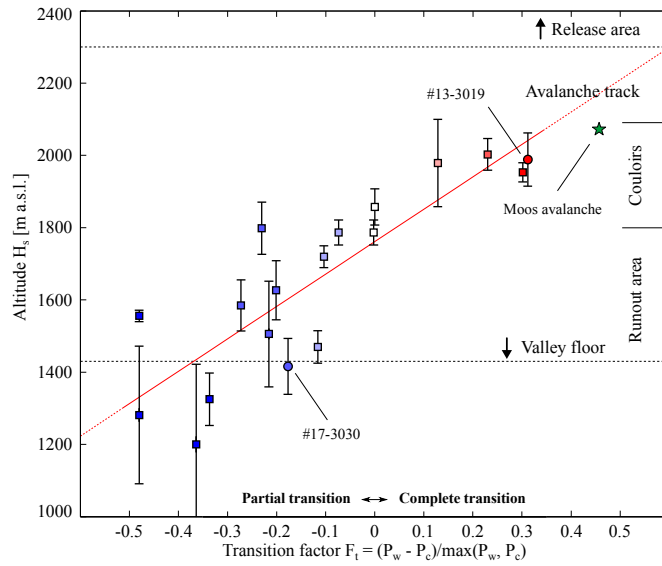
Figure 5. Transition ~~factor~~ index F_t as a function of H_s with a linear regression in red. The transition index F_t has an uncertainty of ± 0.05 to 0.1. Green star belongs to the Moos avalanche mentioned in the introduction. Horizontal dashed lines and annotation on the right side characterizes roughly the VdlS terrain.
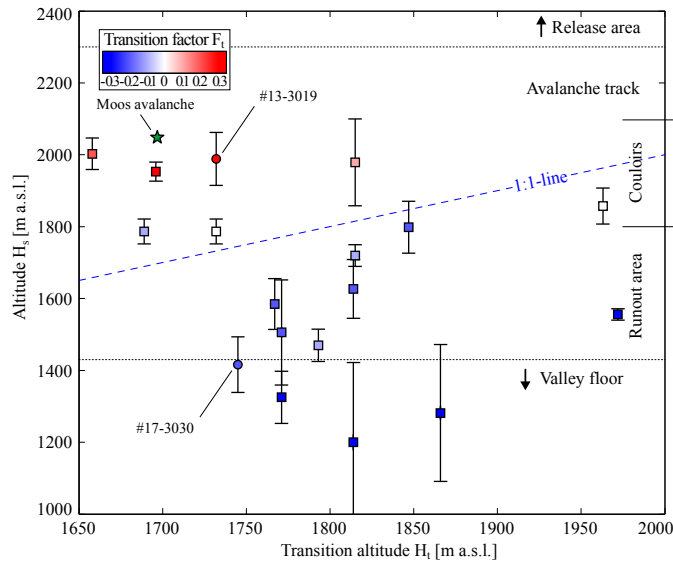

Figure 6. Altitude of transition, H_t, against the altitude of the $-1\,°\mathrm{C}$ —line, H_s. The 1:1–line (dashed blue) divides the avalanches into cases where the transition ~~happen~~ occurs above or below the H_s-line. Horizontal dashed lines and annotation on the right side ~~characterizes~~ characterize roughly the VdlS terrain. The colour indicate the transition ~~factor~~ index from Figure 5.