Systematic Assessment of New Snow Settlement in SNOWPACK

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ABSTRACT: New snow settlement in the very first hours and days after a snowfall has not yet been fully understood. Modelling errors at this initial stage propagate through a whole winter season, thus affecting a correct modelling of crucial snow cover properties such as density, temperature distribution and snow depth. Up to now, parameter tuning for settling in SNOWPACK has mainly been done by visual comparison of modelled with measured settling curves. This can be accomplished by tracking model layers that correspond to positions of combined settlement and temperature sensors (snow harps). As a result, verification of model performance with in situ measurements is possible. Furthermore, using such a harp as a lower boundary condition, snow-cover evolution above this harp can be analysed irrespective of earlier simulation errors. Here comprehensive data sets obtained during a number of snowfall periods are used. In addition to snow harp data, high resolution density profiles taken in the days following a snowfall provide for further verification of the simulated snow-cover evolution. Based on these observations we present a systematic approach to assess the performance of the model both during and a few days after snowfalls. Sensitivity studies allow to locate the most important model parameters which influence the settlement of freshly deposited snow. The specific influence of both type (grain and bond sizes) and state variables (temperature) was investigated in more detail. As a consequence, a new temperature parameterisation is suggested. This proved valuable for enhanced investigation of single snowfall events, while a significant improvement of long-term simulations of snow settling is still pending.

KEYWORDS: New snow, Settlement, SNOWPACK, Snow harps

1 INTRODUCTION

Snow cover models provide avalanche forecasters with supplementary information in cases where digging snow pits is not feasible either due to bad weather conditions, safety concerns, lack of time, or simply inaccessibility of the location. This case study considers SNOWPACK, which is a one-dimensional snow-cover model and was primarily developed for the support of avalanche warning in Switzerland. The model is driven by data from automatic weather stations and can be initialised with observed snow profiles. The evolution of snow microstructure is parameterised allowing for a detailed representation of the snow-cover layers (Bartelt and Lehning (2002), Lehning et al. (2002a, 2002b), Lehning and Fierz (2008)).

The initial amount and the evolution of new snow during and immediately after a snowfall are crucial for avalanche formation. This also concerns the treatment of snow settlement processes, because modelling errors will propagate through a whole winter season, thus affecting all important snow cover properties like density, temperature distribution and snow depth.

First, we describe some inherent problems related to the modelling of new snow properties and their subsequent evolution in the context of settling processes.

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Second, objective methods are developed for enhanced investigation of SNOWPACK's settlement routine. The results of single parameter sensitivity studies lead to the reformulation of the temperature dependency of snow viscosity and a simplification of the settling routines. This results in a slight increase of overall model performance.

2 DATA

Considerable effort was put into thorough processing of relevant data to make reasonable comparisons between modelled and measured values. We only considered comprehensive data sets gathered during the winter 2005/2006 at the Weissfluhjoch study plot, located at 2540 m a.s.l. above the town of Davos, Switzerland. The following measurements were used to prepare optimum input data for the simulations:

- Regular and specialised snow profiles
- Data from 3 different automatic weather stations
- Snow harps (continuous settlement measurements)
- Precipitation gauges and snow depth sensors

We note that the same data was used by C. Zwart in his master thesis to achieve a better parametrisation of new snow densities (Zwart (2007)).

A snow harp is a measurement device developed at the SLF to simultaneously measure the settlement and temperature of a certain snow layer within the snowpack. In order to be able to analyse the settlement of harps in SNOWPACK, it is possible to *tag* a single element at a given height and follow its temporal evolution during the whole season. Consequently, it is possible to compare modelled (tags) to measured (harps) settling curves as shown in Figure 1. In addition, a tagged model layer can be forced to follow the measured settlement of the corresponding harp. Subsequent snowfalls and its settlement will thus not be effected by errors accumulated prior to the fixing time.

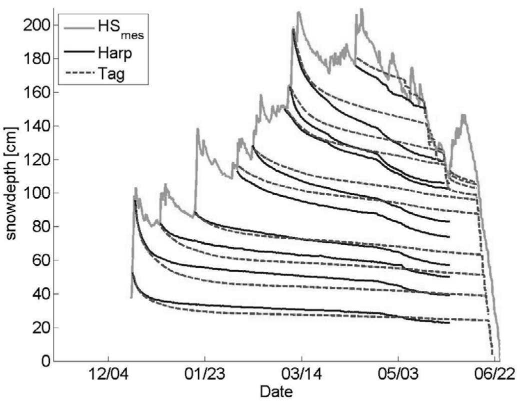

Figure 1. Winter 2005/06 showing measured snow depth (HS_{mes}), modelled (Tag) and measured ($Harp$) settling curves. Initialised with a regular profile on 15 December 2005, SNOWPACK was driven with measured snow depth.

Note that observed snow profiles can be used to initialise SNOWPACK. This method was considered for optimum investigation of subsequent snowfall events.

Figure 2 shows the different settling curves from either using measured snow depth to run SNOWPACK (HS_{mod-HS}) or driving the model with precipitation data ($HS_{mod-SWE}$). Of course, following measurements during snow depth increase yields a better visual agreement. Due to imperfect parameterisation of new snow density, however, the added mass, that is, water equivalent of snowfall can be erroneous in this case. Figure 3 displays this problem by comparing total snow water equivalent (SWE) for the same two runs, (SWE_{mod-HS}) and ($SWE_{mod-SWE}$), respectively.

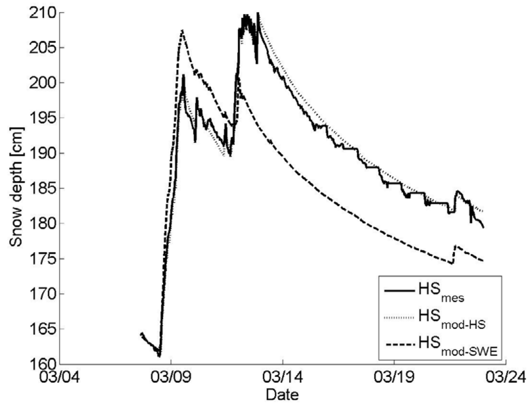

Figure 2. Snow depth comparison illustrating the effect of driving SNOWPACK with either snow depth (HS_{mod-HS}) or precipitation data ($HS_{mod-SWE}$) during a sub-period with 2 major precipitation events. HS_{mes} is the measured height of snow.

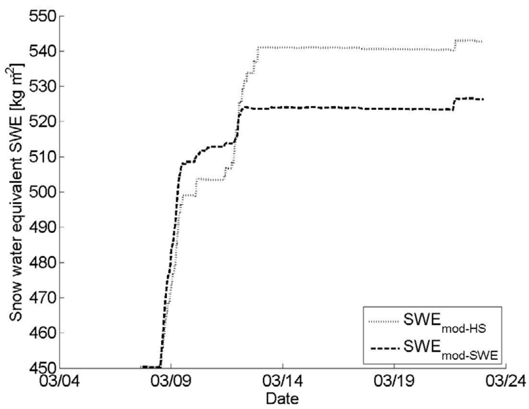

Figure 3. Comparison of snow water equivalent as calculated by SNOWPACK driven either with snow depth (SWE_{mod-HS}) or precipitation data ($SWE_{mod-SWE}$).

For our purpose, correct water equivalent of snowfall is essential and thus precipitation data is used. To do so, accumulated mass between observed regular profiles is redistributed according to the time sequence of precipitation gauge records.

The main investigation period is centred on a large snowfall (approximately 40 cm) occurring on 9 March 2006 (see Figure 1 and 2) when a wealth of data is available.

3 METHODS

A major methodical effort is put into the development of tools for comparing objectively modelled (tags) with measured (harps) settling curves and determining the time when the largest errors are made.

In this study we concentrate on an optimum representation of the initial settling rate of both measured and simulated curves. This can best be done by fitting splines to both modelled and measured curves and comparing their settling rates (slopes) at given times. Splines are used because they achieve good fits while maintaining main features of the curves, for example, kinks. Moreover, the time dependence of differences in height with regard to measurements (harp) can be used to identify the timing and the conditions associated with the largest errors.

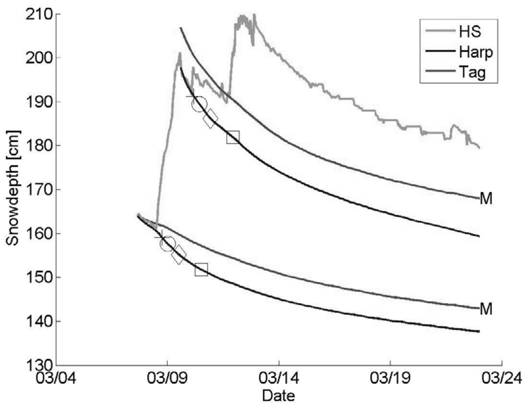

Figure 4. Measured and simulated settlement for harp 8 (lower curves) and harp 9 (upper curves). Modelled curves result from SNOWPACK's original settling routine (run *M*) with harp 7 being kept fixed. The 4 symbols mark times at which settling rates were compared.

Figure 4 shows the settlement of harps 8 & 9 during the main investigation period. Model curves (tags) were calculated using SNOWPACK's original settling routine (run *M*) and keeping harp 7 fixed. Adding calculated curves by varying the values of model parameters soon results in a cluttered graph with no possibility of quantitative evaluation (see Figure 5). Therefore we introduced the so called *Cluster type I* method. At 4 consecutive and coherent time steps right after the snowfall (see symbols in Figure 4), we evaluate the difference in settling rate of each model curve to the corresponding harp measurement. The normalised differences for both harps 8 and 9 are then plotted along the x and y axis of Figure 6, respectively. Here the distance to the origin can be seen as a measure of the model's lack of skill to reproduce measurements. **In particular, this method helps to assess changes in the settlement routines necessary to reproduce the kink of harp 8 at the beginning of the snowfall.**

4 RESULTS

Figure 5 gives an overview of all calculated model runs, while Figure 6 demonstrates an evaluation of the same data set employing the *Cluster type I* method.

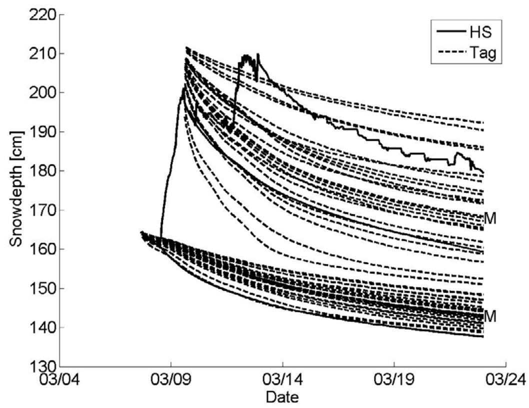

Figure 5. Overview of all sensitivity runs. M marks the run performed with SNOWPACK in its original configuration. [harp 7 fixed]

Obviously, changes in parameter values strongly effect the model curves belonging to harp 9 (new snow) while relatively small reactions only can be seen for model curves relating to harp 8. Notably, the kink right after the beginning of the main snowfall cannot be reproduced by any parameter setting.

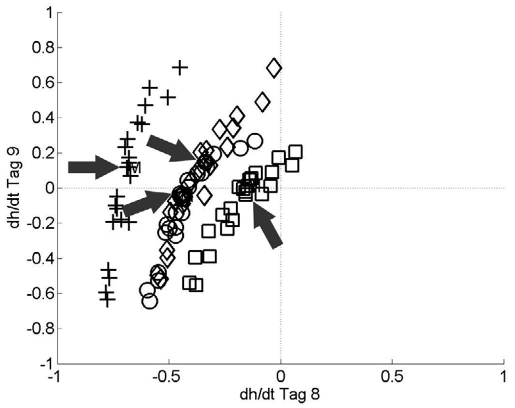

Figure 6. *Cluster type I* analysis at 4 different time steps (symbols represent positions as seen in Figure 4). The normalised differences in settling rates are derived from the model sensitivity runs shown in Figure 5. M (positions marked with arrows) marks the run performed with SNOWPACK in its original configuration. [harp 7 fixed]

Figure 6 shows that all runs vary greatly around run *M*. Furthermore, small improvements for tag

8, that is, moving closer to 0 on the x-axis, result in a large decrease of performance for harp 9. This demonstrates the complex inherent interactions between model parameters. Figure 6 also indicates that nearly no parameter setting achieves significantly better results than the run with SNOWPACK´s in its original configuration (run *M*). This shows that the currently used settlement equations and parameter setting already perform satisfactorily.

A detailed analysis of the temperature dependence of the snow viscosity was nevertheless performed. Following Schneider (2008), this term of the settlement equation was reformulated as:

$$f(T) = a\ \left((T_c - T_s + c)^b\right), \quad (1)$$

where $a = 0.75$, $b = 0.3$, $c = 1$, $T_c = 273.15\ K$ is the melting point temperature of ice and $T_s(K)$ the snow temperature.

Figure 7 illustrates a comparison between model runs performed with the old (dotted line) and new temperature term $f(T)$ (dashed line) for the winter 2005/06. Because the new formulation is mainly trimmed to the heavy snowfall occurring in early March 2006, the best performance is achieved during this period. Yet the overall performance slightly improves.

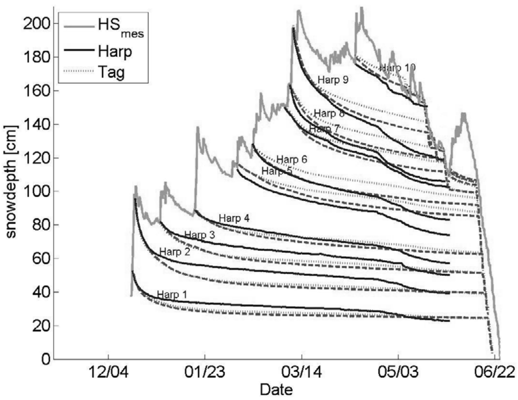

Figure 7. Comparison between model runs of the winter 2005/06 performed with the old (dotted line) and new temperature term (dashed line) of the settlement equation [snow depth used to drive SNOWPACK; no harp fixed]

5 CONCLUSIONS

This study demonstrates the striking need on relevant data sets and thorough processing to assess model performance. Based on this data, model sensitivity studies are conducted and the inherent response of settling rates is evaluated using specific evaluation methods. Here, *cluster type I* is introduced in some detail. The method is shown to be very valuable at assessing model skill and performance.

This study points to the great sensitivity of the model to parameter setting for new snow conditions (harp 9) while hardly no improvement can be noticed in somewhat older snow (harp 8). Indeed, our detailed analysis does not yield a suitable parameter set to simultaneously improve model performance for two types of snow (harps 8 and 9). Furthermore, concentrating on improving model skill on one type only (harp 8) results on an unacceptable decrease of overall model performance.

A final analysis leads to the reformulation of the temperature term in the settlement equations. Even though this change results in a slight enhancement of SNOWPACK's performance only, it can be seen as achievement because the new parameterization is in addition simpler than the original one.

A more elaborated discussion of the problem can be found in Steinkogler (2009).

6 ACKNOWLEDGEMENTS

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