SENSITIVITY OF MODELED SNOW INSTABILITY TO METEOROLOGICAL INPUT UNCERTAINTY

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ABSTRACT: To perform spatial snow cover simulations for numerical avalanche forecasting, interpolation and downscaling of meteorological data is required, which can introduce uncertainties. The repercussions of these uncertainties on modeled snow instability remain mostly unknown. We therefore assessed the contribution of meteorological input uncertainty on modeled snow instability by performing a global sensitivity analysis. We used the model SNOWPACK to simulate snow instability, i.e. the skier stability index and the critical crack length, for a field site equipped with an automatic weather station providing the necessary input for the model. Uncertainty ranges for meteorological forcing covered typical differences observed within a distance of 2 km and an elevation change of 200 m. Two different scenarios were investigated to better understand the influence of meteorological forcing on snow instability during a) the weak layer formation period and b) the slab formation period. Results showed that during the weak layer formation period, the evolution of weak layer properties and subsequent snow instability were sensitive to all input parameters. In particular, increasing air temperature and increasing precipitation led to higher stability indices. Once a certain weak layer had formed, precipitation was the most prominent driver for snow instability during the slab formation period. While with increasing precipitation the skier stability index decreased, the critical crack length increased. Such findings help with selecting model resolution and complexity, interpreting spatial snow simulations and understanding the evolution of snow instability.

Keywords: Avalanche forecasting, snow instability, sensitivity, model uncertainties

1. INTRODUCTION

Snow avalanches are a natural hazard which can endanger roads, villages and human lives. When assessing the avalanche danger in the context of avalanche forecasting, data on current snowpack and meteorological conditions are evaluated in combination with weather forecasts.

Snowpack observations include data on snow stratigraphy and snow instability. The temporal and spatial resolution of such data is very limited. Detailed snow cover models, which simulate the full snowpack stratigraphy, can help fill this gap (e.g. Lafaysse et al., 2013), in particular if they also provide snow instability information (e.g. Lehning et al., 2004; Vernay et al., 2015).

A dry-snow slab avalanche starts with a failure within a so-called weak layer. Such weak layers often form near or at the snow surface and, if subsequently covered by a snowfall, can sometimes persist throughout the season. Whether avalanche release is likely, depends on the complex interaction between slab layers and the weak layer. The two key processes in avalanche release, failure initiation and crack propagation, can respectively be described with a stress-strength approach (or stability index) and a fracture mechanical approach (critical crack length as observed in a propagation saw test; Reuter et al., 2015; Schweizer et al., 2016).

While spatially simulating snow instability for numerical avalanche forecasting, uncertainties due to spatial interpolation of meteorological data may arise. However, only a few studies have so far assessed the uncertainty of snow cover models. A multi-physical ensemble system was built to estimate the uncertainty in modeled snow height, density and albedo resulting from different physical parameterizations within a snow-cover model (Lafaysse et al., 2017). Raleigh et al. (2015) investigated how different error types, magnitudes and distributions of meteorological input parameters influence physically based simulations of snow water equivalent, ablation rates, snow disappearance and ablation. They employed a global sensitivity analysis based on variance decomposition, which allowed to investigate the fractional contribution of different input parameters on the output of non-linear models. Sauter and Obleitner (2015) performed a similar analysis to explore the influence of input uncertainty on surface-energy balance components of snow cover models. However, no study so far addressed the sensitivity

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of modeled snow instability.
We therefore investigated how meteorological input uncertainty influenced modeled snow instability using a global sensitivity analysis. We performed simulations for the winter season 2016-2017, when one weak layer persisted for the entire season and affected the avalanche activity within the region of Davos, Switzerland. We analyzed modeled snow instability parameters related to this weak layer in two steps: we independently investigated the influence of meteorological input uncertainty during the periods of a) weak layer formation and b) slab formation.

Forcing	Distribution	Range	Unit
P	Lognormal	[-75,+300]	%
TA	Normal	[-3.0,+3.0]	°C
RH	Normal	[-25,+25]	%
VW	Normal	[-3.0,+3.0]	ms^{-1}
ISWR	Normal	[-100,+100]	Wm^{-2}
ILWR	Normal	[-25,+25]	Wm^{-2}

Table 1: Input uncertainties introduced as bias to meteorological forcing. All bias were additive and normally distributed, except for P, which had a lognormally distributed multiplicative bias.

2. METHODS

2.1. Study site and data

We used data from the field site Weissfluhjoch (WFJ), located in the eastern Swiss Alps above Davos, at an elevation of 2536 m a.s.l. The field site is equipped with an automatic weather station (AWS) and daily snow measurements are available. Additionally, weekly traditional snow profiles and stability tests were conducted. The winter season 2016-2017 was selected for this study, since the snowpack was marked by a weak basal layer and a pronounced avalanche cycle on 9 March 2017. The weak layer formed in November 2016 at the surface of the shallow snowpack and it was buried by a snowfall on 2 January 2017. For the analysis we will focus on the formation and evolution of this particular layer and its effect on snow instability for the period of high avalanche activity on 9 March 2017.

2.2. Forcing uncertainties

Uncertainties introduced in the measured meteorological data set were similar to those found in nature (Table 1). For example, the uncertainty range for P reflected spatial variations found between windward and lee side of slopes, while uncertainties included in ISWR reflected south- and north-facing slopes. Hence, uncertainties can be seen as systematic bias with a given range and distribution (normally distributed for additive bias and lognormally distributed for multiplicative bias) as suggested by Raleigh et al. (2015). The probability distributions were described by mean (normal: 1, lognormal: 20) and standard deviation (normal: 1, lognormal: 0.5) and then scaled within the given ranges. The bias b was added to the forcing F as $F' = F + b$ for additive bias and $F' = F(1 + b)$ for multiplicative bias. Bias resulting in non-physical forcing values were filtered to a physical range (i.e. RH was filtered within a range of [0,100]%).
To assess whether weak or slab layer formation had a greater impact on snow instability, we examined two different scenarios. First, uncertainties on meteorological forcing were introduced up to the date when the weak basal layer was covered with new snow. The subsequent slab formation process occurred under the same conditions as in the reference run (case WL). Second, the weak layer formation was identical to the reference run, while uncertainties were introduced during the slab formation period (case SL). For each scenario, 14,000 simulations (ensemble) were performed.

2.3. Global sensitivity analysis

To analyze the influence of input uncertainty while considering co-existing sources of uncertainty we used a global sensitivity analysis rather than varying one input factor at a time while keeping all others fixed. Sobol‘ (1990) suggested a robust method for nonlinear models based on variance decomposition. A quasi-random set of input uncertainties was defined (Saltelli and Annoni, 2010; Saltelli et al., 2010) and the total-order sensitivity index (S_{Ti}) was calculated as:

$$S_{Ti} = \frac{E\left[V(\mathbf{Y}|\Phi_{\sim i})\right]}{V(\mathbf{Y})} = 1 - \frac{V\left[E(\mathbf{Y}|\Phi_{\sim i})\right]}{V(\mathbf{Y})},$$

where E is the expectation operator, V is the variance operator, $\mathbf{Y}$ is the model output and $\Phi_{\sim i}$ are all input parameters except Φ_i. We focused on S_{Ti} only since uncertainty interactions were low. The setup for generating input uncertainties and the subsequent sensitivity analysis is described in detail by Raleigh et al. (2015).

2.4. SNOWPACK

We conducted the simulations with the snow cover model SNOWPACK version v1473 (e.g. Lehning et al., 2002). SNOWPACK was driven with meteorological data from the AWS at WFJ, including precipitation (P), air temperature (TA), relative humidity (RH), wind velocity (VW), incoming shortwave (ISWR) and longwave (ILWR) radiation. When introducing input uncertainties, SNOWPACK was forced to explicitly exclude data on measured snow height, outgoing shortwave radiation and snow surface temperature. Neumann boundary conditions were used at the snow-atmosphere interface. The time step for the simulation was 15 min and output was written every 24 h. For the reference run we used data from the optimal data set at WFJ (WSL Institute for Snow and Avalanche Research SLF, 2015).

2.5. Model output

The sensitivity analysis focused on weak and slab layer properties, as well as modeled snow instability. In particular, the skier stability index SK38 and the critical crack length r_c (Gaume et al., 2017) were analyzed. We selected the weak basal layer that formed between 16 November 2016 and 2 January 2017. Only simulated snow layers that were deposited between these two dates and consisted of either depth hoar, surface hoar, facets and rounded facets were considered as weak layer. Then weak layer properties were obtained by a weighted average $\bar{y}$ of the layer properties y_i:

$$\bar{y} = \frac{\sum y_i\, d_i}{\sum d_i},$$

where d_i is the thickness of the simulated layer i. In analogy, slab layer properties were calculated from all layers deposited after 2 January 2017, independent of grain type.

3. RESULTS

3.1. Propagation of input uncertainties to model output

In the reference run there was a melt-freeze crust at the snow surface at around 30 cm in mid November (not shown). Between 16 November 2016 and 2 January 2017, an additional 20 cm of snow accumulated above the crust. As the weather was mostly clear, the shallow snowpack was exposed to strong temperature gradients during that period. After 2 January 2017, several small snow storms occurred such that the snow height reached about 200 cm on 9 March 2017.

The ensemble for case WL showed an approximately constant spread in snow height from the beginning of the season (Figure 1a). In contrast, case SL diverged starting in January with a three times higher spread until 9 March 2017 with snow heights between 100-600 cm (Figure 1b). In around 0.3% of the 14,000 simulations, the weak layer did not form for the case WL. This was mostly related to warmer air temperature. For the analysis, runs without a weak layer were excluded. Furthermore, weak layer properties, such as density and shear strength, increased with increasing P and increasing TA and subsequently determined snow instability. All runs showed an initial increase in snow stability, i.e. SK38 and r_c, with time (Figures 2 and 3). Temporary decreases in snow stability followed the increase in snow height during precipitation events. A decrease in snow stability was also observed during the period of high avalanche activity on 9 March 2017 (grey areas in Figures 1, 2 and 3). For case WL, modeled snow instability indices generally showed a lower variance compared to case SL (yellow colors in Figures 2a and 3a).

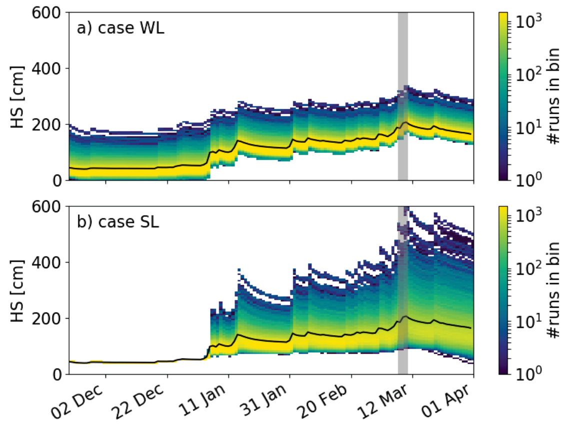

Figure 1: Propagation of input uncertainties to modeled snow height HS for (a) case WL and (b) case SL. Density plots showing the number of simulations in each of the 100 bins in the HS dimension each day. The black lines show the reference run and grey areas highlight the period of high avalanche activity.

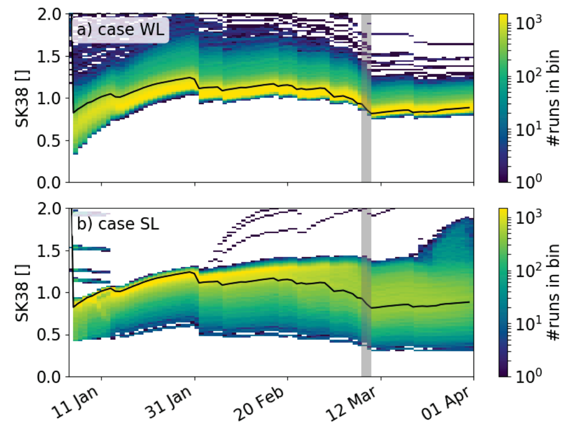

Figure 2: Propagation of input uncertainties to modeled skier stability index SK38 for (a) case WL and (b) case SL. Density plots showing the number of simulations in each of the 100 bins in the SK38 dimension each day. The black lines show the reference run and grey areas highlight the period of high avalanche activity.

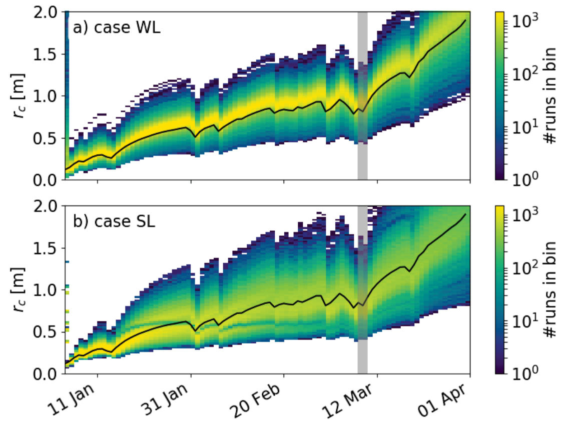

Figure 3: Propagation of input uncertainties to modeled critical crack length r_c for (a) case WL and (b) case SL. Density plots showing the number of simulations in each of the 100 bins in the r_c dimension each day. The black lines show the reference run and grey areas highlight the period of high avalanche activity.

3.2. Evolution of total-order sensitivity indices

During the weak layer formation period, the percentage of faceted layers developing within this period was mostly sensitive to TA - again we were only considering simulations, in which a weak layer formed. The total-order sensitivity indices S_T suggest that weak layer properties, for example density, thickness, shear strength, sphericity and bond size, were most sensitive to TA and P, although all input parameters had a non-negligible influence. Also the stability indices, SK38 and r_c, were sensitive to all input parameters for case WL (Figure 4a,b). While r_c was most sensitive to precipitation, SK38 was mostly sensitive to air temperature (case WL). In contrast, for case SL, the total-order sensitivity clearly highlighted precipitation as the most dominant input parameter for weak and slab layer properties, as well as stability indices (Figure 4c,d).

3.3. Case study: 9 March 2017

Figure 5 shows the input parameters with the highest sensitivity index S_T for SK38 (left) and r_c (right) for case WL (upper) and case SL (lower). In both cases, increased precipitation yielded larger critical crack lengths. This trend is very clear for case SL (Figure 5c), suggesting that once a weak layer formed, precipitation clearly determined crack length. Although during a precipitation event, r_c temporarily decreased (Figure 3) the load by the slab determined the consolidation of the weak layer as well as the slab layers. A higher load induced higher weak layer strength and stiffer slab so that r_c increased. For case WL both, r_c and SK38 increased with increasing precipitation and increasing air temperature (Figure 5a,b). However, higher precipitation for case SL led to lower SK38 (Figure 5c). This suggested that within the stress-strength approach, the increase in stress due to the slab load seemed to dominate compared to the strengthening of the weak layer. With increasing slab thickness skier triggering becomes unlikely and SK38 is no longer meaningful. Instead the natural stability index SN38 may be considered.

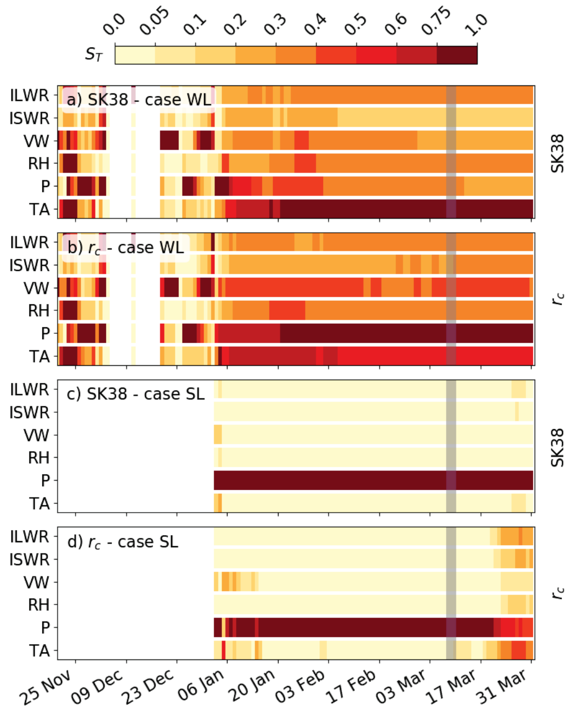

Figure 4: Evolution of the total sensitivity index S_T of the model output SK38 and r_c for case WL and case SL (from top to bottom). Grey area highlights period of high avalanche activity.

4. SUMMARY

We investigated the sensitivity of modeled snow instability on meteorological input uncertainty employing a global sensitivity analysis. In detail we examined two scenarios, case WL and case SL, in which uncertainties were introduced during the weak layer formation period and the slab layer formation period, respectively. Results can be summarized as follows:

Case WL:

- Weak layer properties were highly sensitive to all input parameters, especially P and TA.
- Weak layer thickness increased with increasing P and decreasing TA.

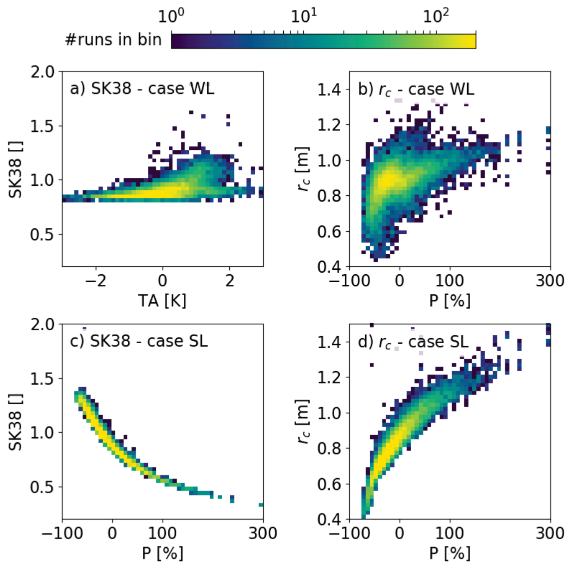

Figure 5: Modeled SK38 (left) and r_c (right) with input uncertainties of most sensitive input parameter for case WL (upper) and case SL (lower) on 9 March 2017. Density plot showing the number of simulations in each of the 50×50 bins.

- Weak layer density and shear strength increased with increasing P and increasing TA.
- Modeled stability indices had a low variance and increased with increasing P and increasing TA (faint increase with other parameters).

Case SL:

- Once a weak layer formed, precipitation was most important for weak and slab layer properties, including modeled snow instability.
- Increasing precipitation increased thickness, density and stiffness of slab layers.
- Increasing precipitation caused faster settling of the weak layer and therefore higher shear strength.
- A general increase of r_c with time could be observed with temporary decreases during precipitation events.
- After an initial increase until the end of January, SK38 decreased.
- On 9 March 2017, r_c increased with increasing precipitation (many factors, such as shear strength contribute), whereas SK38 decreased.

For the two scenarios, we conclude that a) weak layer properties determined modeled snow instability and to properly model these properties, the correct meteorological conditions during the weak layer formation period have to be known and b) once these weak layer properties are known, modeled snow instability is mostly sensitive to precipitation.

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