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The Cryosphere

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WSL Institute for Snow and Avalanche Research SLF

Submission of revised manuscript

Dear Editors,

we would like to submit the revised manuscript entitled

"Temporal evolution of crack propagation propensity in snow in relation to slab and weak layer properties"

by Schweizer, Reuter, van Herwijnen, Richter and Gaume.

We thank the reviewers for the helpful comments, which we have all considered while preparing the revised manuscript.
The major changes we made are as follows.

1. We now provide substantially more details on the various Methods. Furthermore, we now use the adjusted mechanical energy as described by van Herwjinen et al. (2016); due to this change we had to re-do the entire PTV and SMP analysis.
2. We now discuss the results more in depth; the Discussion section is much expanded.
3. We have thoroughly revised the manuscript with regard to wording and terminology.
4. We now provide additional profile data in the Supplementary Material and added a new figure.

With these significant changes we hope that our manuscript now meets the quality standards required for publication in The Cryosphere.

Best regards,
Jürg Schweizer
(on behalf of all authors)

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Reply to Referee #1

We thank referee #1 for the thorough review. The comments were very helpful for preparing the revised manuscript. In the following, we reply to the comments in detail and describe the changes we made in the revised manuscript.

SUMMARY:
The authors monitored the temporal evolution of a weak layer-slab system during winter 2014-2015 in a field site located next to Davos. Typically, each week between 6 January 2015 and 3 March 2015 (8 days of measurements), they performed on the same site located next to an automatic weather station:

- *three propagation saw test (PST) on which they measured the critical crack length, the full or partial crack propagation and the slab displacement field (PIV measurements),*
- *around five SMP profiles,*
- *a classical manual snow profile with a density profile*
- *CT/ECT tests.*

The authors try to explain the observed temporal evolution of the PST critical crack length (general increase with a minimum the 28 January) by investigating the evolution of individual mechanical parameters of the weak layer and slab, namely the load on the weak layer, the weak layer fracture energy and the so-called bulk elastic modulus; and their interaction through the anti-crack model. They used previously developed methods to access these parameters from the measured data. They also used the SNOWPACK model to compute the critical length from the simulated snow profile with meteorological forcings from the automatic weather station. The authors show that monitoring the evolution of individual parameters cannot explain the observed critical crack length trend but that it is necessary to account for the complex interaction between these mechanical variables. The SMP metric is not able to reproduce the observed critical crack length. The SNOWPACK metric shows also an increase of the critical crack length.

GENERAL COMMENTS
The dataset collected by the authors is very interesting combining quantitative stability analysis (PST critical crack length) and highly resolved vertical hardness profile (SMP). Some of the results are of clear interest to the snow and avalanche community: the authors showed that both slab properties and weak layer cannot be individually monitored to understand the crack propagation propensity evolution; they also show that the previously developed SMP stability metric is not capable of capturing the evolution of the critical crack length. However, the methods are not well presented and appear as a black boxes where explanations on the basic assumptions are missing and the methods are mixed without an apparent logic. In particular, the SMP stability metric presentation is not clear in this form. Evaluating the stability metric of SNOWPACK from a modeled snow profile without showing that the modeled snowpack profile has something in common with the observations is not informative. The sensitivity analysis on a three parameters analytic function is based on four single cases. The trend analysis gives too much importance to a single day case that might be not statistically representative. Therefore, I recommend major revisions before publication.

- We agree that our description of the methods was minimal mainly referring to previous work. We changed this approach and now provide more details on each of the methods we use.
- We now provide information on the SNOWPACK simulations so that the reader can assess whether the simulated stratigraphy has something in common with the observations (see below).
- What we called sensitivity analysis should be considered as examples of how the critical cut length changes as a function of time for various scenarios of temporal evolution.

Hence, this paragraph was meant to illustrate how the various parameters interact. We changed the title to «Case studies» as it is obviously not a sensitivity analysis.

- With regard to the temporal evolution and the observed minimal values towards the end of January, we now discuss the representativity more thoroughly. We would like to point out that minimal values obtained with snow instability tests are in general more trustworthy. In the case of the propagation saw test, any measurement and observation errors increase the cut length. Low values of the cut length therefore almost always represent the real conditions.

MAJOR COMMENTS:

1) The dataset collected by the authors is very valuable. Indeed, the authors present it as the first comprehensive time series of a weak layer, slab system. It uses state-of-the-art measuring techniques (SMP, PST) combined with "traditional" measurements (manual stratigraphy and density, CT/ECT). Since one of the objective and strength of the paper is this dataset, it appears logical to provide this dataset as supplementary files (Caaml file for stratigraphy, stability tests, text file for SMP and avi file for PST videos).

We now provide the manual profiles as well as the SMP profile performed at the profile location for each day as Supplementary Material.
Providing further data is not straightforward. We are not dealing with 'simple' weather data, but with data from various sources (SMP, PTV, SNOWPACK, manual snow profiles), which then have to be processed to get to the results. Furthermore, the processing is not trivial.
In addition, we included a figure (new Figure 1) to the main text showing the SNOWPACK simulation (see below), and the manual snow profile as well as the SMP profile for one specific date (28 January 2015).
And of course, we will provide the data on request to others who like to collaborate.

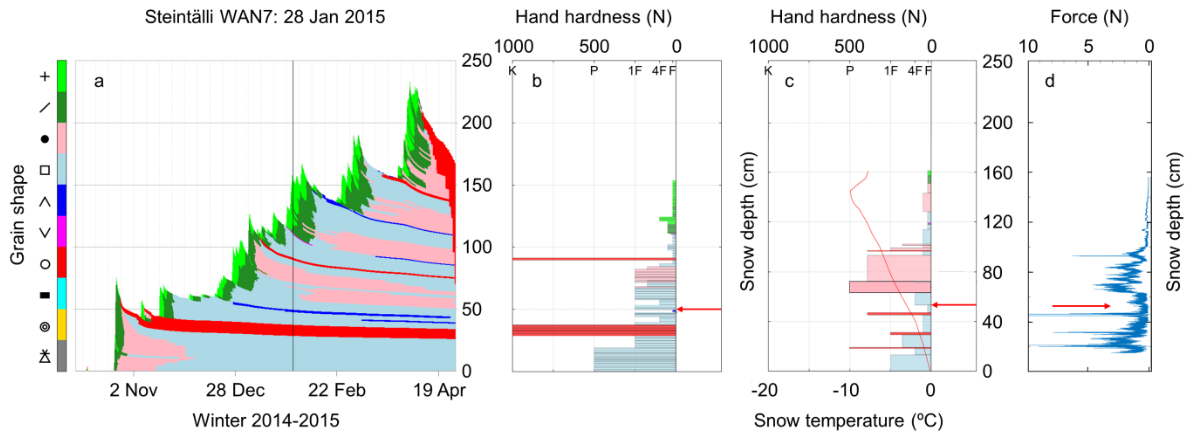

Figure: (a) SNOWPACK simulation for the location of the automatic weather station (AWS) WAN7 for winter 2014-2015 showing the evolution of grain shape, black vertical line indicates date of snow profile (28 Jan 2015), (b) simulated snow profile for 28 Jan 2015, (c) manually observed snow profile at the location of the AWS on 28 Jan 2015, (d) corresponding SMP penetration force signal measured at the location of the manual profile. Red arrows point to the weak layer.

2) The writing style on the mechanical background is often unscientific and requires precision and consistency. I have listed some of these problems:

- *about the elastic modulus. You used the following terms without proper definition:"elastic modulus", "bulk modulus", "modulus", "effective modulus", "bulk effective modulus", "mi-*

cro-mechanical modulus", "slab modulus", "stiffness", "elastic modulus with non-elastic parts of deformation". This vocabulary is misleading and is not suited for a scientific paper, where the mechanical concepts behind the used model should be precisely presented, which can be done in a simple way accessible to the snow community.

We carefully revised the manuscript to increase precision and consistency.
For example, we now consistently use the term «effective elastic modulus», and no longer use the terms «stiffness» and «bulk modulus». However, we still frequently use «modulus» or «slab modulus» when we refer to the elastic properties (of the slab) in general.

We acknowledge that the vocabulary on the deformation behavior of the slab was hard to follow. Part of the problem arises from the fact that model assumptions, e.g. linear elasticity, do not fit what is actually observed and can be measured in the field; in addition, the slab is layered and not uniform. Therefore, there is some need for specific terms and it is not sufficient to just talk about the modulus. For example, the modelling approach by Heierli et al. (2008) includes the elastic modulus (Young's modulus), what we measure with PTV is an effective bulk modulus (bulk because layering is disregarded, effective because it includes not only purely elastic parts of deformation), what is derived from the SMP is the micro-mechanical modulus. Nevertheless, as pointed out above, we now consistently use the term «effective elastic modulus» whenever feasible.

- *you use the terms "propagation propensity", "propagation criterion r_c_SMP" ,"critical crack length", "propagation propensity metric", "crack propagation propensity" to refer to the same parameter r_c, or maybe not but this is not clear. Why don't you use consistently the well-defined "critical crack length" and explain only in the introduction that the critical crack length is an indicator of the more general concept of crack propagation propensity?*
- *"initiation probability", "initiation propensity", "initiation criterion", "initiation indices", "skier stability index" ...*
- *delete vague and unspecific claims "reliable", "reliable in general", "distinct pattern", "relevant mechanical properties", "other mechanical properties"*

We thoroughly went through the manuscript and removed redundant or confusing terms, in particular in connection with failure initiation and crack propagation. However, as we present measured as well as modelled values there is some need for distinction between the various measures.
In addition, we now provide definitions of crack propagation propensity and snow instability (page 3, lines 19-27).
Moreover, we thoroughly went through the manuscript and removed vague and unspecific terms such as distinct.

3) It is hard to follow the history of the weak layer-slab system. It is necessary to add a one-page figure with eight sub-figures (one for each day of measurements) showing the manual stratigraphy (at least snow type and density), a SMP profile and the position of the weak layer.

We now provide a figure (new Figure 1 in the revised manuscript, see above) showing the SNOWPACK simulation as well as modelled and observed profiles for 28 January 2015 (see above). In addition, we provide all the manually observed profiles including an SMP profile in the Supplementary Material.

*4) In Heierli's model, the total mechanical energy of a PST crack of length r is composed of two terms: V(r) = w_f * r + Vm(r) where w_f * r is the weak layer fracture energy and Vm(r)*

accounts for elastic deformation energy and changes in gravity potential energy of the slab. In case of a uniform slab, Vm(r) can be computed analytically knowing the density, thickness and elastic modulus of the slab. In case of a FE model of a multilayer slab (density, thickness and elastic modulus per layer known), Vm(r) can be calculated numerically. This is done for the SMP analysis. In case of a measured displacement/deformation field of the PST tests, Vm(r) can also be calculated.
This is done in the PST analysis. In both cases (SMP, PST method), the calculated Vm(r) is used to fit the analytic mono-layer solution. The fitted analytic solution is then differentiated to obtain the critical crack length knowing the weak layer fracture energy (SMP method) or the weak layer fracture energy knowing the critical crack length(PST method). I don't understand why the dVm(r)/dr is not computed directly from the calculated Vm(r)(or with smoothing of Vm(r)). This is not explained in the proposed references (Reuter et al, 2015 or van Herwijnen and Heierli, 2010). The bulk elastic modulus is a fitting parameter and it is unclear how physically-relevant it is. There is no clear reason why Vm(r) on layered material should fit directly the mono-layer analytic solution. Provide a proper explanation and discussion on that. Moreover, recall the main hypothesis (elastic linear, only the slab contributes to deformation energy) of Heierli's model.

We now provide more details in the Methods section and also refer to the recent paper by van Herwijnen et al. (2016) where the PTV method is explained in detail. We reanalyzed all data and now use their refined approach, i.e. the adjusted mechanical energy to account for differences between the model of Heierli et al. (2008) and the FE simulations.
Taking the derivative of the raw data to derive w_f would not work, as there is too much scatter and this would result in very unreliable values of w_f.
We agree that the critical cut length can be computed with the FE model using the SMP slab properties and the SMP-derived specific fracture energy w_f, but would require an iterative approach to find r_c.

5) Section 2.4 describing the SMP signal processing is vague and unscientific. Many critical details are missing. It does not allow the reader to reproduce the presented method and appears as a black box. It requires a deep rewriting. It mixes method using different concepts that measures the same things differently e.g. Johnson and Schneebeli (1999) and shot-noise model used by Proksch, 2015. The window size for analysis, the SMP version, the adjustment parameters of (Proksch et al, 2015, calculated on a few alpine snow samples), the finite element layer mesh, etc. are missing.
There is additional linear scaling with no convincing explanation. The calculation of layer Young's modulus from SMP elementary failure element is known to be poor and is inconsistent with the one based on density (Scapozza, 2004) used by the snow cover modeling (p5 l30). The failure initiation criterion S is not detailed and it is hard to notice that it does not incorporate snow load in comparison to SK38 which does, ... The reference to other papers is far from being sufficient and clear explanations won't take more than 30 lines.

As mentioned above we now provide more details in general and in particular on the methods and not simply refer to previous work.
The additional linear scaling is simply introduced to obtain SMP-derived values that are comparable to other macroscopic mechanical properties since the raw processed data only represent microscopic values not directly related to common material properties.
In the absence of a sound calibration of the SMP-derived microstructural properties scaling with the PTV-derived values represents a reasonable alternative. This is now more clearly described and discussed (page 7, lines 17-22; page 16, lines 6-11).
Furthermore, it is clear that SMP-derived values have some deficiencies, see Reuter et al. (2013). We now discuss this more thoroughly in the revised manuscript (page 15, lines 31-33; page 16, lines 1-5). In addition, we included an alternative approach for determining the

effective elastic modulus by using the SMP-derived density and the density-modulus relation reported by Scapozza (2004) (page 7, lines 23-26).

6) The authors used the snow cover model forced by a nearby automatic weather station as an input of a new critical crack length estimator (Gaume et al. 2014a, 2016). Without any clue on how close the snowpack simulation to the observed snowpack, it is impossible to exploit the results of this analysis. It is well-known that one point evaluation of a snow cover model on stability criterion is difficult. Note that the only variables missing in Eq. (1) is the weak layer strength that could be fitted to get r_c_snp = r_c_obs, similarly to what is done for the PST.

Additionally, it is not clear to me how the avalanche activity index (concerning the area all around Davos?) can help to analyze the measurement done in this particular site.

The SNOWPACK simulation reproduced the snow stratigraphy reasonably well – with the notable exception that the melt-freeze crust (resulting from a high-elevation rain event) below the weak layer was not simulated. We now provide the simulated stratigraphy (new Figure 1 in the revised manuscript; see above).
We certainly agree that stability predictions from simulated snow stratigraphy are challenging. We strongly believe that these stability predictions should be validated at locations of automatic weather stations.
With regard to the comment on Eq. (1), we agree that the only missing variable is the weak layer strength, however, we are not sure we understand the reviewer's point. The shear strength cannot be determined form the measured critical cut length, otherwise the model would no longer be predictive. The shear strength is obtained from the parametrization implemented in the snow cover model SNOWPACK based on the work of Jamieson and Johnston (2001).
As we perform our measurements in a representative study plot commonly used in operational forecasting to extrapolate to the surrounding terrain (e.g., Gauthier et al., 2010; Jamieson et al., 2007), we added the avalanche activity data for comparison with the local stability evaluations. This is not better motivated (page 9, lines 20-22).

7) The pattern of the PST critical crack length is a general increase with a local minimum for one measurement day (28 January). As discussed (p6 l20-23, p10 l3-6), the spatial variability can significantly affect the stability even a few meters away. Given the poor representativity of one day of measurement to define a trend, and potential spatial variability, it would be reasonable when speaking of trend to not focus on the minimum observed the 28 January but on the general trend (continuous increase ofr_c). Note that this does not challenge the fact that the SMP should reproduce the same trend (since measured a few cm away from the PST); but the comparison with SNOWPACK is challenged. The explanations "we deem it unlikely that the observed pattern is entirely the result of spatial variability and does not reflect the temporal evolution", "Previous studies performed in level study plots have shown that measurements in general are reliable and that the effect of spatial variations is relatively small" are not convincing, at least in this form.

We re-considered the local minimum that we observed at the end of January 2015. In fact, low critical cut lengths were not only observed on 28 January but also on 5 February. On 5 February there are only two measurements with a large difference between them. However, low critical cut lengths are in general more trustworthy than high ones, if they concurrently occur, since any error while performing the test will increase the cut length. Furthermore, on 28 January 2015, for the first time, all cracks propagated to the end of the PST column indicating that the crack propagation propensity had increased. Finally, the additional loading towards the end of January 2015 resulted in many avalanches and shooting cracks were

frequently observed also indicating increased propagation propensity. We re-assessed the issue of measurement accuracy and spatial variability, reworded the corresponding statements (page 14, lines 11-33).
The sentence "*Previous studies performed in level study plots have shown that measurements in general are reliable and that the effect of spatial variations is relatively small"* is supported by two references to previous work just following this sentence (page 14, lines 27-30).

8) The sensitivity analysis is poor and based on four different cases. To my opinion, this cannot be called a sensitivity analysis. Differentiating Eq. (2) with respect to E, sigma and wf provides a way to perform this sensitivity analysis properly.
Note that the general comments are general and require re-wording of several parts of the paper and additional explanations, and not only taking into account specific minor points listed below.

The purpose of this paragraph is to illustrate how changes of the modulus, the load and the specific fracture energy with time will affect the temporal evolution of the critical cut length. We no longer call this a sensitivity study, but selected a more appropriate title for the paragraph: «Case studies».
We agree, that differentiating Eq. (2) with respect to E, σ and w_f would reveal the dependence of the critical cut length for a single parameter. However, these dependencies, considered independently are obvious: the cut length decreases with increasing load, and increases with increasing slab modulus and weak layer fracture energy. However, their interplay in course of time cannot easily be assessed – and the four examples we provide simply show that entirely different evolutions are possible.

MINOR COMMENTS:

abstract: the following terms are too vague : "distinct pattern", "other mechanical properties" "some of the relevant mechanical properties"

We removed "distinct" throughout the manuscript, and clarified the terms: *" … by simply monitoring mechanical properties such as slab load, slab modulus or weak layer specific fracture energy."*

p1 l25: "how much stress due to a skier is transferred". Misleading sentence. All the stress is transferred to the ground. But it is distributed on a larger surface. Reword.

We reworded the sentence: *"… the slab layers determine the magnitude of the stress due to a skier at the depth of the weak layer"* (page 1, line 29).

p1 l28: "with respect to the weak layer, a snowpack a weakness is" -> "the weak layer is"

We reworded the sentence as suggested (page 2, line 2).

p2 l2: "conceptual model". Describe this model in a few words.

We added a sentence describing the effect of slab thickness (or weak layer depth): *"With increasing slab depth conditions for failure initiation become less favourable whereas conditions for crack propagation become more favourable."* (page 2, lines 10-11).

p2 l7: "though the strengthening may lag behind the loading". Sound unscientific. Delete.

We reworded to: *"… the strength increase may lag behind the loading during a snowfall."* (page 2, line 15).

p2, l27: References to the model Surfex-Crocus (Vionnet, V. et al. Model Development The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2. Geoscientific Model Development 5, 773–791 (2012)) and Mepra (e.g. 1. Giraud, G.MEPRA an expert system for avalanche risk forecasting. in International Snow Science Workshop 97–104 (1992)) are clearly missing.

Thanks for pointing this out. We are certainly aware of the French model forecasting chain and rate it highly. We added two references to articles mentioning MEPRA (Giraud, 1993; Vernay et al., 2015) (page 3, line 3)
However, it is unclear to us how the temporal evolution of strength is modeled, and in general how the strength is derived. We are not aware that in the various publications about MEPRA this is described in detail.

p3 Section 2.1: Is the snowpack completely dry during measurement period?

Yes, the snowpack was completely dry – apart from some melting at the surface in early January resulting in a thin crust (see new Figure 1).

p4 l1-2: "The weak layer . . . December 2014". Explain how you know that.

We know as we closely follow the snowpack evolution and are in the field several times a week. This was the decisive weak layer at the end of December 2014. As mentioned on page 4, lines 16-19, there are no profiles available that were performed at fracture lines to support this assumption, but the particular weak layer consistently showed up as the primary failure layer in snow instability tests in the days following the avalanche cycle.

p4 l2-3: "While no fracture . . . January 2015". I don't understand. Reword.

See reply above. We reworded the last three sentences of this paragraph (page 4, lines 20-23).

p4 l7: "The manual snow profile served as a reference". Do you mean that you performed manual stratigraphic matching to adjust the other snow profiles to the manual profile?

The manual snow profile served as a reference to, for example, indicate the depth of the weak layer or other prominent layers.

p4 l10: "at least three PST". It appears from Figure 1a) that there two other dates where less PST were performed.

As mentioned some test results had to be discarded since the cut was not performed consistently close to the interface which we only realized once we analyzed the videos. For that reason, we only have two test results on two days (21 January and 3 February 2015). We now provide this information (page 5, lines 9-11).

p4 l14: "we cut the layer of faceted crystals at its upper interface". One of the main difficulty of the PST is to follow the weak layer of interest. As explained in Section2.1, there was another FC layer just above the weak layer of interest. Showing the SMP profiles (see main comments) could help the reader to evaluate the likelihood of deviation of the saw cut in the weak layer.

As we filmed all tests we can easily assess whether the tests were properly performed – and have of course done so (see reply above). We now also discuss the difficulties or properly performing the tests (page 14, lines 14-18).
As mentioned above, we will provide one SMP profile per measurement day in the Supplementary Material. However, the SMP profiles are less suited to assess a potential deviation while cutting the weak layer.

p4 l18: Give version of SMP.

We used SMP version 2 (page 5, line 20).

p4 l25: "the displacement of the markers was used to estimate the mechanical energy Vm (r) with increasing crack length". As far as I understand, at this step, you also need the load, i.e. the density of the manual profile. Add explanation if this is correct.

Thanks for pointing this out; we added that the density of the manual profile is used to evaluate the mechanical energy (page 6, line 18).

p4 section 2.3: The critical crack length of the modeled PST is inherently equal (or very close) to the observed critical crack length since the observation is used to fit w_f. This might not appear clearly to the reader. Please add this kind of explanation.

The critical crack length is modelled from the weak layer fracture energy w_f as derived from the SMP. It is independent of the observed critical crack length. We now better explain the derivation of the modelled critical cut length r_c^{SMP} in section 2.4 and explicitly mention that the SMP-derived modelled critical cut length is independent of the observed critical cut length (page 8, lines 10-11).

p5 l28: "the shear modulus of the weak layer which was estimated". How ?

Following Gaume et al. (2016) we used a constant value of the shear modulus G_{WL} = 0.5 MPa according to previous results of laboratory experiments by Reiweger et al. (2010) and Camponovo and Schweizer (2001); for the Poisson's ratio of the slab we assumed a value of 0.2.
We reworded this statement to: *"For the shear modulus of the weak layer we assumed a constant value of 0.5 MPa, based on laboratory experiments (Camponovo and Schweizer, 2001; Reiweger et al., 2010)."* (page 9, lines 12-14).

p5 l30: I suggest to explicitly indicate the power law relation used here.

We now provide the relation as suggested (page 7, line 26).

p6 Eq2: To my opinion, this equation in this form does not give any information to the reader. Delete or give detail on all terms.

We now introduce the equation earlier in the Methods section and provide all details (now Eq. 7 in the revised manuscript).

p6 l23-26: "By then, the weak layer of ... resulting in a load of almost 4 kPa." Belong to the load section 3.2?

This part of the sentence simply makes the link between slab thickness and density on one hand and load on the other hand so that the reader can better relate load values to commonly used parameters such as slab thickness.

p7 l29: "0.3 J m -2 to about 1.5 J m -2". Recall that this range results from a linear scaling between w_f_SMP and w_f_PTV.

We now recall the scaling in the Discussion section (page 16, lines 6-11).

p8 l3: S = shear_strength / skier stress should be described in Methods. Adding two lines of description is not a big deal and would clarify the message. See main comments.

As mentioned above, we now introduce the SMP-derived metrics of instability in more detail in the Methods section of the revised manuscript.

p8 l10: SK38 = shear_strength / (skier stress + weight_stress) should be described in Methods. See main comments.

We now introduce the SK38 in the Methods section of the revised manuscript (page 9, lines 1-4).

p8 l22-24: The CT/ECT tests could be better used to evaluate the initiation criteria (SMP, SK38).

Thanks for this suggestion; we now discuss the CT/ECT results with respect to the initiation criteria in the revised manuscript (page 16, lines 31-32; page 17, lines1-4; page 17, line 19).

p9 l14-18: I don't understand this paragraph. The rc_obs is used to compute w_f_PTV. That w_f_PTV as input in Heierli's model gives the same trend for r_c does not appear to me as a finding ??? Clarify.

This paragraph is to illustrate that under certain assumptions for the temporal evolution of E, σ and w_f the critical cut length can at some times decrease and at others increase. The values of E, σ and w_f were taken such that they overall about mimic the observations, but were not identical to them. These are, as mentioned above, just case studies to illustrate how the various parameters interplay.

p9 l27-28: "Only when the load had reached 2 kPa, all cracks fully propagated towards the end of the column. This finding suggests that the slab was initially not strong enough to support the propagation". I don't understand the logic link between these two sentences (load/strength ?). Clarify.

We suggest that the tensile strength of the slab was initially not large enough so that cracks did not propagate to the very end of the column, but slab failures occurred. Slab density generally increases with increasing load, and tensile strength also increases with density. We now better explain this in the revised manuscript (page 13, lines 24-26).

p10 l7 "5.9 cm". This is not a range.

We now specify that the range is the difference between minimal and maximal values (page 14, line 19).

p10 l15-19: "The errors associated with the parameters ... the dots in the PTV analysis)."This a new info that belongs to Methods and Results sections.

We think it is common practice to discuss errors and uncertainties in the Discussion section.

p10 l19-22: Adding error-bars on the figures 2a, 3a would help to illustrate this discussion. Moreover, you might go further in this discussion. Indeed w_f depends only on one layer *whereas E is an integrated value on the slab layers and might thus be less sensitive to the spatial variations of one layer.*

We now show the errors in Figures 3a and 4a. Thanks for the suggestion; we added this point to the Discussion section (page 16, lines 18-20).

p10 l26: "validated" -> "evaluated"

Reuter et al. (2015) in fact validated their SMP-derived metrics with independent observations. Hence we prefer to keep validated.

p11 l3: "is in line with the observations in particular when considering the CT and ECT scores.". What are the others ?

We referred to avalanche activity.

p11 l10: "– suggesting that the propagation propensity decreased". Delete

We have completely re-worded this paragraph.

p11 l10-11: "This behavior follows from the fact that two of the essential variables, the bulk modulus and the weak layer shear strength also increase with time." From your sensitivity analysis (figures 6a,b) and the fact that you get the same results for Eq. (1), this is not a sufficient explanation.

We explain in detail in the following lines why we think that r_c^{SNP} shows this behavior. We tried to further clarify this in the revised manuscript (page 17, lines 29-34; page18, lines 1-12).

p11 l14-15: "However, it seems premature to rate this metric as it has to be considered as being still in an experimental state." I agree this is a very valuable criterion to help to synthesize the data of snowpack models. However, the explanation is evasive. To my opinion, evaluation of this metric on one point stability observations with potential errors in meteorological forcing and SNOWPACK modeling is the main problem. See main comments. Delete or reword.

We are not aware of any more appropriate way of validating parameters derived from modelled snow stratigraphy other than with measurements in study plots surrounding an automatic weather station. We strongly believe that snow instability predictions from a numerical snow cover model need to be validated with fracture mechanical experiments, or in-situ snow instability tests in general, directly at the location of the weather station. The model of course needs to be driven with these local data otherwise there is already an unknown spatial bias.

p11 l19: "The parameter most strongly influencing the critical cut length seems to be the load". Not shown in results. Can be quantified. See main comments.

We agree that this statement is not supported since we missed to previously mention this in the Results and Discussion sections. We now discuss this finding earlier in the revised manuscript.

Figures: what is the running median smoother (kernel size?)

The dashed lines now simply connect the median values per day.

Figure 1: a) give r_c in m for consistency. b) indicate in the figure what is the black solid line.

The black solid line is described in the figure caption: load as provided by SNOWPACK.

References

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Reply to Referee #2

We thank the reviewer for the constructive review and valuable comments that were very helpful for preparing the revised manuscript. In the following, we reply to the comments in detail and describe the changes we made in the revised manuscript.

This paper presents a unique dataset of temporal changes in crack propagation propensity over the course of a season, and how that propagation propensity related to temporal changes in the slab and weak layer. The authors utilized the latest tools for their work, including analyzing high speed video with PTV, making measurements with the SMP, and modelling the evolution of the snow cover with SNOWPACK. The paper is a valuable addition to the literature, and I believe it should be published after it is revised.

My first suggestion is that the authors consider a different title. Since the paper really focuses on crack propagation propensity, the title should better reflect that. Perhaps something along the lines of "Temporal evolution of crack propagation propensity in view of slab and weak layer properties" or similar? Or, even more specifically, "Temporal evolution of critical cut lengths. . ."?

Thanks for the suggestion. We changed the title to «*Temporal evolution of crack propagation propensity in snow in relation to slab and weak layer properties*».

Also, it would be nice if the authors could briefly describe more of the methods used. I know that they will not want to repeat long sections of previous work, but if it would be useful for the reader if they could provide even a few more details about some of the SMP and SNOWPACK derived parameters. More background information will help the reader better assess those parameters and how they performed.

We now describe the methods in more detail so that the paper becomes more self-contained.

Major comments:
One primary concern about the paper has to do with Figure 1a and the evolution of the cut length of the PSTs. In this graph it appears that the authors are mixing results that go to END with result that are SFs. Can the authors discuss and defend why they feel this is an appropriate treatment of these data? In my experience I have seen situations where SFs have longer cut lengths, but then as the PSTs transition to END results the cut lengths decrease. At this point, I am not convinced that you can treat the two sets of results (END and SFs) as the same and show a temporal trend with them. I would suggest that they defend this, or they only consider the tests that went to END.

Thanks for rising this point. The critical cut length we reported in Figure 1a (now Figure 2a) is independent of the subsequent dynamic phase of crack propagation. Whether or not a crack will arrest, possibly resulting in a slab fracture, or run to the end of the column, will depend on slab as well as weak layer properties – just as the conditions for the onset of the running crack depend on slab as well as weak layer properties. More specifically, recent research indicates that the tensile strength of the slab may decide on how far cracks propagate (Gaume et al., 2015; Schweizer et al., 2014). However, the onset entirely depends on the balance between the energy available for fracture, i.e. the mechanical energy released due an incremental advance of the crack, and the fracture energy, i.e. the energy required for crack growth, or in other words the resistance to crack propagation (see page 5, lines 14-19).

We checked our extensive data base of propagation saw tests and contrast in the figure below the critical lengths for tests with fracture arrests (ARR, SF) and those with full propagation (END) results. There is for our dataset (N = 427) no significant difference between the crack lengths (p = 0.46).

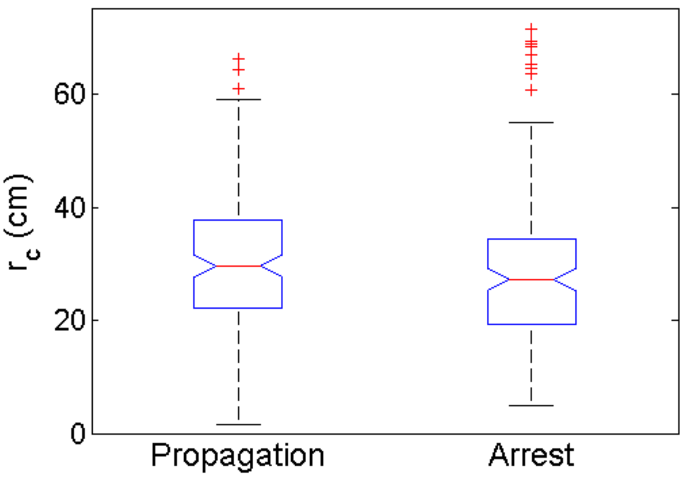

Figure: Critical cut length as observed in PST's as a function of the propagation result. Propagation (on the left) includes all tests where the crack propagated to the very end (END). Arrest (on the right) includes all tests where the crack arrested (ARR) – with or without visible fracture across the slab (SF). Total number of PST results: N = 427, unpublished data.

Furthermore, we certainly agree with the observation by the reviewer that cut lengths may decrease while the result changes from SF to END. In our experience this is usually related to a change in slab properties, e.g. due to additional load, which then will affect the onset as well as the dynamic crack propagation phase. This is actually what we observe towards the end of January 2015 and is likely the reason for the transition from SF to END fractures in our dataset.

Another primary concern about this paper is that I feel a much more robust discussion of the results is warranted. The authors have presented many interesting results, both in terms of the temporal evolution of various parameters and in the comparison of different methods of tracking those temporal changes (between the field tests, PTV, the SMP, and SNOWPACK). However, in my opinion the authors do not fully discuss many of these findings. Some examples:

- *The temporal changes of effective elastic modulus of the slab derived from PTV and derived from the SMP do not match (Figure 2). However, this discrepancy is not discussed. Which one of these two techniques do the authors believe is closer to capturing the "true" change in the elastic modulus? It seems to me that the PTV results more closely align with changes I've observed in the field. If this is the case for these data, can the author suggest ways the SMP techniques can be improved?*

We agree that there are some open questions, and discrepancies, with regard to the various methods we apply. Most methods have been validated independently, and so far not been contrasted. So far, only Reuter et al. (2013) made an initial attempt to compare various measurements methods; these authors are about to prepare a more in-depth manuscript for a peer-reviewed journal.

We now discuss the discrepancies in more detail, but it is beyond the scope of the manuscript to provide a full comparison of the methods. This also requires a much larger dataset.

- *The SMP's derived critical cut length did not match the observed changes in the PST. Why do the authors think this is the case? Is this some shortcoming in the SMP technique, or are the data presented in this paper somehow different from the data used to develop the SMP derived critical cut length? Does this finding shed additional uncertainty on the SMP derived cut length?*

We agree with the reviewer's observation of a certain discrepancy. We have re-analyzed the data based on the new findings by van Herwijnen et al. (2016) and the temporal evolution of the SMP-derived critical cut length does now better match.
The difference in part stems from the fact that the SMP-derived modulus is not really well related to other independent measurements of the modulus (Reuter et al., 2013). We now provide an alternative approach by deriving density from the SMP (Proksch et al., 2015) and then determining the modulus based on the parameterization provided by Scapozza (2004).

- *On page 12, line 10 the authors state that this metric is experimental so it is premature to rate it. I disagree with this statement. If the metric is seen as useful enough to be included in the paper, then I feel that it is appropriate to fully evaluate it and rate its usefulness.*

We agree and now discuss the results for the new metrics in substantially more detail.

- *Another point that is not fully discussed is the difference between the elastic modulus values calculated using PTV and those calculated with the SMP. It would be nice to have a paragraph discussing these differences, why they occur, and whether there are ways to get better measurements out of some of the techniques. This could be placed after the paragraph ending on Page 11, Line 19. Looking at Figure 2, the numbers for the SMP seem strange (staying the same or even going down over the season), while the numbers for PTV seem more realistic. What do the authors think about this and how might they explain it?*

We agree and now discuss this issue in more detail. We have recently shown (van Herwijnen et al., 2016) that the PTV-derived modulus fits relatively well with results from laboratory experiments in the same range of strain rates. For the SMP-derived modulus this calibration however is lacking.

Minor comments:

- *Most figures feature a dashed line that is a "running median smoother". It would be helpful to know how the authors calculate this smoother. Also, are the cut lengths in Figure 1a treated the same whether the test went to END or was SF? It appears they were, but the authors may wish to state that in the text.*

We have replaced the median smoother. The dashed lines we now show, simply connect the median values per day.
The cut lengths are treated the same whether the crack did run to the end or arrested (resulting in a slab fracture). See also reply above. We now explicitly mention this in the Methods section of the revised manuscript (page 5, lines 14-19).

- *Page 2, Line 1. It is true that Sigrist and Schweizer (2007) were "among the first to emphasize the importance of the slab layers and weak layers", but there were others that* *emphasized that point either prior to, or at the same time as, 2007. Those include the MS thesis by B.C. Johnson (2001), the paper by Johnson and Jamieson (2004 in CRST), the PhD dissertation by van Herwijnen (2005), the paper by van Herwijnen and Jamieson (2007 in CRST), and the thesis by Gauthier (2007). Since this has been an important point, I'd encourage the authors to add some of those other publications to this citation. Other earlier work also talks about the slab, but in terms of "emphasizing" the slab, it really began to be more clearly stated in the 2000s with the work by Johnson, Jamieson, van Herwijnen, Sigrist and Schweizer.*

We reworded the sentence to emphasize the explicit interaction of slab and weak layer properties for evaluating the critical cut length: *"Sigrist and Schweizer (2007) first described the interaction of slab and weak layer properties for evaluating the critical cut length. By interpreting their results in a fracture mechanical framework they concluded that the energy that has to be exceeded to fracture a weak layer depends on the material properties of the weak layer, whereas the energy that is available for crack propagation mainly depends on the material properties of the overlaying slab, and may also depend on the collapse height of the weak layer."* (page 2, lines 3-7)

- *Page 2, line 18 and 19. Do the authors believe that the "shear strength of the weak layer is important for failure initiation" in the case of a triggered avalanche from flat terrain?*

Yes, it is certainly important. In flat terrain, a skier not only induces compressive stresses, but also shear stress of similar intensity (Monti et al., 2016; Schweizer, 1997). Hence, the shear stress induced by a skier is very significant even in flat terrain. It is thus more likely that under these mixed-mode conditions the failure begins in shear (or mixed mode) rather than in pure compression because weak layers are weaker in shear than in compression (Reiweger and Schweizer, 2010).

- *Page 7, line 6. When the authors state that "cracks did not always fully propagate", it would be useful if they stated how many tests were done and how many propagated (i.e., something along the lines of "when we did the first PSTs, cracks fully propagated in two of five tests, while slab fractures occurred in the other three tests" or whatever the numbers were).*

We now provide this information in the revised Table 1, and it can also be seen in Figure 2a.

- *Page 7, line 8. Like above, it would be nicer to know the number of tests instead of just writing "all tests".*

We added the number of tests as suggested (page 19, lines 7-9).

- *Page 7, line 18. It seems to me that the data demonstrate that the propagation propensity decreased definitively (rather than slightly) between the first two days because on the second day all of the tests were SF while on the first day there were some that went to END. This could be due to the shallower nature of the snow in that part of the plot, as discussed by the authors, or it might have to do with a change in the slab. I have observed a decrease in propagation propensity (from more END results to more SF results) when a slab loses tensile strength due to near-surface faceting.*

Thanks for pointing this out. We included this point into the Discussion section.

- *Page 9, line 15 and Figure 5. Did all of the ECTs propagate across the column (ECTPs) or did some not (ECTNs)? That should be made clear here or on Figure 5.*

Almost all ECTs propagated across the column. We now provide this information in the revised Table 1.

Typographical/grammatical errors:

Thanks for these suggestions which we considered in the revised manuscript as follows:

- *Page 1, Line 8, add "(PSTs)" after "propagation saw tests" since "PST" is used later in the abstract.*

Added as suggested.

- *Page 1, Line 21, delete "considering the slab,"*

Deleted as suggested.

- *Page 1, Line 32, replace "but" with "and"*

Changed as suggested.

- *Page 2, line 14 and 15. It seems the information for those two sentences comes from a single reference, but the authors cite both Jamieson and Schweizer, 2000 and Schweizer et al., 1998. Which reference is correct?*

Whereas the study by Jamieson and Schweizer (2000) is more comprehensive, the strength increase of the order 100 Pa d^{-1} is only mentioned in Schweizer et al. (1998).

- *Page 3, line 3, delete "exists"*

We prefer to keep "exists".

- *Page 4, line 13, add an "s" to "PST" so it reads "PSTs"*

Changed as suggested.

- *Page 5, line 3, delete the comma that is after "modulus"*

Deleted as suggested.

- *Page 7, line 9. You cannot have two semicolons in the same sentence. You will need to re-word to remove one of them.*

Removed as suggested.

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Temporal evolution of crack propagation propensity in snow in relation to slab and weak layer properties

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Abstract. If a weak snow layer below a cohesive slab is present in the snow cover, unstable snow conditions can prevail for days or even weeks. We monitored the temporal evolution of a weak layer of faceted crystals as well as the overlaying slab layers at the location of an automatic weather station in the Steintälli field site above Davos (Eastern Swiss Alps). We focussed on the crack propagation propensity and performed propagation saw tests (PSTs) on seven sampling days during a two-month period from early January to early March 2015. Based on video images taken during the tests we determined the mechanical properties of the slab and the weak layer and compared them to the results derived from concurrently performed measurements of penetration resistance using the snow micro-penetrometer (SMP). The critical cut length, observed in PSTs, overall increased during the measurement period. The increase was not steady and the lowest values of critical cut length were observed around the middle of the measurement period. The relevant mechanical properties, the slab effective elastic modulus and the weak layer specific fracture, overall increased as well. However, the changes with time differed suggesting that the critical cut length cannot be assessed by simply monitoring a single mechanical property such as slab load, slab modulus or weak layer specific fracture energy. Rather, crack propagation propensity is the result of a complex interplay between the mechanical properties of the slab and the weak layer. We then compared our field observations to newly developed metrics of snow instability related to either failure initiation or crack propagation propensity. The metrics were either derived from the SMP signal or calculated from simulated snow stratigraphy (SNOWPACK). They partially reproduced the observed temporal evolution of critical cut length and instability test scores. Whereas our unique dataset of quantitative measures of snow instability provides new insights into the complex slab-weak layer interaction, it also showed some deficiencies of the modelled metrics of instability – calling for an improved representation of the mechanical properties.

1 Introduction

Dry-snow slab avalanche release is governed by failure processes within the layered snow cover. Whether a failure initiates and a resulting macroscopic crack will propagate, depends on the complex interaction between slab layers, the weak layer and to some extent the substratum, i.e. the layers below the weak layer. For example, the thickness and characteristics of the slab layers determine the magnitude of the stress at the depth of the weak layer due to a skier (Habermann et al., 2008; Monti et al., 2016; Thumlert and Jamieson, 2014), and also how much deformation energy can be released to drive crack propagation (Gaume et al., 2014b; Heierli et al., 2008; McClung, 1979). On the other hand, a weak layer is a prerequisite for failure initiation and offers a path for crack propagation. Sigrist and Schweizer (2007) first described the interaction of slab and weak layer properties for evaluating the critical cut length. By interpreting their results in a fracture mechanical framework they concluded that the energy that has to be exceeded to fracture a weak layer depends on the material properties of the weak layer, whereas the energy that is available for crack propagation mainly depends on the material properties of the overlaying slab, and may also depend on the collapse height of the weak layer. Given the two most relevant processes in dry-snow slab avalanche release, failure initiation and crack propagation (e.g., Schweizer et al., 2003a), van Herwijnen and Jamieson (2007) suggested a conceptual model on the effect of the slab properties, in particular slab depth, on these failure processes. With increasing slab depth conditions for failure initiation become less favourable whereas conditions for crack propagation become more favourable.

Temporal changes in snow instability hence stem from changes in slab and weak layer properties – separately or in combination. For example, during a snowfall the probability of failure initiation in the weak layer increases due to the additional load. However, the additional load will also promote strengthening of the weak layer (e.g., Zeidler and Jamieson, 2006a) – though the strength increase may lag behind loading during a snowfall. Changes of weak layer strength have been studied in detail (e.g., Chalmers and Jamieson, 2001; Gauthier et al., 2010; Jamieson and Johnston, 1999; Zeidler and Jamieson, 2006a, b) and more frequently than changes of slab properties. However, to the best of our knowledge, there are hardly any studies that investigated how temporal changes affect the complex interplay between slab and weak layer properties.

Repeated measurements of weak layer shear strength revealed how various types of weak layers gain strength over time (Jamieson et al., 2007). Overall, an increase in strength was almost always observed in all studies while at the same time the load usually increased. Jamieson and Schweizer (2000) reported the shear strength over time for 19 buried surface hoar layers. Typical weak layer strength gain was on the order of 100 Pa d^{-1} during the initial weeks after burial (Schweizer et al., 1998). Occasionally measured decreasing strength with time was attributed to spatial variability within the study site or errors associated with measurement technique (Jamieson and Johnston, 1999).

Many of the above mentioned studies monitoring strength changes of weak layers focussed on relating stability trends with observed local or regional avalanche activity (e.g., Jamieson et al., 2007). However, observed avalanche activity was often not related to the stability index, i.e. the ratio of strength to stress (e.g., Föhn, 1987), calculated from the study plot measurements. While the shear strength of the weak layer is important for failure initiation, dry-snow slab avalanches release due to crack propagation which requires the release of deformation energy stored in the slab layers. This conceptual mismatch has long been recognized. For example, Schweizer et al. (1998) pointed out that since the shear frame measurements will primarily provide information on the strength and strength changes of weak layers, the 'effective reactivity (propagation potential)' depending on the slab characteristics should be assessed by supplementary tests. Nevertheless, temporal changes of slab characteristics were rarely monitored, apart of course, from the load.

The temporal evolution of shear strength has been modelled for persistent and non-persistent weak layers (e.g., Chalmers, 2001; Conway and Wilbour, 1999; Hayes et al., 2005; Lehning et al., 2004; Zeidler and Jamieson, 2006a, b) so that the evolution of the stability index can be monitored or even forecasted (Giraud, 1993; Vernay et al., 2015). Conway and Wilbour (1999) suggested a model for natural avalanches during storms by comparing the load to the strength by assuming that failure occurs at the base of the new snow layers; their strength solely depends on density which increases with increasing overburden stress. Föhn and Hächler (1978) exclusively focused on slab properties as they studied how the slab layers settle during major snow storms. They proposed to follow the settlement (coefficient) over time to assess the probability of large natural dry-snow avalanches.

With the development of the propagation saw test (PST; Gauthier and Jamieson, 2006), now a well-established snow instability test exists providing a quantitative test result, the critical cut length. Furthermore, the PST allows determining the relevant slab and weak layer properties (Reuter et al., 2015; Schweizer et al., 2011; Sigrist and Schweizer, 2007; van Herwijnen and Heierli, 2010; van Herwijnen et al., 2016). Recently, Birkeland et al. (2014) repeatedly performed propagation saw tests on a layer of buried surface hoar; they focussed on conditions for fracture arrest.

A number of studies have focussed on the temporal evolution of spatial patterns on small uniform slopes – inter alia testing the hypothesis that variability should increase in the absence of major external forcing such as a snowfall (Birkeland and Landry, 2002; Birkeland et al., 2004; Logan et al., 2007). Hendrikx et al. (2009) used the Extended Column Test (Simenhois and Birkeland, 2009) to investigate spatial variations of the propagation potential. They assessed the spatial variability of two sites each on two days and found increased spatial clustering on the second sampling day.

For clarification, we shortly define the following two terms: snow instability and crack propagation propensity. As Reuter et al. (2015) have pointed out both high failure initiation and high crack propagation propensity are required to describe unstable snowpack conditions. More recently, Reuter et al. (2016b) suggested to complement the failure initiation and crack propagation criteria with a tensile criterion related to dynamic crack propagation. Hence, snow instability cannot be assessed with a single stability criterion as suggested in the past (e.g., Föhn, 1987) but only by a combination of indices related to the essential processes in dry-snow slab avalanche release. With regard to crack propagation propensity, we refer to this term to describe (1) in general, whether snowpack characteristics favour self-sustained crack propagation possibly resulting in a snow slab avalanche, and (2) when interpreting propagation saw tests, whether the critical crack length is less than about one third of the column length and the crack propagates to the end of the column.

The aim of the present study is to repeatedly measure the slab and weak layer properties in a study plot to monitor their temporal evolution and to investigate their interaction in view of assessing snow instability. During the winter 2014-2015 we followed a layer of faceted crystals that was responsible for wide-spread avalanche activity in the region of Davos (Eastern Swiss Alps) over the course of two months. We performed propagation saw tests, which we analysed based on the video recordings of the tests and compared the results to concurrently performed measurements of penetration resistance using the snow micro-penetrometer (SMP) (Schneebeli and Johnson, 1998). As we performed our measurements in a level study plot equipped with an automatic weather station, we also simulated the evolution of snow stratigraphy with the numerical snow cover model SNOWPACK. Finally, we compared our observations to metrics of instability derived from either the SMP signals or simulated with SNOWPACK. The acquired dataset provides a comprehensive time series of quantitative measures of snow instability; it allows insight into the complex interplay between slab and weak layer properties that jointly govern snow instability.

2 Methods

We followed the evolution of a weak layer of faceted crystals in the level study plot surrounding the automatic weather station WAN7 (2442 m a.s.l.) located in the Steintälli field site above Davos, eastern Swiss Alps (46.808° N, 9.788° E). Measurements were performed on eight days between 6 January and 3 March 2015, typically once a week during the two month study period (Table 1).

2.1 Weak layer formation

On 1 December 2014 the manually observed snow profile at the study plot Weissfluhjoch (2540 m a.s.l.) (located 3 km to the northeast of WAN7) showed a melt-freeze crust with 1 cm recently fallen snow on top. On 2-3 December 2014, a minor storm accumulated an additional 12 cm of new snow. During the following two weeks, the snow above the crust settled and transformed into a layer of faceted crystals due to near-surface faceting (Birkeland, 1998); this layer of faceted crystals was buried by a snowfall on 16 December 2014. The 2-3 cm thick melt-freeze crust was consistently found throughout the winter below the layer of faceted crystals that formed the 5-8 cm thick weak layer. As of mid January 2015 the layer was classified as rounded facets (FCxr) with a grain size of 1-1.5 mm. Above the weak layer was another layer of faceted crystals overlain by well consolidated slab layers that had formed in late December 2014 and early January 2015 (Figure 1). The weak layer was likely responsible for wide-spread avalanche activity in the region of Davos on 30-31 December 2014 when many natural dry-snow slab avalanches were observed. Since no snow profiles at fracture lines were recorded, we do not know the depth and type of failure layer. However, the weak layer we monitored consistently failed in snow instability tests in early January 2015, and there were no other prominent weak layers within the snow cover. This observation suggests that it was also the primary failure layer of the late-December avalanches.

2.2 Field measurements

On each of the eight sampling days we observed a manual snow profile, including layer density, according to Fierz et al. (2009). The detailed density profile is required for the analysis by particle tracking velocimetry (PTV) of the PSTs (see below). The manual snow profile served as reference for most other measurements and was completed with the two snow instability tests that can easily be performed in flat terrain: the compression test (CT) (Jamieson, 1999) and the extended column test (ECT) (Simenhois and Birkeland, 2009).

On each sampling day, except for 19 February 2015, we also conducted at least three propagation saw tests in the immediate vicinity of the snow profile. The tests were performed according to Greene et al. (2010), albeit with longer columns. Initially, column length was around 1.5 m, and it increased towards 2 m at the end of the study period as the weak layer became more deeply buried (slab thickness increased from 59 to 148 cm) (Bair et al., 2014; Gaume et al., 2015). Using a 2-mm thick snow saw, we cut the layer of faceted crystals at its upper interface, where CT and ECT results indicated that the failure occurred. Black markers (2.5 cm in diameter) were inserted into the snowpack; we filmed all tests with a video camera for subsequent analysis by particle tracking velocimetry (van Herwijnen et al., 2010). The video recording also allowed us to accurately determine the critical value of the crack length r_c^{OBS}, when the crack started to propagate. Furthermore, we could also assess whether the tests were properly performed, e.g., whether the saw cut was within the weak layer. In some cases, we had to discard a test result since the cut was not performed consistently close to the layer interface; this resulted in only two values of the critical cut length on 21 January and 3 February 2015.

In the PST experiments, cracks did not always propagate to the end of the column, but arrested with a slab fracture (Table 1). These propagation results are termed END and SF, respectively (e.g., Greene et al., 2010). In the following, while reporting the critical cut length when crack propagation initiates, we do not differentiate between these two propagation results since the critical crack length is independent of the subsequent phase of dynamic crack propagation. Whether or not a running crack will arrest may depend on the tensile strength of the slab (Gaume et al., 2015; Schweizer et al., 2014). However, the onset of crack propagation entirely depends on the balance between the energy available for fracture, i.e. the mechanical energy released due an incremental advance of the crack, and the specific fracture energy, i.e. the energy required for crack growth, or in other words the resistance to crack propagation.

Concurrently, we performed several SMP measurements (SMP version 2), at least three at the location of the manual snow profile, and at least one at each of the PST locations; thus in total at least 6 measurements per sampling day. The SMP measurements at the PST locations were conducted before isolating the columns, close to the end of the column where the saw cut was initiated. This procedure allowed comparing the SMP-derived properties with those from the PTV analysis.

2.3 PTV analysis

Using a particle tracking velocimetry algorithm (PTV; Crocker and Grier, 1996) the displacement field of the slab prior to crack propagation was calculated from the video image; it shows bending of the slab due to the saw cut (of length *r*) during the PST. Based on the displacement field of the slab, the effective elastic modulus of the slab E^{*PTV} and the specific fracture energy of the weak layer w_f^{PTV} were determined (van Herwijnen and Heierli, 2010; van Herwijnen et al., 2016). The approach is based on the work by Heierli et al. (2008) who suggested for the geometry of the PST (of unit width) an expression for the total energy of the system $V(r)$ as a function of crack length r which consists of the fracture energy $V_f(r)$ and the mechanical energy $V_m(r)$:

$$V(r) = V_f(r) + V_m(r) = w_f r + V_m(r). \quad (1)$$

The mechanical energy includes two terms, a fracture mechanical and a bending term:

$$V_m(r) = -\frac{\pi\gamma r^2}{4E'}(\tau^2 + \sigma^2) - \frac{r^3}{6E'D}[\lambda_{\tau\tau}\tau^2 + \lambda_{\sigma\tau}\tau\sigma + \lambda_{\sigma\sigma}\sigma^2] \quad (2)$$

where w_f is the specific fracture energy, D is the slab thickness, γ is a constant of about one, depending on Dundur's elastic mismatch parameter, $E' = E/(1-\nu^2)$ is the plane strain elastic modulus of the slab, and ν the Poisson's ratio (assumed $\nu = 0.2$). The load of the slab on the weak layer consists of the shear stress $\tau = -\rho g D \sin\theta$ and the normal stress $\sigma = -\rho g D \cos\theta$. Furthermore,

$$\lambda_{\tau\tau} = 1 + \frac{9}{4}\eta\left(\frac{r}{D}\right)^{-1} + \frac{9}{4}\eta^2\left(\frac{r}{D}\right)^{-2}, \quad (3)$$

$$\lambda_{\tau\sigma} = \frac{9}{2}\eta + \frac{9}{2}\eta^2\left(\frac{r}{D}\right)^{-1}, \quad (4)$$

$$\lambda_{\sigma\sigma} = 3\eta^2 + \frac{9}{4}\eta\frac{r}{D} + \frac{9}{5}\left(\frac{r}{D}\right)^2. \quad (5)$$

with $\eta = \sqrt{4(1+\nu)/5}$.

However, by comparing estimates obtained with the analytical expression for the mechanical energy provided by Heierli et al. (2008) with finite element (FE) simulations, van Herwijnen et al. (2016) recently showed that Eq. 2 underestimates the mechanical energy for realistic values of the ratio of crack length to slab thickness r/D. Therefore, they introduced a correction factor that accounts for the sensitivity to r/D and the slope angle θ to obtain an adjusted mechanical energy $V_m^*(r)$.

According to theorem of Clapeyron, for a linear-elastic system, the mechanical energy can be estimated from the gravitational potential energy. The gravitational potential energy was computed from the measured displacement field, assuming a layered slab and using the manually observed density profile, to determine the mechanical energy as a function of crack length. This measured mechanical energy was then fitted to the adjusted mechanical energy $V_m^*(r)$ to obtain the effective elastic modulus of the slab $E^{*\mathrm{PTV}}$, the fit parameter. It is defined as the modulus of a uniform slab of equal mean density yielding the same displacement as the real slab. To determine the specific fracture energy w_f^{PTV}, the analytical expression for the adjusted mechanical energy with the best fit modulus is differentiated with regard to the crack length at the critical cut length r_c^{OBS}. In other words, the slope of $V_m^*(r)$ at the critical crack length corresponds to the specific fracture energy of the weak layer. For a more detailed description on deriving the effective elastic modulus and the specific fracture energy, the reader is referred to van Herwijnen et al. (2016).

2.4 SMP signal processing

We used the penetration resistance data acquired with the SMP to obtain detailed data on the layering of the snow cover to derive mechanical properties following the approach described in Reuter et al. (2015).

Based on the manually observed snow profile, layers were manually defined from the corresponding sections of the SMP signal, i.e. several slab layers, a weak layer and a basal layer. The shot-noise model by Löwe and van Herwijnen (2012) was then applied to determine snow micro-structural parameters, namely the rupture force f, the deflection at rupture δ and the structural element size L. These three parameters were calculated over a moving window of 2.5 mm with 50% overlap and averaged over each layer. Furthermore, for each layer the snow density was derived according to Proksch et al. (2015), allowing to calculate the load on the weak layer. The micro-mechanical modulus for the slab layers and the strength of the weak layer σ_{WL} were calculated according to Johnson and Schneebeli (1999). The weak layer specific fracture energy $w_{\mathrm{f}}^{\mathrm{SMP}}$ was calculated as the minimum of the integrated penetration resistance across each moving window within the weak layer (Reuter et al., 2013). Finally, the penetration depth PS was estimated by integrating the penetration resistance F from the snow surface to the depth PS where a threshold value of the absorbed energy was reached (Schweizer and Reuter, 2015).

The effective elastic modulus of the slab $E^{*\mathrm{SMP}}$ was determined by performing FE simulations of the experimental setup taking into account the slab layering (for details see Reuter et al., 2015). The FE model consisted of all the slab layers, the weak layer and a basal layer, each with density, micro-mechanical modulus and thickness values derived from the SMP measurement. The mechanical strain energy $V_{\mathrm{m}}^{\mathrm{FEM}}(r)$ was then calculated for a stratified slab bending over a crack of increasing length r. In order to recover an effective elastic modulus $E^{*\mathrm{SMP}}$, the analytical expression for the adjusted mechanical energy $V_m^*(r)$was fitted to the modelled values of mechanical energy $V_{\mathrm{m}}^{\mathrm{FEM}}(r)$. Hence, we followed the same approach as for the PTV analysis, and we also used the newly developed correction factor to obtain the adjusted mechanical energy $V_m^*(r)$.

The SMP-derived weak layer specific fracture energy and the effective elastic modulus were scaled by a linear factor of 2.8 and 2.5, respectively, to approximately match the corresponding values derived from the PTV analysis. Scaling of the specific fracture energy and the modulus was performed as there is no calibration yet of the microstructural mechanical properties that can be derived from the SMP signal. Whereas the microstructural properties derived from the SMP are physically based, they cannot be expected to directly represent the corresponding macroscopic properties (Reuter et al., 2016a).

In addition, an alternative effective elastic modulus $E_\rho^{*\mathrm{SMP}}$was derived, following the same approach with the same FE model as described above. However, rather than using the micro-mechanical modulus, for each layer the modulus was determined using the SMP-derived density and applying the parametrization provided by Scapozza (2004): $E = 1.873 \times 10^5 e^{0.0149\rho}$.

Based on the mechanical parameters estimated from the SMP measurements, two metrics of point instability were derived, as suggested by Reuter et al. (2015).

The first metric is the failure initiation criterion S, a strength-over-stress criterion describing the propensity of the weak layer to fail in case of skier loading:

$$S = \frac{\sigma_{WL}}{\Delta\tau_{\mathrm{FEM}}} \tag{6}$$

where σ_{WL} is the SMP-derived micro-mechanical strength of the weak layer and $\Delta\tau_{\mathrm{FEM}}$ the maximum additional shear stress at the depth of the weak layer due to skier loading. The maximum shear stress at the depth of the weak layer was modeled with the 2D linear elastic FE model originally presented by Habermann et al. (2008) to calculate the shear stress $\Delta\tau_{\mathrm{FEM}}$ below a layered slab due to the weight of a skier.

The second metric is the crack propagation criterion r_c^{SMP}, an SMP-derived critical cut length. It is derived by numerically solving Eq. 7, which is obtained by finding the extremum of the total energy of the cracked system *V(r)* (Eq. 1) with respect to *r* and ensuring that it is a maximum: $\frac{d}{dr}V(r) = w_f + \frac{d}{dr}V_m(r) = 0$, which yields (Schweizer et al., 2011):

$$w_f(E', r_c) = \frac{D}{2E'}\left[w_0 + w_1\frac{r_c}{D} + w_2\left(\frac{r_c}{D}\right)^2 + w_3\left(\frac{r_c}{D}\right)^3 + w_4\left(\frac{r_c}{D}\right)^4\right], \quad (7)$$

with

$$w_0 = \frac{3\eta^2}{4}\tau^2,$$

$$w_1 = \left(\pi\gamma + \frac{3\eta}{2}\right)\tau^2 + 3\eta^2\tau\sigma + \pi\gamma\sigma^2,$$

$$w_2 = \tau^2 + \frac{9\eta}{2}\tau\sigma + 3\eta^2\sigma^2,$$

$$w_3 = 3\eta\sigma^2,$$

$$w_4 = 3\sigma^2.$$

By inserting the effective elastic modulus of the slab E_ρ^{*SMP} and weak layer specific fracture energy w_f^{SMP} into Eq. 7 the crack propagation criterion r_c^{SMP} was obtained. Hence this modelled critical cut length is independent of the critical cut length r_c^{OBS} measured in the field. For a more detailed description on how to obtain the above mentioned mechanical properties as well as the SMP-derived metrics of point instability, the reader is referred to Reuter et al. (2015).

2.5 Snow cover modelling

We compared results from field measurements to output of the numerical snow cover model SNOWPACK (e.g., Lehning et al., 2004) driven by meteorological input from the automatic weather station WAN7. This weather station is located in the study plot where we performed the field measurements. Meteorological input contained air temperature and relative humidity (Rotronic MP100H HygroClip, ventilated), wind speed and direction (YOUNG wind monitor), incoming short and long wave radiation (Campbell CNR1), and snow height (Campbell SR50). Data gaps shorter than one day were filled by linear interpolation. Gaps longer than one day were filled with data from the nearby AWS Weissfluhjoch (2540 m a.s.l.; 3 km to the northeast). Variables were filtered by introducing reasonable lower and upper limits, e.g. 5 and 100 % for relative humidity. The modelling time step was 15 min after resampling the data from the AWS with a sampling rate of 10 min. The model was initiated on 1 October 2014, when no snow was present at the AWS and ran until the end of May. Neumann boundary conditions for estimating the snow surface temperature and atmospheric stability corrections for estimating turbulent exchange were the preferred adjustments concerning the energy balance model (Stössel et al., 2010).

From the model output, we evaluated the skier stability index SK38 introduced by Jamieson and Johnston (1998). It is defined as the ratio of shear strength to shear stress: $\mathrm{SK38} = \frac{\tau_s}{\tau+\Delta\tau}$ with τ the shear stress due to the weight of the overlaying slab, $\Delta\tau = 155/h$ the additional shear stress due to a skier with h the slab depth (Föhn, 1987; Monti et al., 2016), and τ_s the shear strength as parameterized with density and grain type according to Jamieson and Johnston (2001).

In addition, we estimated the critical cut length r_c^{SNP} from the snow stratigraphy provided by SNOWPACK. We used SNOWPACK model output to derive all the required mechanical properties of the snow layers. The critical cut length was then estimated based on the relation given by Gaume et al. (2014a, Eq. 5) (see Gaume et al., 2016 for a detailed derivation). Based on discrete element modelling they suggested the critical cut length, in the flat (for slope angle $\theta = 0°$), to essentially depend on the plain strain elastic modulus of the slab E', slab load σ, and weak layer shear strength τ_s :

$$r_c^{\mathrm{SNP}} = \Lambda\sqrt{\frac{2\,\tau_s}{\sigma}} \qquad (8)$$

with $\Lambda = (E'\,D\,D_{\mathrm{WL}}/G_{\mathrm{WL}})^{1/2}$, D the slab thickness, D_{WL} the weak layer thickness and G_{WL} its shear modulus. All the required parameters are provided by SNOWPACK, except for the elastic moduli E' and G_{WL}. For the shear modulus of the weak layer we assumed a constant value of 0.5 MPa, based on laboratory experiments (Camponovo and Schweizer, 2001; Reiweger et al., 2010). For the elastic modulus of the slab, we followed the same FE approach as described above for the SMP analysis to derive an effective elastic modulus taking into account slab layering rather than using a slab modulus based on the average slab density. Hence, for each layer of the modelled snow stratigraphy an elastic modulus was calculated from density based on the relation provided by Scapozza (2004). With these properties (modulus, layer density and thickness) a FE simulation was performed to determine the effective elastic modulus $E^{*\mathrm{SNP}}$.

2.6 Avalanche activity

Study plot measurements are commonly used in operational forecasting to make assessments about the avalanche danger in the surrounding terrain (e.g., Gauthier et al., 2010). We therefore compared the results obtained from the field measurements to the observed avalanche activity in the region of Davos. These observations include the number, type and size of avalanches recorded by personnel from the local ski areas, the avalanche warning service, SLF staff members, and others. We then calculated the avalanche activity index per day as described by Schweizer et al. (2003b). The index is a weighted sum of the number of observed avalanches per day including natural as well as artificially triggered avalanches; the weights depend on the avalanche size and are 0.01, 0.1, 1 and 10 for Canadian size classes 1 to 4, respectively (McClung and Schaerer, 2006).

2.7 Case studies

To explore the complex interaction between slab and weak layer properties on the critical cut length in a PST, we considered a few cases with exemplary temporal evolutions of slab load, slab elastic modulus and weak layer specific fracture energy.

To this end we numerically solved Eq. 7 to obtain the corresponding critical crack length, and hence its evolution over time. These examples are not meant as a sensitivity study where one parameter is varied and the other held constant, but as an illustration of the interaction when most or all parameters change.

3 Results

3.1 Propagation saw test results

On 6 January 2015, when we did the first propagation saw tests, cracks did not always fully propagate to the end of the column, but slab fractures were observed in three tests (Table 1, Figure 2a). Eight days later, on 14 January 2015, when the PSTs were performed on a slightly more shallow part of the study plot surrounding the automatic weather station WAN7, all five tests resulted in slab fractures. As of 28 January 2015, 22 days after the first measurements, all cracks fully propagated to the end of the column. After 56 days, on 3 March 2015, in all three tests cracks still fully propagated while the critical crack length had increased to about 50 cm. By then, the weak layer of faceted crystals was buried below a slab of about 150 cm in thickness with an average density of about 270 kg m^{-3}, resulting in a load of almost 4 kPa.

During our measurement series, the critical cut length r_c^{OBS} was initially about 23-30 cm, and slightly increased up to 21 January 2015. Consistently shorter cut lengths were observed on the following measurement day, on 28 January 2015, the date when all cracks fully propagated for the first time. On the following sampling day, 3 February 2015, one test again yielded a short cut length, 17 cm, the shortest value recorded during our sampling period. Subsequently, the cut lengths increased with time.

3.2 Load

On 6 January 2015, the weak layer was buried below a slab of 59 cm (total snow depth HS = 115 cm) and the initial load was about 1.4 kPa (Table 1, Figure 2b). The load did not change much during the following week but then continuously increased due to snowfalls to almost 3 kPa by early February 2015. After a fair weather period in February with no new snow for more than two weeks, the snow depth increased again, and on the last sampling day (3 March 2015) the load was about 3.9 kPa.

The density derived from the SMP signal agreed well with the manually measured density (not shown) and accordingly the increase in load above the weak layer was well represented by the SMP measurements (Figure 2b). For the numerical snow cover model SNOWPACK, values of load as calculated from average density and slab thickness were often slightly lower than those measured in the field. The underestimation is mainly due to the fact that the modelled snow depth was about 25 cm lower than measured at the location of the manual snow profiles.

3.3 Effective elastic modulus of the slab

The effective elastic modulus of the slab was derived from the bending of the slab during the propagation saw test via the PTV analysis E^{*PTV} (Figure 3a) as well as from the SMP signal analysis using the FE model with either the micro-mechanical modulus or a modulus derived from SMP density, yielding E^{*SMP} and E_{ρ}^{*SMP}, respectively (Figure 3b). The effective elastic modulus of the slab obtained from the PTV analysis showed an overall increase from about 2.5 to 10 MPa during the two-month sampling period. However, the increase was not steady; for example, on 13 February 2015 relatively low values between 2.4 and 6.1 MPa were obtained.

The SMP-derived effective elastic modulus E^{*SMP} initially did not change much with median values of approximately 3 MPa during the first 16 days. It then increased until the end of January to about 5 MPa. However, subsequently, it decreased and on the last measuring day low values of only about 1.8 MPa were derived.

The alternative SMP-derived modulus E_{ρ}^{*SMP} also increased from initially 8 MPa to about 22 MPa in early February. Thereafter E_{ρ}^{*SMP} did not change much anymore with values between 19 and 26 MPa (median values per day).

3.4 Weak layer specific fracture energy

The PTV analysis suggests that the weak layer specific fracture energy w_f^{PTV} overall increased with time from about 0.6 J m^{-2} to about 2.2 J m^{-2}, mostly after the end of January 2015 (Figure 4a). The SMP analysis revealed a similar tendency of increasing weak layer specific fracture energy with time. Overall, w_f^{SMP} increased from about 0.5 J m^{-2} to 1.4 J m^{-2} and most of the increase occurred towards mid February (Figure 4b).

3.5 SMP-derived metrics of instability

The failure initiation criterion S derived from SMP resistance data was initially about 300, indicating a transitional value for failure initiation propensity given the threshold reported by Reuter et al. (2015). They observed that a value of the initiation criterion of about 230 divided between the cases with and without concurrently observed signs of instability. The index then increased to about 600 towards the end of January and further to about 1100 by the end of the sampling period (Figure 5a).

The SMP-derived critical cut length r_c^{SMP} overall increased from about 40 cm to 70 cm (Figure 5b). Again the increase was not steady with a similar tendency with time as shown for the weak layer specific fracture energy w_f^{SMP}. At the three sampling days between end of January and mid February similar values of r_c^{SMP} were derived, namely about 55 cm.

3.6 SNOWPACK derived metrics of instability

The skier stability index SK38 (Figure 5c) for the investigated weak layer showed values between 1.1 and 1.35 in early January 2015; these values are in the range of transitional stability (1 to 1.5) according to Jamieson and Johnston (1998). With the snowfalls at the end of January and early February (Figure 1) the index then decreased towards 1.0 indicating increased triggering probability. Subsequently, during much of February, when there was no snowfall, the skier stability index SK38 gradually increased towards 1.3 and decreased again to overall the lowest values of about 1 towards the end of the observation period.

The modelled critical cut length r_c^{SNP} (Figure 5d), on the other hand, steadily increased from about 20 cm in early January to 60 cm in early March 2015.

3.7 Avalanche activity

The highest avalanche activity in the region of Davos was observed around the end of the year 2014 (Figure 6), before our first measurements were performed. In January 2015, avalanches were occasionally observed, in particular on 18 January, a sunny Sunday after a snowfall. Towards late January and early February, there was a period of increased avalanche activity. The last peak was on 3 March 2015, again after a major snowfall, but during this period avalanches did no longer run on the weak layer of facets we monitored; the observed fracture depths were much lower than the burial depth of the weak layer we investigated. Overall, avalanche activity clearly decreased since early January 2015. However, after each significant snowfall avalanches were again observed (e.g. on 18, 28 and 31 January, Figure 6), i.e. the weak layer of facets was still reactive, a true persistent weak layer.

The overall decrease in avalanche activity until the end of February is in line with the observed results of the CTs and ECTs we performed concurrently on each sampling day. The scores increased from values just below 20 taps to values of around 30 taps (red asterisks in Figure 6). On the first measuring day, no crack propagation was observed with the extended column test (Table 1). Subsequently, the fracture type in ECTs was always P (propagation across the entire column), except on 28 January when one ECT did not fracture (X). The increased avalanche activity towards the end of January and early February coincides with the lowest values of observed critical cut length.

3.8 Case studies

The observed temporal evolution of the critical cut length in our PSTs showed an unsteady increase with the lowest values in the middle of the measuring period and an increase thereafter. To explore whether this type of pattern is possible at all, we numerically solved Eq. 7 to find out how the critical cut length changes with time for various scenarios of the temporal evolution of the specific fracture energy of the weak layer w_f, the load σ and the modulus of the slab E.

In the first simplified scenario, all input parameters were assumed to increase, corresponding to a situation when the slab thickens and becomes stiffer, while at the same time the weak layer toughens due to the increased load (Figure 7a). In this scenario, the critical cut length did almost not change, showing a very slight increase (Figure 7b). The combination of increasing load and increasing slab modulus provided a bit more energy to drive the crack, but just as much about to compensate the increased specific fracture energy of the weak layer. This indicates that in this scenario the load had a larger effect than the modulus, since an increasing modulus reduces the amount of strain energy available due to less deformation.

In the second simplified scenario, the specific fracture energy of the weak layer increased as the load increased, while the slab modulus remained constant (Figure 7c). This scenario resulted in a decreasing critical cut length (Figure 7d).

Due to the increasing load, more energy was available to drive the crack, which outweighed the additional energy required to advance the crack due to the weak layer toughening.

In the third simplified scenario, the load remained constant, while the slab modulus and the weak layer specific fracture energy increased (Figure 7e); this scenario corresponds to a fair weather period where the slab stiffens due to settlement and the weak layer toughens due to ongoing sintering with time. In this scenario, the critical cut length substantially increased (Figures 7f). Due to the higher slab modulus less energy was released to drive crack propagation while at the same time the weak layer became tougher.

Finally, in our last scenario, we attempted to roughly mimic the temporal evolution of the critical cut length as observed in our PSTs. We assumed the load to increase approximately as observed, the modulus to triple and the specific fracture energy of the weak layer to increase as well, but not continuously (Figure 7g). With these assumptions, the critical cut length first increased, had a local minimum approximately in the middle of the considered time period and finally increased again (Figures 7h).

Alternatively, the sensitivity of the critical cut length could be explored with Eq. 8. In fact, this would reveal the same trends for the critical cut length, if the temporal evolution of the shear strength followed the one assumed for the weak layer specific fracture energy.

4 Discussion

We repeatedly performed propagation saw tests in a level study plot to follow the temporal evolution of a weak layer of faceted crystals and of the overlaying slab layers by combining state-of-the-art measurement techniques and numerical snow cover simulations. Specifically, we used particle tracking velocimetry, the snow micro-penetrometer and the snow cover model SNOWPACK to estimate snow mechanical properties and derive snow instability criteria.

4.1 Observed critical cut length (PST)

While performing the propagation saw tests in the study plot, we initially observed a mixture of END and SF test results; mixed test results are typically not found in critical conditions. Only when the load had reached 2 kPa, all cracks fully propagated towards the end of the column. This observation suggests that the tensile strength of the slab was initially not large enough to allow crack propagation (Gaume et al., 2015), in particular at the more shallow locations. Other changes in slab properties that might have favoured slab fractures, e.g. faceting, were not observed.

The initial absence of full crack propagation in our field tests contrasted with the high avalanche activity observed during that time. The contrasting observations may be due to the fact that we made our measurements in a wind-sheltered study plot that may not be very representative of wind-affected starting zones in the area. In typical lee-slope starting zones, the tensile strength of the slab might have been larger; moreover, the tensile stress might be lower on slopes since less bending is expected prior to natural avalanche release than observed in PSTs in flat terrain (McClung and Borstad, 2012). In general, slab layers are more variable in terms of penetration resistance than weak layers reflecting the dynamic conditions of snowfall and wind during deposition of the slab (Schweizer et al., 2008). Since the properties of the slab layers are particularly important for crack propagation, variable crack propagation propensity has to be expected. The observed discrepancy highlights some of the limitations when extrapolating instability from flat field study sites.

As of 28 January 2015 all cracks in PSTs propagated to the very end of the column. This is in line with the results of the other stability test performed: sudden fractures (SP/SC) in CTs and full crack propagation (P) in ECTs.

Overall the observed critical cut length doubled from about 25 cm to about 50 cm by early March. However, the increase was not steady. Despite the overall increase in critical cut length, the lowest values were observed at the end of January and in early February. This pattern of the temporal evolution of the critical cut length in PSTs was rather unexpected since weak layers typically gain strength with time (e.g., Jamieson and Schweizer, 2000).

Consistently low values of the critical cut length in PSTs, between 19 and 24 cm, were observed on 28 January 2015. On the following sampling day, the lowest value (17 cm) was observed, but also a rather high value of 38 cm. In general, low values or scores in snow instability tests are more trustworthy than high values. In the case of the propagation saw test, any measurement and observation errors increase the cut length. In our case, we were cutting at the top of a weak layer of faceted crystals, and the layer above was not much harder and as well consisted of faceted crystals. Hence, it was relatively easy to move the saw out of the weak layer. We were able to identify such deviations on the video recordings, but only on the side facing the camera. The high values may therefore be due to imperfect sawing and show the difficulty in obtaining consistent PST results in weak layers which are not very well defined.

The median range, i.e. the difference between the highest and the lowest value, of the PST results on a given sampling day was 5.9 cm, so that the resulting uncertainty in the mean is about 2-3 cm. Reuter and Schweizer (2012) reported a standard deviation of the critical cut length on days with surface warming of about 5 cm. Similar variations for PST results on a single day at a single location have been reported by Gauthier and Jamieson (2008).

Therefore, we have no reason to dismiss these low values or attribute them to measurement errors. However, they may be related to spatial variations in weak layer and slab properties within the study plot. In fact, on 14 January 2015 we performed the PSTs at a location were the snow depth was below average compared to the rest of the study plot. On all other days snow stratigraphy was very similar, exemplified by mostly similar SMP profiles (not shown). Similar snow stratigraphy in study plots has, for instance, been shown by Pielmeier and Schneebeli (2001). Previous snow instability studies performed in level study plots suggested that measurements in general are reliable and that the effect of spatial variations is relatively small. Jamieson (1995) reported a mean coefficient of variation of shear strength of about 15% for sets of measurements in study plots. Correspondingly, variations in stability indices derived from study plot measurements of load and shear strength, two measurements that have comparable errors as the PST, were found to be indicative of avalanche activity (e.g., Jamieson et al., 2007). Though the PST results may be influenced by some small scale spatial variability of the snowpack in the study plot, we deem it unlikely that the observed minimum values are entirely the result of spatial variability, but indicate in fact a period of high propagation propensity. This interpretation is supported by the increased avalanche activity observed in late January and early February when many skier-triggered avalanches were observed (Figure 6).

4.2 Load, modulus and specific fracture energy

The temporal evolution of the parameters influencing the critical cut length, namely the load, the effective elastic slab modulus and the weak layer specific fracture energy, all exhibited similar, mostly increasing trends. The load obviously increased (Fig. 2b) and the results derived from the manual density measurements and the SMP profiles agreed well – in accordance with recent comparison studies (Proksch et al., 2015; Proksch et al., 2016).

The PTV-derived effective elastic modulus also increased, but the increase was not steady with some low values on 13 February 2015 (Figure 3a). These low values were also observed with the SMP (Figure 3b). The SMP-derived effective elastic modulus $E^{*\mathrm{SMP}}$, however, showed very low values on the very last sampling days – resulting in an overall decrease. When estimating the effective elastic modulus from the SMP-derived density, the agreement in temporal evolution was better. Indeed, overall $E_{\rho}^{*\mathrm{SMP}}$ also increased. The observation that the SMP-derived modulus occasionally decreases compared to the previous measurement day, for example, on 3 February and 3 March 2015 can be explained by the fact that on these days each a snowfall period ended. With the addition of new snow on the top of the existing slab, the effective elastic modulus in general decreases, unless the old slab layers below substantially settle so that the penetration resistance increases. In other words, the additional load due to the new snow leads to a thicker slab of lower average density, but also resulting in a lower effective elastic modulus.

In general, the weak layer specific fracture energy is expected to increase with time as sintering will increase bonding between crystals – unless the weak layer is subject to a large temperature gradient (e.g., van Herwijnen and Miller, 2013). Indeed, the PTV-derived weak layer specific fracture energy $w_{\mathrm{f}}^{\mathrm{PTV}}$ and the microstructural related specific fracture energy derived from the SMP signal $w_{\mathrm{f}}^{\mathrm{SMP}}$ exhibited a similar overall increasing trend (Figure 4). However, independent of the evaluation method, the increase occurred mostly after early February. This observation suggests that the weak layer toughening mainly occurred during the fair weather period without additional loading in February. A constant weak layer specific fracture energy in combination with additional loading by snowfall in January would have resulted in a decreasing critical cut length, in line with field observations.

With respect to the absolute values of the specific fracture energy, these should be considered as effective values since it is clear that they are too high compared to the specific fracture energy of ice (McClung, 2015). For the PTV-derived values, the discrepancy is most likely related to the fact that the observed bending in a PST includes non-elastic parts of deformation, thereby increasing the specific fracture energy to physically unrealistic values; for an in-depth discussion of this issue see van Herwijnen et al. (2016).

Compared to the weak layer specific fracture energy, the PTV- and SMP-derived values of the effective elastic modulus agreed less well. In particular, it is known that $E^{*\mathrm{SMP}}$ does not relate well to the PTV-derived modulus (Reuter et al., 2013). On the other hand, van Herwijnen et al. (2016) recently showed that the PTV-derived modulus fits relatively well with results from laboratory experiments in the same range of strain rates. The SMP-derived modulus $E^{*\mathrm{SMP}}$ includes the complex interaction between the cone and surrounding snow microstructure and does obviously not reflect simple elastic deformation, but breaking, jamming and other local effects occur (LeBaron et al., 2014; van Herwijnen, 2013). Obviously, the SMP-derived modulus $E_{\rho}^{*\mathrm{SMP}}$, which relies on the relatively robust density derivation, agreed somewhat better with the PTV-derived modulus.

Whereas the temporal evolution can well be compared, the absolute values cannot, since the SMP-derived values of $E^{*\mathrm{SMP}}$ and $w_{\mathrm{f}}^{\mathrm{SMP}}$ were scaled to the corresponding PTV values to ease comparison. The scaling was performed using a larger dataset (unpublished) of side-by-side PST and SMP measurements. It is beyond the scope of this study to provide a quantitative comparison of the two methods; it will be the subject of a publication currently in preparation (Reuter et al., 2016a). To conclude the discussion on the PTV and SMP-derived values, below we present an error assessment – as far as this is possible.

The errors associated with the parameters derived from the PTV analysis (i.e. the measurement uncertainty) were about 20% (or about 1 MPa) for the modulus and about 18% (or about 0.14 J/m^2) for the weak layer specific fracture energy. These estimates are based on calculating these properties 1000 times for each experiment accounting for the uncertainty in the input parameters (uncertainty in the distance measurements in the field, density measurements, and especially the location estimates of the dots in the PTV analysis). van Herwijnen et al. (2016) showed that the reproducibility of side-by-side measurements for the slab modulus was good (even though they have greater uncertainty), whereas the reproducibility for the weak layer specific fracture energy was lower. The better reproducibility for the modulus might be related to the fact that the modulus is an integrated property over all slab layers and hence may be less sensitive to spatial variations of one layer.

The errors of the SMP-derived parameters are more difficult to assess. However, Proksch et al. (2015) showed that the SMP-derived density is a reliable measure. Their finding is supported by our measurements showing good reproducibility between SMP-derived and manually measured load (Figure 2b). However, in particular the derivation of the effective elastic modulus is more prone to errors. In general, the variability of SMP-derived microstructural parameters is rather high. Thus, any value which is indirectly derived from these microstructural parameters will exhibit large variations; in particular values of the deflection at rupture δ are relatively unreliable (Löwe and van Herwijnen, 2012).

4.3 Metrics of instability

The SMP-derived metrics of point snow instability, the failure initiation criterion S and the crack propagation criterion $r_{\mathrm{c}}^{\mathrm{SMP}}$, were recently developed and validated (Reuter et al., 2015). Here, we applied them for the first time to monitor the temporal evolution of instability. The failure initiation criterion S increased with time suggesting that initiating a failure in the weak layer became increasingly difficult during the sampling period. This tendency is supported by the results of the two small column snow instability tests (Table 1, Figure 6). CT/ECT scores increased from around 20 to 30 taps. The absolute values of S were rather high, in the range that was considered as rather stable by Reuter et al. (2015). Again, this is in agreement with the rather high scores of the CTs and ECTs and is related to the fact that by the end of January 2015 the weak layer was buried below a thick slab of more than 1 m. Weak layers buried deeper than 1 m are not frequently triggered by skiers (e.g., Schweizer and Jamieson, 2007).

The crack propagation criterion r_c^{SMP} overall increased in agreement with the observations (Figure 2a). It showed a similar evolution with time as the SMP-derived weak layer specific fracture energy, which is used to calculate r_c^{SMP}. A relative decrease towards the end of January was also observed but was less prominent than for r_c^{OBS}. Despite substantial scatter, until early February about half of the values were between 35 and 45 cm. Only after mid February r_c^{SMP} values increased to about 70 cm. Considering the threshold values indicating unstable conditions $S < 234$ and $r_c^{SMP} < 41$ cm suggested by Reuter et al. (2015), the two criteria predict unstable conditions in early January. In fact, signs of instability were observed by the field team on 6 January and 28 January 2015; on the latter day the lowest values of critical cut length were observed in PSTs. However, at that day the failure initiation criterion was already high ($S \approx 590$), since the slab thickness was >1 m.

Based on the simulated snow stratigraphy provided by SNOWPACK, we presented two corresponding metrics of instability. Overall, snow stratigraphy was well simulated, as exemplified by the comparison shown in Figure 1. Despite large differences in vertical resolution, the simulated SNOWPACK profile, the manually observed profile and the SMP profile qualitatively agreed well.

The SNOWPACK-derived skier stability index SK38 varied between about 1.0 and 1.35 and did not show any trend with time. This is in contrast to the increasing scores obtained with CTs and ECTs. Whereas the skier stability index SK38 initially increased in agreement with the observation, it subsequently mainly reflected whether there was any loading by new snow. After the end of January when the weak layer was deeply buried, the SK38 did no longer indicate skier triggering but yielded almost the same value as the natural stability index (not shown) since $\Delta\tau$, the additional shear stress due to a skier, became negligibly small. Accordingly, increasing load due to snowfall resulted in a decreasing SK38 as shown towards the end of February and in early March. In other words, the SK38 became dominated by the static shear stress. In contrast, the SMP-derived initiation criterion S does not include the static shear stress, and hence showed a different behaviour with time. As Schweizer and Reuter (2015) pointed out, the dynamic load, rather than the static load due to the weight of the slab, is essential for initiating a failure due to the well-known deformation rate dependence of snow strength (e.g., Reiweger and Schweizer, 2010).

The modelled critical cut length r_c^{SNP} (Eq. 8) based on recent findings by Gaume et al. (2016) steadily increased over the two-month period. All three essential variables, namely the load, the slab modulus and the weak layer shear strength overall increased with time. Whereas an increase of the load – all other variables remaining unchanged – would result in a decrease of the critical cut length, increasing slab modulus as well as increasing weak layer shear strength leads to increasing critical cut length. The latter two variables are directly related to snow density which in general increases with time – except for the average slab density which may temporarily decrease after a snowfall. In our case, with regard to the critical crack length r_c^{SNP}, the effect of increasing load was clearly over-compensated by the effects of increasing slab effective modulus and increasing weak layer shear strength.

The discrepancy with the observed critical cut length seems to be due to the weak layer shear strength which strongly increased with increasing density from initially 0.9 to 1.9 kPa in early March – though persistent weak layers are known to hardly settle despite increasing overburden pressure due to their anisotropic microstructure (e.g., Reiweger and Schweizer, 2010; Walters and Adams, 2014). In fact, the SMP analysis of the weak layer strength (not shown) suggests that the increase was not as prominent as shown by SNOWPACK where the shear strength is parameterized based on the extensive shear frame measurements by Jamieson and Johnston (2001). Whereas Gaume et al. (2016) recently showed that the modelled critical cut length r_c^{SNP} of the weak layer we tested was lower than of the adjacent layers – suggesting that the modelled critical cut length can well discriminate between weak layers and other layers within a given snow stratigraphy, it seems more challenging to predict changes over time since small changes of the contributing variables may decide whether the critical cut length increases or decreases.

4.4 Case studies

In general, considering the fracture mechanical approach (Anderson, 2005) reveals that in a first order approximation $r_c \sim \frac{w_f E}{\sigma^2}$; the critical crack length decreases with increasing load, and increases with either increasing slab elastic modulus or increasing specific fracture energy of the weak layer. To explore the complex interaction of these parameters described by Eq. 7, we presented four case studies. They show how the temporal evolution of the load and the modulus of the slab, and the specific fracture energy of the weak layer affects the changes of the critical cut length with time. The most influential parameter seems to be the load. Even with an increasing weak layer specific fracture energy, the increasing load caused the cut length to decrease (Figures 7c,d). This consistent decrease was however not observed in the field, where only towards the end of January the critical crack length decreased and then clearly increased towards the end of the measurement period. This suggests that the increase in slab modulus and/or specific fracture energy (over)-compensated the effect of the increasing load. The fourth case, more or less mimicking the observed changes with time of the three variables, shows that under certain conditions the cut length may increase or decrease with time, primarily due to subtle changes of slab properties. Exploring Eq. 8 relating slab modulus and load, and weak layer shear strength provided very similar results (not shown) and confirms the findings of the case studies.

5 Conclusions

We monitored the temporal evolution of a weak layer of faceted crystals that was one of the critical weaknesses during the winter 2014-2015 in the region of Davos (Eastern Swiss Alps). We focused on the crack propagation propensity and performed propagation saw tests on seven sampling days during a two-month period from early January to early March 2015. Tests were completed with objective measurements, namely by resistance profiles acquired with the snow micro-penetrometer and particle tracking velocimetry based on video images of the PSTs. Our dataset represents the first comprehensive time series of quantitative measures of critical cut length and related mechanical properties of slab layers and weak layer. In addition, we compared our field observations to newly developed metrics of instability either derived from the SMP signal or from modelled snow stratigraphy.

The critical cut length, observed in the PSTs, showed an overall tendency to increase with time. However, the lowest values were observed towards the end of January/early February. These low values were not expected and seem to be the result of the complex interaction of slab and weak layer properties – rather than of measurements errors or large spatial variations within the study plot.

The relevant mechanical properties, the effective elastic modulus of the slab and the weak layer specific fracture energy, overall increased, independent of the evaluation method. Only the SMP-derived effective elastic modulus $E^{*\mathrm{SMP}}$ showed a different behaviour. However, the increase was not steady and these small changes likely affected the critical cut length as exemplified with the case studies. These findings suggest that it is not possible to assess the critical cut length, or in general crack propagation propensity, by simply monitoring a subset of these mechanical properties. One has to consider the complex interaction between the effective elastic modulus of the slab, the load due to the slab, and the weak layer specific fracture energy. Furthermore, these properties have to be determined with good accuracy since otherwise reliably modelling the critical cut length is not possible.

We then applied traditional (such as the SK38) and newly-developed metrics of snow instability describing either the failure initiation or the crack propagation propensity. These metrics were derived from the SMP signal or calculated from simulated snow stratigraphy (SNOWPACK) and partially reproduced the observed temporal patterns. Whereas the SMP-derived initiation criterion appropriately indicated that triggering probability overall decreased, the skier stability index provided by SNOWPACK did not show this tendency, but indicated the period of increased avalanche activity towards the end of January. The predicted critical cut lengths, r_c^{SMP} and r_c^{SNP}, overall increased with time. Whereas the SMP-derived propagation criterion r_c^{SMP} partly reproduced the unsteady increase with some lower values towards the end of January, the SNOWPACK-derived critical cut length r_c^{SNP} did not show any of the observed variation in critical cut length, apart from the overall increase.

Whereas the PST combined with the PTV approach seems to provide the most reliable measure of propagation propensity and corresponding mechanical properties, the procedure is time consuming. However, this disadvantage can only be outweighed, if modelled metrics of instability become more reliable. This will require further validation studies – best performed by comprehensive field measurements in study plots equipped with an automatic weather station, and possibly an enhancement of the representation of mechanical properties in the model based on cold laboratory studies.

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Tables

Table 1: Snowpack characteristics and snow instability test results on the eight measurements days. For the PST the total number of tests and the number of tests with crack propagation to the end of the column, for the CT the score and the fracture type (SP: sudden planar, SC: sudden collapse), and for the ECT the fracture type (X: no fracture, N: initiation, but no propagation, P: propagation to column end) and the score are given (Greene et al., 2010).

Date	Snow depth (cm)	Slab thickness (cm)	Slab density (kg m^{-3})	Load (kPa)	Test results		
					PST total/END	CT	ECT
06 Jan 2015	115	59	245	1.42	5/2	19 SP	X, N20
14 Jan 2015	110	56	272	1.50	5/0	19 SC, 21 SC	P21
21 Jan 2015	126	72	275	1.94	2/1	13 SC	P21
28 Jan 2015	161	108	207	2.20	3/3	29 SC	X, P27
03 Feb 2015	172	117	242	2.78	3/3	22 SC	P27
13 Feb 2015	139	97	309	2.94	4/4	28 SP	P22
19 Feb 2015	147	n/a	n/a	n/a	n/a	n/a	n/a
03 Mar 2015	193	148	269	3.90	3/3	26 SC	P30, P30

Figures

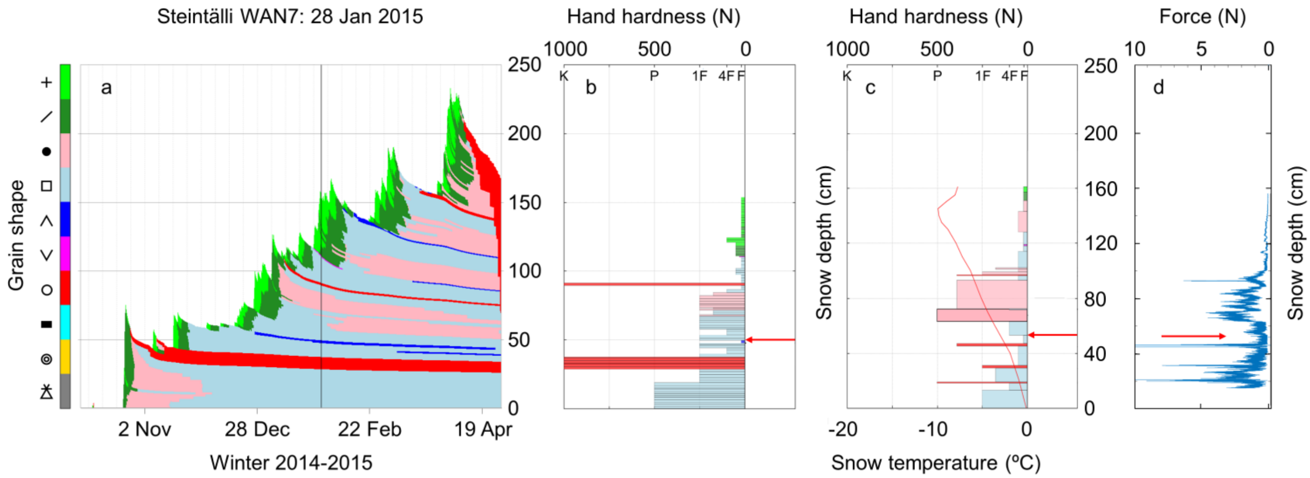

Figure 1: (a) SNOWPACK simulation for the location of the automatic weather station (AWS) WAN7 for winter 2014-2015 showing the evolution of grain shape, black vertical line indicates date of snow profile (28 Jan 2015), (b) simulated snow profile for 28 Jan 2015, (c) manually observed snow profile at the location of the AWS on 28 Jan 2015, (d) corresponding SMP penetration force signal measured at the location of the manual profile. Red arrows point to the weak layer.

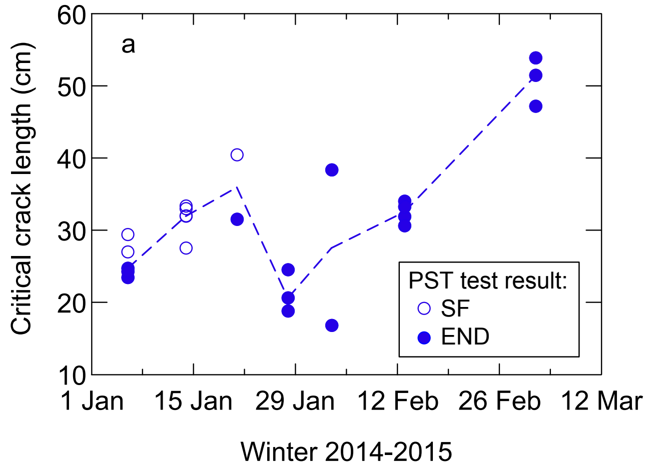

Figure 2: (a) Critical cut length as observed in propagation saw tests ($N = 23$). Full circles indicate crack propagation to the very end of the column (END), open circles indicate partial propagation resulting in a fracture across the slab (SF); dashed line connects the median values per day. (b) Load on the weak layer: red open circles (connected by dotted line) show the load as calculated from the manually observed density and layer thickness; blue diamonds are corresponding SMP-derived values ($N = 50$). The black solid line indicates the load as provided by SNOWPACK.

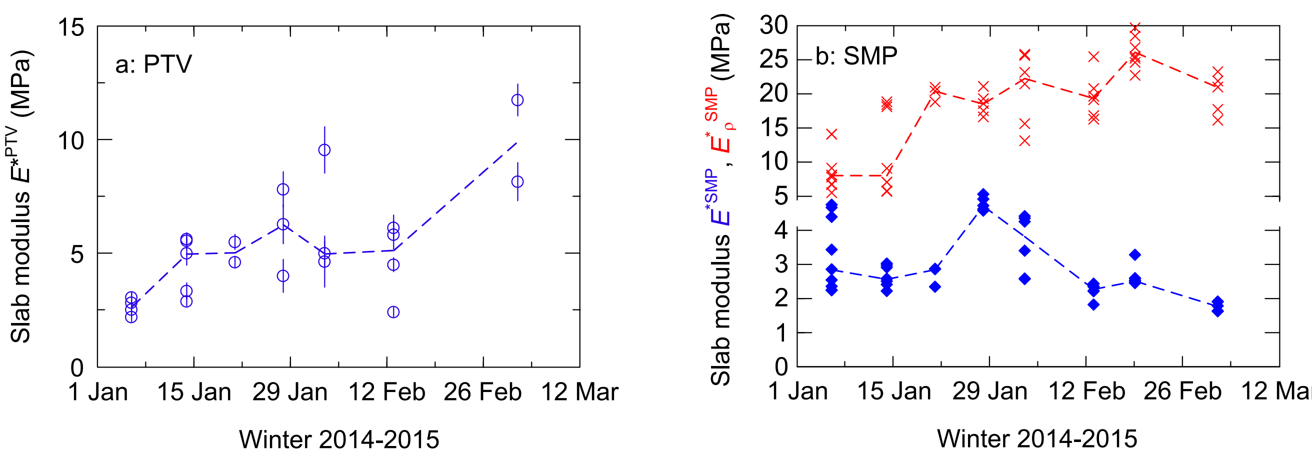

Figure 3: Effective elastic modulus of the slab derived from (a) the bending of the slab via PTV analysis with vertical lines denoting measurement uncertainty ($N = 24$), and (b) from the SMP signal analysis ($N = 50$), either directly E^{*SMP} (solid blue triangles) or via density $E^{*}_{\rho}{}^{SMP}$ (red crosses). Dashed lines connect the median values per day.

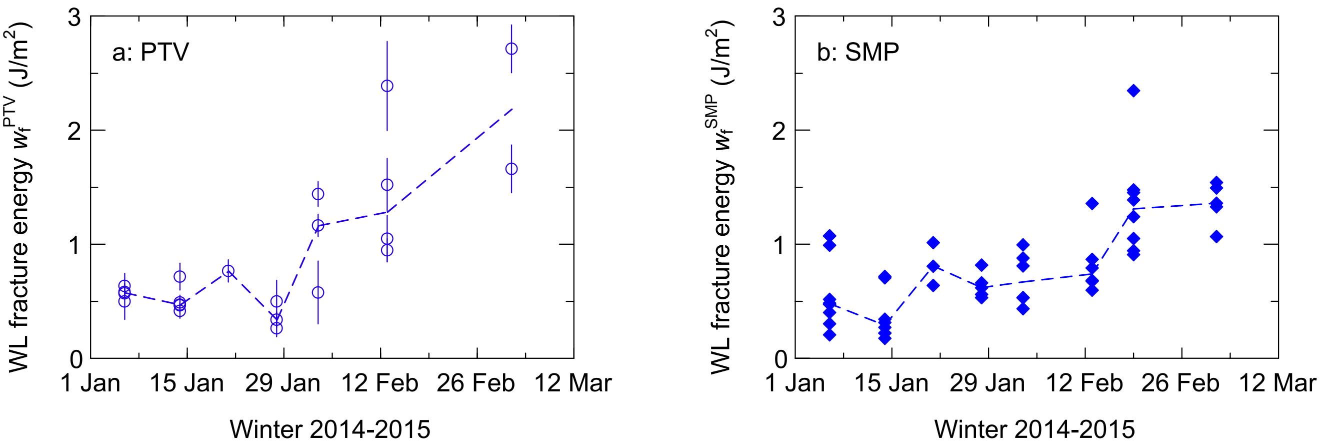

Figure 4: Weak layer specific fracture energy derived from (a) the bending of the slab via PTV analysis (*N* = 24) with vertical lines denoting measurement uncertainty, and (b) from the SMP signal analysis (*N* = 50). Dashed lines connect the median values per day.

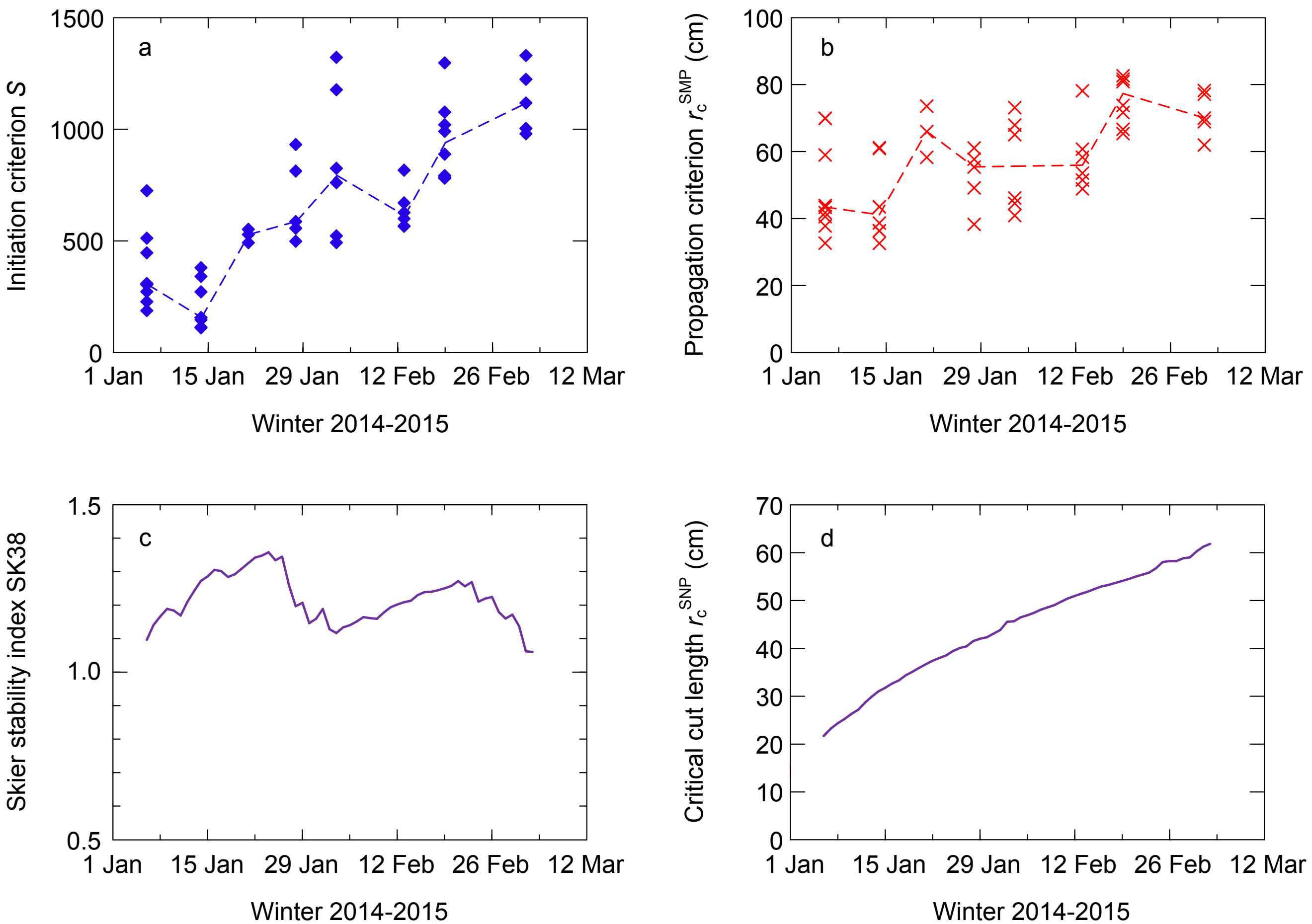

Figure 5: Instability criteria: (a) SMP-derived failure initiation criterion *S*, and (b) SMP-derived crack propagation criterion r_c^{SMP}; dashed lines connect median values per day ($N = 50$). Output of the numerical snow cover model SNOWPACK: (c) Skier stability index SK38, and (d) modelled critical cut length r_c^{SNP}.

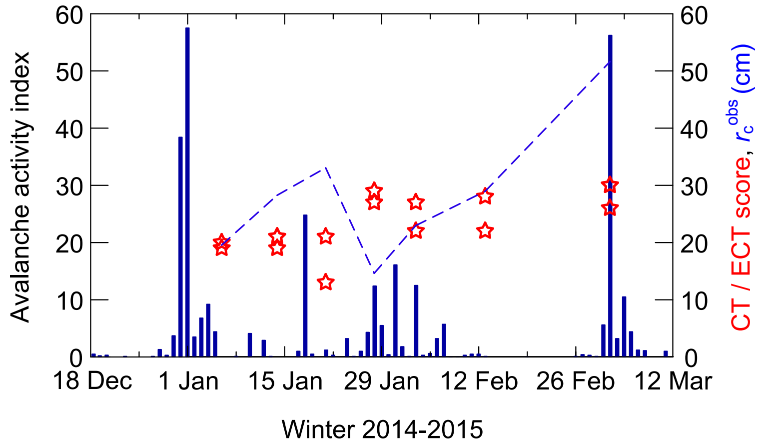

Figure 6: Avalanche activity index for the region of Davos (columns), results of the CTs and ECTs performed concurrently with the snow profile observations on seven out of eight sampling days (red asterisks), the number of taps (score) is shown, and the observed critical cut length r_c^{obs} (dashed blue line, as in Fig. 2).

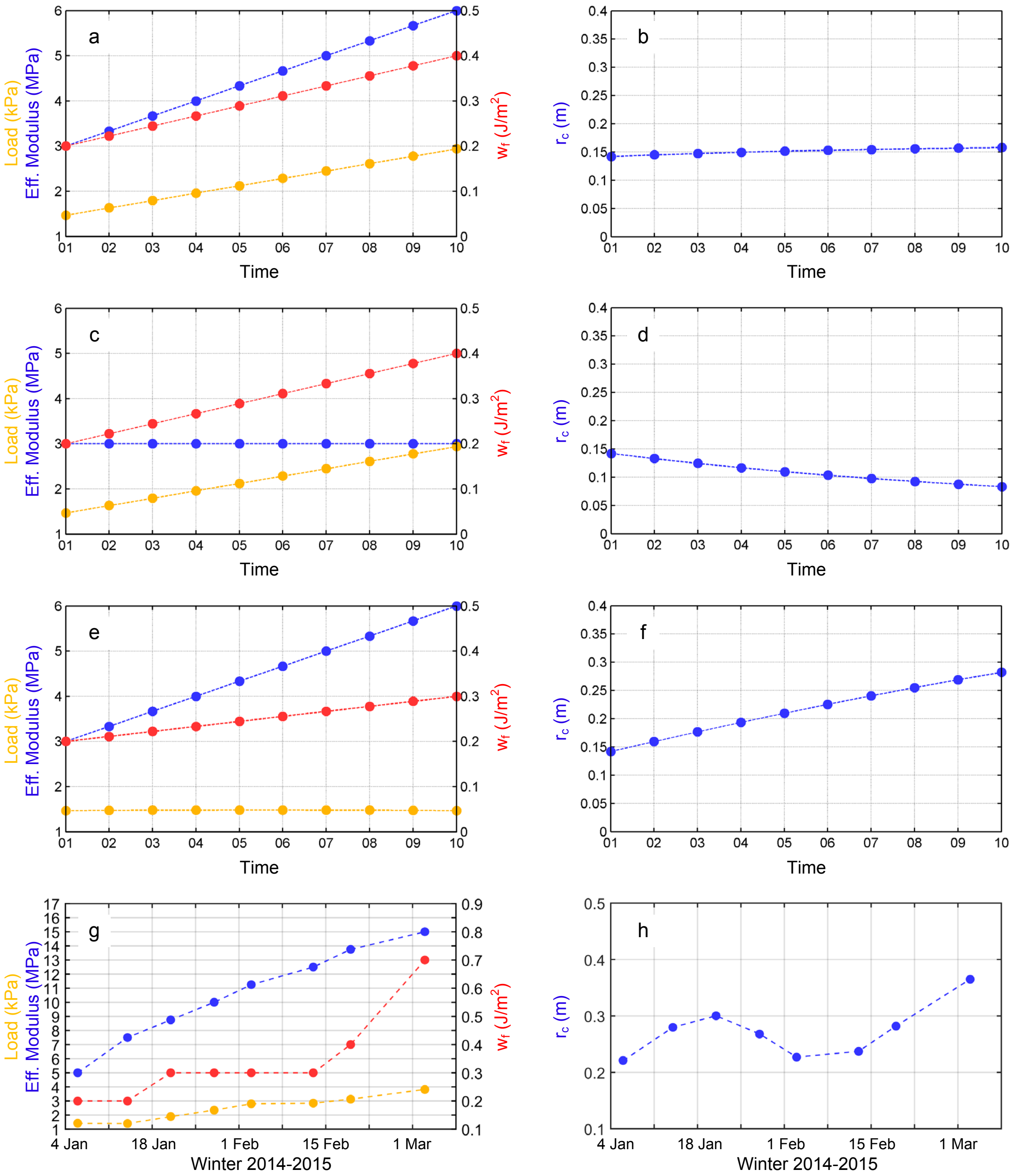

Figure 7: Sensitivity study on how the critical cut length r_c varies as a function of the load and the effective modulus of the slab, and the specific fracture energy of the weak layer w_f. Arbitrary units of time for the three simplified scenarios shown in panels (a) to (f). In the last scenario (g,h), the situation during the sampling period is supposed to be roughly mimicked.