AN OBJECTIVE SNOW PROFILE COMPARISON METHOD

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ABSTRACT: With the increasing use of numerical models predicting the snow cover status, the need for a simple and standardized evaluation procedure arises. We present such a method that compares numerical model profiles with snow pit profiles and provides a quantitative statistical agreement-disagreement measure. The method can also be used to compare several model profiles with each other. The first step of the method is the mapping of the model profile layers onto the layers of the observed profile. This mapping is necessary to adjust for deviating total snow depth and shifted positions of the layers. Following the mapping, the individual profile parameters such as grain type, grain size, liquid water content, temperature and density are compared. The result of the comparison is a score between 0 (profiles show no agreement) and 1 (profiles are identical) for each parameter. The parameter scores can be combined to give an overall profile score between 0 and 1. The method facilitates evaluation studies and allows to quantify improvements made in the modeling of processes in the snow cover. The paper explains the basic idea of the method and illustrates its application and usefulness using SNOWPACK model profiles and the corresponding snow pit observation from the Swiss Alps.

KEYWORDS: snow pit, profile, snow cover simulation, SNOWPACK, evaluation, grain type.

1. INTRODUCTION

Detailed snow cover simulation models are a prerequisite to make progress in avalanche forecasting as well as in many other related fields such as hydrology, ecology or meteorology. Recently, such models have become available (Lehning et al., 1999; Brun et al., 1992) and are used for a variety of purposes. However, the processes in the snow cover are difficult to observe and the evaluation and calibration of such models is a great problem (Fierz and Lehning, 2000).

One of the most precious sources of snow cover information are snow pit profiles taken by experienced observers. However, a direct use for snow cover simulation evaluation is difficult because of the difference in parameters simulated and observed (e.g. bond size versus hand hardness) and not least because of the different formats and resolutions used. These differences arise from simulation requirements and practical constraints in the field respectively.

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This paper presents an algorithm that objectively and automatically compares snow pit profiles to simulated SNOWPACK profiles. For a variety of parameters, distances between the observed and the simulated profiles are determined and then translated into an agreement – disagreement score. Those scores are finally combined to give an overall score of profile agreement. The proposed method is intended to supplement not replace the visual inspection and comparison of profiles of density, temperature, grain type and grain size. Note that the method could also be used to simply compare different model profiles.

2. COMPARISON ALGORITHM

The first problem encountered is how to compare different layers of the modeled and observed profiles. In general, the modeled profile has a much higher resolution and finer structure than the observed profile and an error in the calculated settling rate might have shifted the layers. Therefore it is necessary to perform a mapping. The first step in the mapping is to adjust for potentially different snow heights in the modeled and observed profiles.

2.1. Stretching

We stretch the model profile linearly. Let $z_i^{'mod}$ describe the nodes (layer boundaries) of the

model profile and $z_{nM}^{'mod}$ and z_{nO}^{obs} the total snow heights of the model and observed profiles, respectively. Then we map into the new coordinates z_i^{mod}:

$$z_i^{mod} = z_i^{'mod} \frac{z_{nO}^{obs}}{z_{nM}^{'mod}} =: z_i^{'mod}\ s\,. \qquad (1)$$

Here *s* is the stretch factor which is constant for all layers. The index of the nodes or layer boundaries is *i*: 0 <= *i* <= *nM*. All model profile quantities of significance for the profile comparison keep their identical values, except for the density and the volumetric fractions. They have to be adjusted to insure mass consistency[1]. We may use for the new layer density, ρ_l^{mod}:

$$\rho_l^{mod} = \frac{\rho_l^{'mod}}{s}\,. \qquad (2)$$

Here *l* is the layer index (0 < *l* <= *nM*). Neglecting the mass of air that is added or removed while stretching and considering for the volumetric contents, θ:

$$\theta_l^{ice} + \theta_l^{water} + \theta_l^{air} = 1\,, \qquad (3)$$

we can use the same stretch factor for the volumetric contents of ice and water:

$$\theta_l^{water} = \frac{\theta_l^{'water}}{s} \quad \text{and} \quad \theta_l^{ice} = \frac{\theta_l^{'ice}}{s}\,. \qquad (4)$$

After eliminating the problem of possibly differing total snow height, we turn to the mapping of individual layers of the observed profiles onto layers of the model profile. We propose the following algorithms:

2.2. Mapping

a) Layer Characteristics

For layer characteristics such as grain type, grain size or the volumetric water content we propose the following. We choose the observed profile to be the master profile and try to find for each observed layer the best correspondence in the model profile. For the layer *i* in the observed profile between z_{i-1}^{obs} and z_i^{obs}, a height range is determined for the corresponding model profile in which the parameters are compared. The height range depends on the total snow depth and the location within the snow cover. An increased tolerance range is allowed for layers in the middle of the snow cover:

$$z_{upper}^{mod} = z_i^{obs} + W\,t_i\,; \quad z_{lower}^{mod} = z_{i-1}^{obs} - W\,t_{i-1}\,. \qquad (5)$$

With

$$t_i = \frac{(z_{nO}^{obs} - z_i^{obs})\, z_i^{obs}}{z_{nO}^{obs}}\,, \qquad (6)$$

we define suitable tolerance functions that have a maximum in the middle of the snow cover. The maximum range of the tolerance is determined by the factor, *W*. We propose to use *W* = 0.2. The lower and upper limits of the determined height range are usually not identical with model layer boundaries and in those cases the entire layer at the lower and the upper boundary of the height range respectively is included.

In summary, the mapping function determines for each observed layer a selection of one or more layers in the model profile. As described below, a normalized distance will then be calculated between the observed layer and this selection of model layers.

b) Point Measurements

For point measurements such as temperature or (depending on the measurement device) density the mapping is less complicated. For the series of point measurements, T^{obs}, at snow depths z_j^{obs}, we make a linear interpolation. In our finite element SNOWPACK model, temperature is a parameter defined at the layer boundaries (element nodes). We therefore interpolate between the two model nodes above and below z_j^{obs}:

$$T^{mod}(z_j^{obs}) = \frac{z_i^{mod} - z_j^{obs}}{z_i^{mod} - z_{i-1}^{mod}}\, T_i^{mod} + \frac{z_j^{obs} - z_{i-1}^{mod}}{z_i^{mod} - z_{i-1}^{mod}}\, T_{i-1}^{mod}\,. \qquad (7)$$

c) Bulk Measurements

For the series of bulk measurements (such as density), R^{obs}, with interface depths, z_j^{obs}, we construct corresponding values from the model profile by introducing artificial model nodes at the heights, z_j^{obs}:

[1] In case of a small difference between measured and modeled snow depth the adjustment of density and volumetric contents may be neglected.

Table 1: Matrix of normalized distances for all combinations of grain types. Given are the standard symbols (SYMB), the international classification (*INTL.*) and the Swiss classification (SLF).

Norm. Distance Grain Types		*INTL.*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*4c*
		SLF	1	2	3	4	5	7	6	9
INTL.	SLF	SYMB	+	/	●	□	Λ	○	V	∩
1	1	+	0	0.2	0.5	0.8	1	1	1	0.8
2	2	/	0.2	0	0.2	0.6	1	1	1	0.6
3	3	●	0.5	0.2	0	0.6	0.9	1	1	0.5
4	4	□	0.8	0.6	0.6	0	0.2	1	1	0.2
5	5	Λ	1	1	0.9	0.2	0	1	1	0.3
6	7	○	1	1	1	1	1	0	1	1
7	6	V	1	1	1	1	1	1	0	1
4c	9	∩	0.8	0.6	0.5	0.2	0.3	1	1	0

$$R_j^{mod} = \frac{1}{z_j^{obs} - z_{j-1}^{obs}} \left(R_m^{mod} (z_m^{mod} - z_{j-1}^{obs}) + \sum_{i=1}^{n-1} R_{m+i}^{mod} (z_{m+i}^{mod} - z_{m+i-1}^{mod}) + R_n^{mod} (z_j^{obs} - z_{n-1}^{mod}) \right),$$

$$\text{where } z_{m-1}^{mod} < z_{j-1}^{obs} \le z_m^{mod} \text{ and } z_{n-1}^{mod} \le z_j^{obs} < z_n^{mod} \tag{8}$$

In summary, Eq. (8) means that we select a bulk portion of the model profile exactly matching the height range over which the bulk measurement has been performed. The density of the model is averaged over this height range.

2.3. Distance Measures

For each parameter, the comparison between the measured and modeled profiles yields a normalized quantitative measure of distance. The current implementation as discussed below is might be improved in later versions.

a) Grain Type

The comparison is based on the international morphological classification proposed by Colbeck et al. (1990). Each layer is characterized by two basic grain shapes *F1* and *F2*, the latter standing for the minority type. If only one type is present, *F2* is set equal to *F1*. At present, we neglect ice lenses and melt freeze crusts because they are still unsatisfactorily represented in SNOWPACK. Whenever a unrecognized type is encountered in the observed profile the normalized distance measure (see below) is set to 1.

For all model layers *k* within the tolerance borders (Eq. (5)), the difference to the observed layer *l* is determined as follows:

$$\begin{aligned} d_{lk}^{11} &= d(F1_l^{obs}, F1_k^{\text{mod}}) \\ d_{lk}^{22} &= d(F2_l^{obs}, F2_k^{\text{mod}}) \\ d_{lk}^{12} &= d(F1_l^{obs}, F2_k^{\text{mod}}) \\ d_{lk}^{21} &= d(F2_l^{obs}, F1_k^{\text{mod}}) \end{aligned} \tag{9}$$

where Table 1 gives the measure of agreement *d()* for all combinations of basic grain types *F*. We now have four distance measures between the basic grain shapes but need to combine that into one distance number for the combination observed layer *l* – model layer *k*. We define therefore:

$$d_{lk}^{straight} = \frac{d_{lk}^{11} + d_{lk}^{22}}{2}$$

and

$$d_{lk}^{cross} = \min\left(1, 0.1 + \frac{d_{lk}^{12} + d_{lk}^{21}}{2}\right) \tag{10}$$

We add 0.1 to the cross term in order to account for the majority-minority mismatch. We may now calculate the measure of agreement d_{lk}^{type} for each model layer *k* as:

$$d_{lk}^{type} = \min\left(d_{lk}^{straight}, \; d_{lk}^{cross}\right). \tag{11}$$

The next step is to calculate the actual distance for the observed layer, which corresponds to one or more model layers. We define this difference as the weighted average of the differences over the extent of the observed layer. Let us assume that the model height range

as determined by Eq. (5) starts with z_m^{mod} and ends with z_n^{mod}. Introducing the layer thickness, *L*, a normalized difference for each observed layer can be defined as:

$$d^{type}{}_l^{obs} = \min_{\substack{z_{l2}^{mod} \le z_n^{mod} \\ z_{l1}^{mod} \ge z_m^{mod}}} \left(\frac{1}{\sum_{l=l1}^{l2} L_l^{mod}} , \right. \qquad (12)$$

$$\left. \sum_{l=l1}^{l2} d^{type}{}_l^{mod} \; L_l^{mod} \right)$$

with *l1*, *l2* such that:

$$\sum_{l=l1}^{l2} L_l^{mod} \le L_l^{obs} \text{ and } \sum_{l=l1}^{l2+1} L_l^{mod} > L_l^{obs} .$$

In summary, Eq. (12) states that we take a window of depth z_n^{mod} and slide it through the height range as determined by Eq. (5) to find the best correspondence.

Finally, the distance for the whole profile, i.e. for all observed layers, is obtained. The normalized measure of the quality of the model grain type profile is calculated by a weighted average over all observed layers:

$$d_{profile}^{type} = \frac{1}{z_{nO}^{obs}} \sum_{l=1}^{nO} d^{type}{}_l^{obs} \; L_l^{obs} . \qquad (13a)$$

Instead of the depth weighting in Eq. (13a), we alternatively propose to perform a simple average over the number of observed layers since most of the time especially the thin layers are important to judge the stability of a snowpack:

$$d_{profile}^{type} = \frac{1}{nO} \sum_{l=1}^{nO} d^{type}{}_l^{obs} . \qquad (13)$$

b) Grain Size

For grain size, we define a relative deviation by arbitrarily postulating that the difference in the largest grains between the model profile and the observed profile is only due to a different definition of the grain size. Therefore we normalize the layer grain sizes, rg, by the size of the largest grains in each profile:

$$rg_n = \frac{rg}{\max(rg)} . \qquad (14)$$

Note that this normalization is done separately for the model and the observed profiles. Then we obtain a normalized distance measure:

$$d^{size}{}_l^{mod} = \left| rg_n^{obs} - rg_n^{mod} \right| , \qquad (15)$$

and the overall normalized deviation for each observed layer and finally the whole profile is obtained identically to Eqs. (12) and (13), respectively.

c) Liquid Water Content

In the field, the liquid water content is estimated in five classes (observation classes, *OC*). In the model, we arbitrarily limit the liquid water content to 8% (model liquid water content, MLWC). For the comparison, we only want to distinguish the three classes "dry" "wet" and "saturated" and call them comparison values, *cv* (0-2). We define those values according to Table 2. The normalized distance measure is then:

$$d^{wet}{}_l^{mod} = \frac{\left| cv^{obs} - cv^{mod} \right|}{2} , \qquad (16)$$

and the overall normalized deviation for each observed layer and finally the whole profile is again obtained in analogy to Eqs. (12) and (13), respectively.

Table 2: Comparison values for snow moisture.

MLWC (%)	*cv*	*OC* (1-5)
0	0	1
0 < MLWC < 8	1	1-2, 2, 2-3
>8	2	3,4,5

d) Temperature and Density

Since temperature and density measurements in the field are usually taken at regular intervals[2], we obtain from the mapping of point as well as bulk measurements, vectors with an equal and identical spacing of length *N* and we do not have to perform a layer depth weighting. In order to receive a distance measure between 0 and 1 we normalize again. We use the maximum and minimum values for normalization. Since we are also interested in a possible offset, we determine one maximum and minimum value for the combined observation / model data set. This approach will create large distances for systematic deviations:

[2] Where not taken at regular intervals, there is usually a weighting according to importance, such that each measurement point can be assumed to have the same importance. For example, the resolution of temperature measurements at the surface may be higher than close to the ground.

Figure 1: Snow pit profile taken on the morning of March 6 2000. The visualization is the standard profile plot used by the Swiss avalanche forecasters.

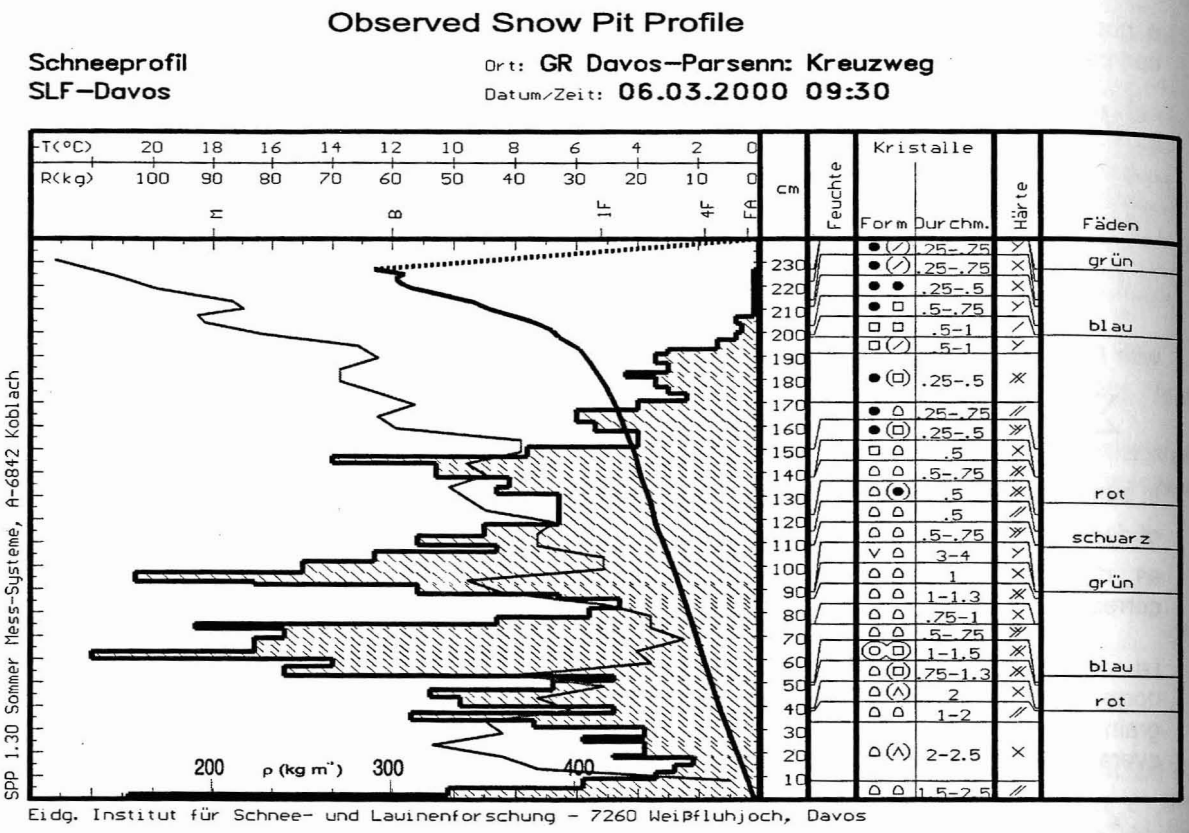
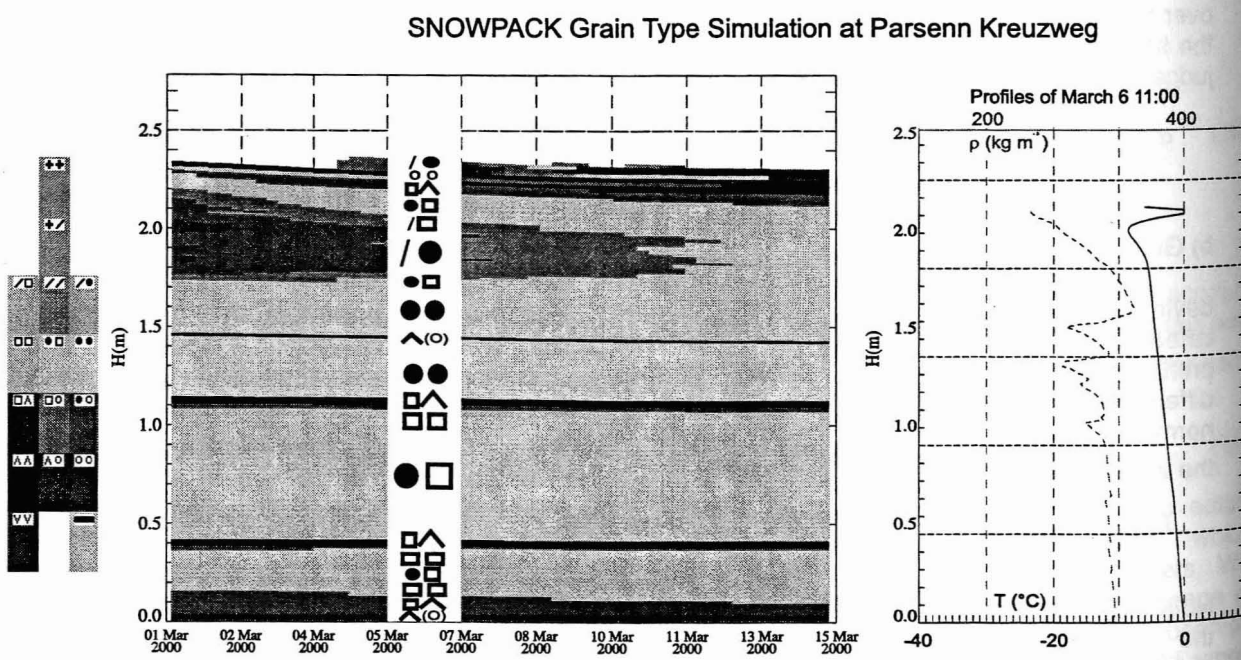


Figure 2: Simulated snow cover profile. The visualization is used by the Swiss avalanche forecasters. The grain type symbols have been added to facilitate the interpretation of the b/w print.



$$d^{T,\rho.}_{profile} = \frac{1}{N} \frac{\sum_{i=1}^{N} \left| T, \rho_i^{obs} - T, \rho_i^{mod} \right|}{\max(T, \rho^{obs/\mathrm{mod}}) - \min(T, \rho,^{obs/\mathrm{mod}})} \quad (17)$$

2.4. Overall Distance

The distance measures of the individual parameters all have the characteristic that they describe the distance between two profiles as a number between 0 and 1. If desired, these individual distances can be combined in a weighted sum to yield a single number that describes the overall distance between two profiles:

$$d_{profile} = \frac{1}{\sum_{i=type,size,wet,T,\rho} w^i} \sum_{i=type,size,wet,T,\rho} w^i d^i_{profile} \quad (18)$$

In the results section below we will use the weights of 35, 25, 25, 10 and 5 for grain type, temperature, density, grain size and liquid water content respectively in order to get an agreement score. We use an agreement score instead of the distance. We define the agreement score as one minus the corresponding distance value.

3. APPLICATION EXAMPLE

We apply the algorithm as presented above to compare a SNOWPACK model simulation with snow pit observations at the IMIS station (Lehning et al., 1999) Parsenn Kreuzweg in the Parsenn ski area above Davos. The manual profile is shown in Fig. 1 and the corresponding simulated profile is given in Fig. 2. The visual inspection of the graphs illustrate the difficulty in judging the accuracy of a simulation when compared to a manual profile: Different resolutions, different parameters and different presentations of the profiles prevent an easy interpretation. With our comparison method an objective, reproducible and quantitative agreement score results.

The simulation has been run starting at October 1 1999 with no snow and running through the winter without re-initialization. Both profiles are dry and therefore the normalized agreement for the parameter liquid water content is 1 (distance 0). We focus on density, temperature and especially grain type and only mention that the agreement for the grain size is 0.8. When comparing the two density profiles we see that the model (Fig. 2) fails to reproduce the layer of lower density at approximately 30 cm above ground (Fig. 1). The corresponding score of the comparison method is therefore comparatively low (0.7). Temperature shows a good agreement except in the uppermost layers. The real agreement is much better than indicated in the two profile graphs, which have a time lag of two hours[3]. The high score for temperature of 0.9 shows that the model reproduces well the observed temperature distribution.

When looking at the grain type, only an agreement of 0.3 is reached. This is caused by the fact that the snow pit observer detected many layers with "rounded faceted" crystals. These crystals have experienced faceting and subsequent rounding. The Swiss observers treat this species as a separate basic grain type (SLF code 9: ∩), especially because the subsequent rounding does increase the stability of those layers significantly. However, in the model version of the first simulation (Fig. 2) these forms are not represented. Subsequently, the model metamorphism and classification codes were altered to recognize these faceted rounded crystals. The comparison algorithm was used again for the new model version. The agreement code now rose to 0.7, because the model was able to reproduce most of the rounded faceted crystals in the lower half of the profile (not shown).

The overall score (Eq. 18) calculated with the weights of Section 2.4 is 0.65 for the original version of SNOWPACK. The results for the improved version yield an overall agreement score of 0.77.

4. CONCLUSIONS

The paper presented an objective and quantitative snow profile comparison algorithm, which is needed to perform routine and extensive snow cover model evaluation. This algorithm has been implemented to interface with our operational SNOWPACK model simulations and the observed snow pit profiles, which are available from a data base. The objective model comparison method is therefore a valuable tool for detailed snow cover model evaluations.

[3] Note that this time lag is caused by the resolution of the model graphic routines and has been avoided for the calculation of the agreement score.

The effectiveness of the comparison algorithm has been shown by comparing a simulated profile at an IMIS automatic snow and weather station with an observed, detailed snow pit profiles from the Swiss Alps. The agreement score for the parameter grain type increased from 0.3 to 0.7 after introducing an additional grain type in the simulation. This grain type (rounded faceted crystals) was predominant in the lower parts of the observed profile. This model improvement increased the overall profile agreement score from 0.65 to 0.77.

Some of the distance functions introduced are very heuristic and may be changed when more experience will have been gathered. The algorithm can be extended to include more parameters and can also be applied to compare two different model simulations. When using this comparison method it has always be kept in mind that manual profiles also exhibit a significant amount of subjectivity.

Further evaluations with the proposed method using profiles gathered during a whole year and from different sites are currently undertaken. The method could also be used as a standard procedure in the snow cover model intercomparison project SNOWMIP.

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