OPERATIONAL USE OF A SNOWPACK MODEL FOR THE AVALANCHE WARNING SERVICE IN SWITZERLAND: Model Development and First Experiences

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ABSTRACT

The national Swiss avalanche warning service must provide high quality avalanche danger forecasts with an increasing spatial resolution. For this purpose, forecasters require objective tools to judge local and regional avalanche danger. One important prerequisite for such objective methods is to characterize the snowpack status and to assess the snowpack - atmosphere interaction with a high spatial and temporal resolution. A snowpack model can provide this information if it is able to simulate the crucial physical processes such as snowpack settlement, formation of surface hoar and finally weak layer evolution.

This contribution presents a one-dimensional model based on finite element numerics which is directly coupled to the measurements of the new automatic weather and snow stations which operate at typical avalanche starting zone altitudes between 2000 and 3000 m ASL in the Swiss Alps. A simple prototype of the model is already in operational use and calculates snowpack parameters for over 40 locations with weather and snow stations. First results from the model are encouraging. Important parameters such as new snow heights, temperature profiles and density profiles can reliably be calculated. Major research work is devoted towards an improvement of the metamorphism scheme, which is currently based on the French model CROCUS. Especially the addition of new parameters such as grain bond size and coordination number should establish a link to thermal and mechanical properties. The final goal will be a description of weak layer development and an assessment of the mechanical stability of a layer. In addition, the coupling of the model to the Swiss weather forecast model and a description of wind erosion and accumulation is in preparation.

1. INTRODUCTION

Modeling the physical properties of the snowpack and its interaction with the atmosphere can provide valuable information for avalanche forecasting which is not available from standard automatic measurements. Those measurements, on the other hand, are necessary as boundary conditions for the model and contain already significant basic information. This paper describes the development of an operational snowpack model that runs on data of 40 new automatic weather and snow stations in the Swiss Alps.

The thermodynamic and mechanical properties of the seasonal snowpack are important not only to avalanche forecasting but also to hydrology (water storage), soil mechanics (permafrost changes) and ecology (vegetation, erosion). Therefore, numerical models of the snowpack have been developed (Morris, 1983; Motoyama, 1986, Jordan, 1991; Brun, et al., 1989) in different disciplines. Also at the SLF a model (DAISY) describing temperature distribution, energy and mass fluxes in a snowpack has been developed and compared against measurements (Bader and Weilenmann, 1992). The model performs well in terms of the energy balance.

The French chain SAFRAN-CROCUS-MEPRA (Durand et al., 1993; Brun et al., 1989; Brun et al., 1992; Giraud, 1992) is an advanced model package used for the avalanche warning service in France. It calculates "representative" snow cover characteristics for geometrical pyramids representing a region in the French Alps. With this idealized and simplified approach, a realistic evaluation against measurements and observations is difficult and the known small scale and local variabilty of the snowpack is not taken into account. In addition, since transport of snow by wind is not treated by the model, its practical applicability is limited.

Fierz (1998) shows that the evolution of weak layers, one of the most critical parts for avalanche prediction, is still unsatisfactorily represented in CROCUS. This problem can be attributed to the fact that research snow metamorphism in general (Bader et al., 1939; Colbeck et al., 1990) as well as investigations of depth hoar development (Akitaya, 1974; Marbouty, 1980; Fukuzawa and Akitaya, 1993) and the resulting parameterizations concentrated on single snow grains.

While a comprehensive modeling approach to snow metamorphism is missing at present, many particular problems on snow microstructure and metamorphism have been addressed recently (Edens and Brown, 1998; Brown et al., 1998; Satyawali, 1998). This knowledge is available, needs to be adapted, completed and incorporated into a complete description of snow properties and metamorphism which can be used in a numerical model.

Recently, Bartelt and Lehning (1998) have developed a general one-dimensional snowpack model for different applications within the SLF, which is described in the following.

2. MODEL SUMMARY

The 1D-model numerically solves the transient heat transfer and creep/settlement equations using the finite element method. Water transport is treated using a simple threshold model. The material snow is considered as a three component (solid, liquid, gas) porous medium. Phase changes between solid and liquid components are modeled as volumetric heat sources and sinks as well as an energy constraint on the temperature field. The microstructural parameter changes are additionally followed over time. The constitutive equations for heat transfer and settlement will finally be formulated in terms of these parameters. Since the model is based on the finite element method, all parameters are considered as element data. This means that the layered structure of the snowpack is modeled. In fact, sudden changes in layer properties - such as thin ice layers or weak layers are easily captured by the finite element discretization. The size of the elements is adjustable to the layer characteristics. The model has a very modular structure and is accompanied by a user-friendly graphical interface to visualize simulation results. A detailed description of the model is in Bartelt and Lehning (1998).

2.1. Initialization and boundary conditions

The initial state of the snowcover for each station is contained in a file, which is read when the program starts. This information includes the layer characteristics such as age, height, temperature, ice content, water content, grain size, sphericity, dendricity and bond radius of the element. In addition, some quantities for book keeping are stored in the initialization file. The model can also start with zero snow depth (in autumn). The initialization file has a free format and can easily be created or edited manually, for example to start with a snow pit profile.

During the development of the model, special attention was paid to interfacing the code to the snow and avalanche data base recently established at the Swiss Federal Institute for Snow and Avalanche Research (SLF). From the 40 automatic weather and snow stations in the Swiss Alps the data is transmitted in 30 minutes intervals to the SLF and is stored in the new data base. The measured parameters include air temperature, humidity, wind, reflected shortwave radiation, snow surface temperature, snow height, ground surface temperature and three temperatures in the snowpack, typically at 25, 50 and 100 cm heights. In operational mode, air temperature, humidity, wind, reflected shortwave radiation, snow surface temperature, snow height and ground surface temperature are used as input (boundary) conditions to drive the snowpack model. With the start of the model a data base query is initiated that reads the time series of the aforementioned parameters since the last model run for all stations.

2.2. Data control

Since erroneous measurements are quite common a procedure controls the time series for outliers based upon a Huber type skipped mean, which uses the median absolute deviation (Hampel, 1985). Gaps are filled by an interpolation routine. The snow height measurements require special treatment, because they determine the amount of new snow and are at the same time particularly prone to measurement errors. In addition to the check for outliers, a maximum increase and decrease in snow height from one time step to the following is defined. On sunny days, the snow height measurements show a strong dependency on solar heating of the instrument. This error is corrected using a statistical model and smoothing the resulting corrected and interpolated time series.

2.3. Treatment of new snow, melting and sublimation

A special feature of the finite element model is that the number of finite elements is dynamically allocated. Thus, the program data structures allow the modeling of snow accumulation and ablation. The height of new snow is estimated from the difference between the predicted settling and the measured total snow height. That means that new elements of snow are added to the snowpack when the total snow height increases. For those cases the measured snow height is always equal to the model snowheight. The new snow densities are estimated using the following relationship statistically derived from measurements in Davos:

$$\rho = \alpha + \beta \ TA \ + \gamma \ TSS + \delta \ RH + \eta \ VW + \phi \ TA \ TSS \ + \mu \ TA \ VW \ + \nu \ RH \ VW \tag{1}$$

Table 1 gives the explanation of the quantities involved and a preliminary estimation of the parameters (further measurements are currently being taken also at different locations) based upon a robust regression analysis. All terms are significant on the 99.9 % level and an approximate multiple correlation coefficient (r^2) of 0.9 is obtained. At present, the data has a limited range of the explanatory variables air temperature and surface temperature as well as of the observed densities (Table 1). To avoid erroneous extrapolation, the density prediction is thus limited to a range from 30 to 150 kg m^{-3}. Also note that the regression is valid for a 30 to 60 minute time interval and not for 24 hour new snow.

If there is melting in the very top element (see 2.4.), the available latent heat flux at the surface is used to evaporate the meltwater. Sublimation directly from the ice phase may take place additionally, if all the water has been evaporated and not all the latent heat flux has been used up. The reduced ice content in the very top element is not expressed as a reduced density but as a reduced height of this element. If the element completely melts or sublimates away, the element is taken away from the element mesh.

Table 1: Quantities and parameters for the new snow density model based on a first dataset of 49 observations.

Quantity	Description	Unit	Range measured
ρ	snow density	kg m^{-3}	32 - 140
TA	air temperature	°C	-7 - +2
TSS	surface temperature	°C	-10 - 0
RH	relative humidity	%	50 - 100
VW	wind speed	m s^{-1}	0 - 5
Parameter		**Value**	
α		70	
β		30	
γ		10	
δ		0.4	
η		30	
ϕ		6	
μ		-3	
ν		-0.5	

2.4. Temperature distribution, water transport and settlement

The instationary heat transfer equations are solved with a fully implicit time integration scheme. The effective thermal conductivity, k, is calculated as (Jordan, 1991):

$$k = k_S + L\, b\, D_{VA} \frac{\partial \rho_V}{\partial T}, \qquad k_S = a(k_I \theta_I + k_W \theta_W + k_V \theta_V) \tag{2}$$

Here k_S is the conductivity of snow, L is the latent heat of sublimation, D_{VA} is the diffusivity of water vapor in air (2.2 10^{-5} m^{2}s^{-1}) and ρ_V is the water vapor density. $k_{(I,W,V)}$ and $\theta_{(I,W,V)}$ are the conductivities and volumetric contents of ice, water and vapor, respectively. The two parameters a and b are set to 0.33 and 5.0, respectively.

Since snow transports heat slowly, the solution is stable for even large timesteps and small finite element sizes. Both Dirichlet (prescribed surface temperature) or Neumann (convective and radiative heat exchanges) boundary conditions are possible. The Neumann boundary conditions suffer the severe disadvantage that the incoming longwave radiation is not measured at the automatic stations and can only be approximated. We use the formula of Brutsaert and Imboden (1975). However, the alternative strategy of constraining the snowpack temperature will underestimate the heat energy flux when the surface temperature is at 0 °C. In periods of snowmelt, the Dirichlet boundary condition will therefore also underestimate meltwater production and settling. A model option is to switch from Dirichlet to Neumann boundary conditions when a surface temperature of 0°C is reached.

A simple water transport scheme moves excess water downward. Excess water is the amount of water that is not evaporated (see 2.3.) and exceeds a threshold value, which is currently set at 3 % by volume. The energy transported by meltwater into colder snowpack depths is taken into account by meltwater re-freezing.

Different simple viscosity laws are compared. The following relationship has been derived from observed settling curves and is used at present:

$$\eta = 7.0\, 10^{-3}\, \rho^{(5.0 - 0.025T)} \tag{3}$$

Here η is the compactive viscosity (kg m^{-1} s^{-1}) and T is the snow temperature (°C).

2.5. Metamorphism

The French metamorphism system (Brun et al., 1992) is used as a basis. In addition to the parameters dendricity, sphericity and grain size, the parameters coordination number and bond size / neck size are introduced. The model distinguishes between high temperature gradient (TG > 10 °C m^{-1}), low TG and 0°C isothermal conditions. For the unsaturated and saturated isothermal snowpack, grain growth and bond growth formulations based on the results of Colbeck (1973), Raymond and Tusima (1979) and Brun (1989) are adapted. The growth rates for low TG conditions are taken from Brown et al. (1998). For high TG conditions the growth model of Satyawali (1994) is implemented. At present, the coordination number is a function of density only but its relationship to grain shape will be investigated. The two parameters sphericity and dendricity change according to the French model (Brun et al., 1992). Pressure sintering causes further change in the bond size and is also considered (Mahajan and Brown, 1993). The microstructural parameters will be used for an improved formulation for the thermal conductivity and a link to the mechanical properties such as the viscosity will be established.

2.6. Output and dissemination of results

The current state of the snowcover is written to a file when the program terminates. With the start of the next run, this file is then used for the initialization.

At regular intervals, the program writes information on new snow heights and water equivalents, formation of surface hoar, surface run-off and a reduced set of profile information including temperature, density and microstructure parameters to the data base. This information is accessed and visualized by the avalanche forecasters at our institute. A smaller set of parameters is also transmitted together with the measured data from the stations to approximately 100 local committees concerned with road, railway, residence area and ski area protection. Especially the new snow heights, water equivalents, a surface hoar index and the temperature profile are important for those local experts.

3. SAMPLE CALCULATIONS

For three stations in the Swiss Alps with very distinct characteristics, sample calculations are presented. The station Rotschalp is situated on a flat terrace in a south slope at 1870 m altitude above the Brienzer lake in the canton Bern. The station Bedretto in the canton Ticino is situated in a basin depression within a north slope at 2100m altitude. Piz Kesch is a high Alpine station in the canton Grischuna at 2725 m altitude and is also located on flat ground in a depression with an opening towards the south-east. Fig. 1 presents a comparison between the model and the measured snowheights for the winter 1997/98 using the Neumann boundary conditions. Presented are the 110 (Rotschalp) respectively 117 (Piz Kesch and Bedretto) days before March 6 1998. The overall agreement is very satisfactory. However, certain periods are modeled more accurately than others. For some periods at the stations Piz Kesch and Bedretto the settling rate is underestimated (Figs. 1b and 1c). This can be expected since no link between viscosity and microstructure is implemented at present. Further causes for an underestimation of the settling rate are a possible overestimation of the initial density, wind influence (erosion and additional pressure) and measurement errors which have not been corrected by the data control procedure. An underestimation also occurs after the big snowfall event (day 65) at Rotschalp.

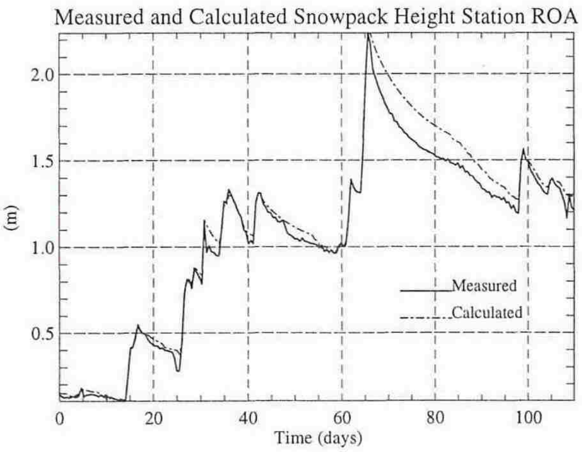

Fig. 1a: Snowpack heights at the station Rotschalp for the days before March 6 using Neumann boundary conditions.

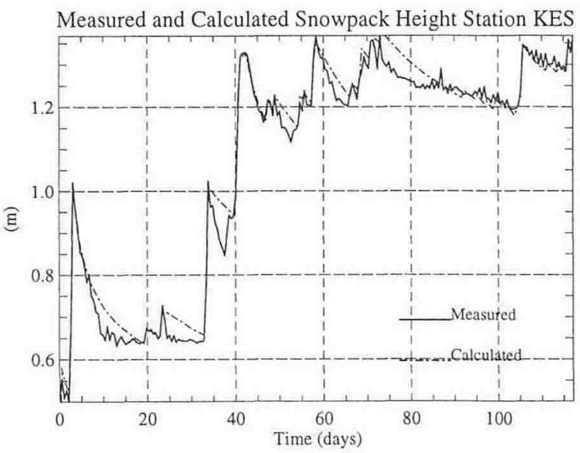

Fig. 1b: Snowpack heights at the station Piz Kesch.

Of particular interest is the subsequent snowmelt period. Between day 82 and 97 a considerable amount of snow is lost from ablation and the change in snowpack height is very well captured through the model. It must be added that during periods of snowfall the model snowheight is re-adjusted to the measurements (see 2.3.). Therefore only the periods without snowfall can be used for evaluation purposes.

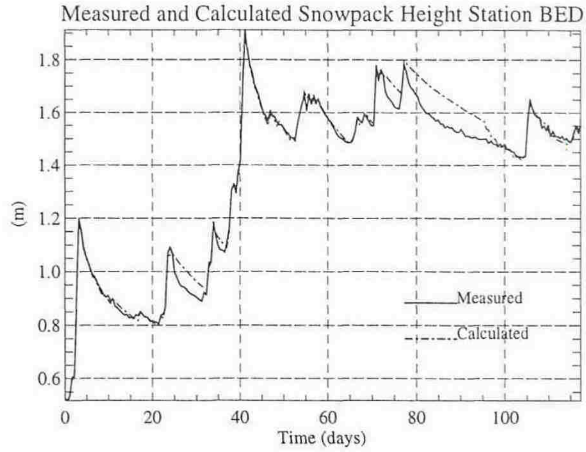

Fig. 1c: Snowpack heights at the station Bedretto.

The automatic stations measure snowpack temperatures at 25, 50 and 100 cm above ground. Fig. 2 shows a comparison between the measured and modeled temperatures at 50 cm for the three stations. Deviations up to 3 °C can be observed. In general the temperatures are overestimated by the model. The prediction of isothermal conditions is too early for the station Rotschalp (Fig. 2a). For low total snowpack heights the time variation is not captured well by the model, indicating that an improvement of the formulations for boundary conditions as well as for the thermal conductivity is possible.

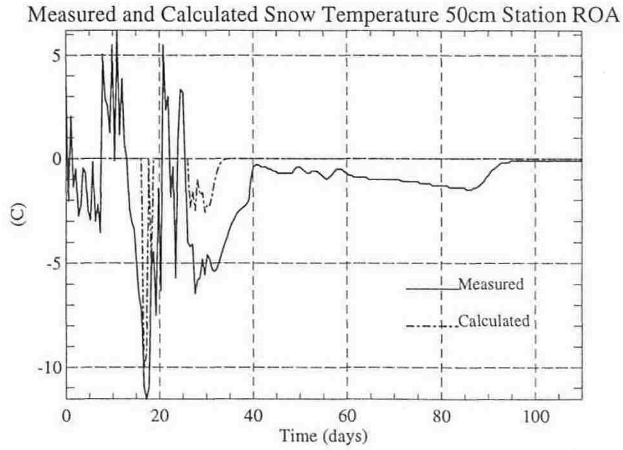

Fig. 2a: Temperatures at location Rotschalp at 50 cm height over the ground using Neumann boundary conditions. Note that for total snow heights smaller than 50 cm the model curve is set to zero, while the measurement curve displays the sensor temperature in air.

Fig. 3a shows for the example Rotschalp that the temperature distribution is more reliable using the Dirichlet boundary condition. Especially the onset of an isothermal snowpack is modeled more accurately. This is an important information for the avalanche forecaster. For the stations Piz Kesch and Bedretto there is an even closer agreement between measured and modeled temperatures (not shown).

However, the melting event (see above) cannot be captured with the Dirichlet boundary condition (Fig. 3b). Therefore, the boundary conditions should be chosen according to the surface temperature. For surface temperatures up to 0 °C the Dirichlet boundary condition should be used.

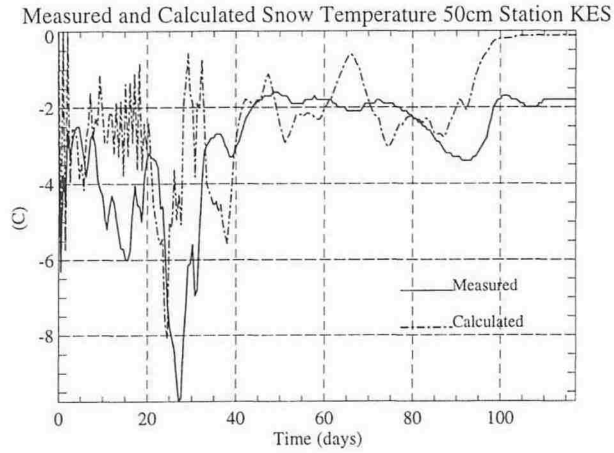

Fig. 2b: Temperatures at location Piz Kesch.

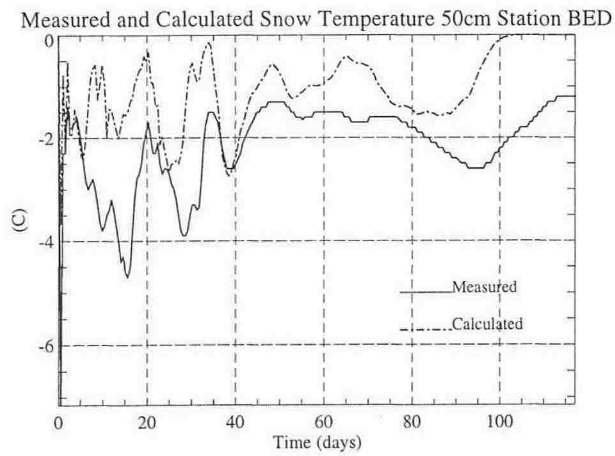

Fig. 2c: Temperatures at location Bedretto.

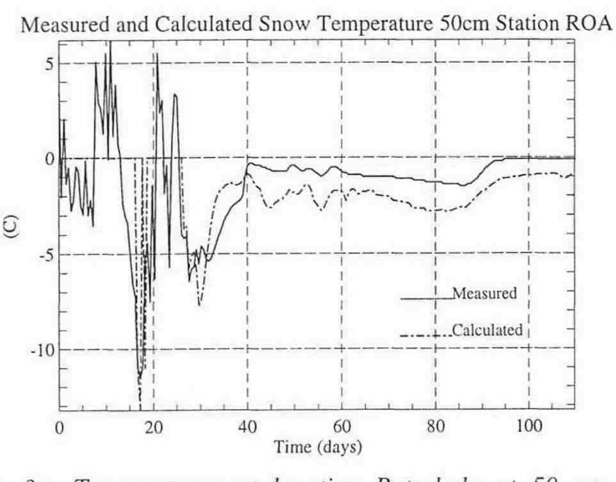

Fig. 3a: Temperatures at location Rotschalp at 50 cm height over the ground using Dirichlet boundary conditions.

Finally, Fig. 4 gives an example of the density distribution or the station Rotschalp. The density profile for March 6 (Fig. 4a) gives a realistic picture, although the densities at the lower layers might be too high. Further evaluation work is needed here. The time evolution (Fig. 4b) shows that some layer structure is preserved, despite the fact that at present the viscosity is a function of density and temperature only. The melting periods are nicely represented: elements disappear from the surface and the narrow dark lines indicate how water moves into the snow pack but does not reach the ground yet.

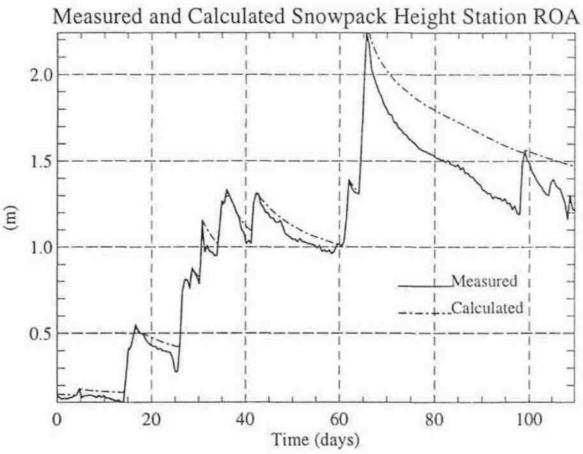

Fig. 3b: Snowpack heights at location Rotschalp using Dirichlet boundary conditions.

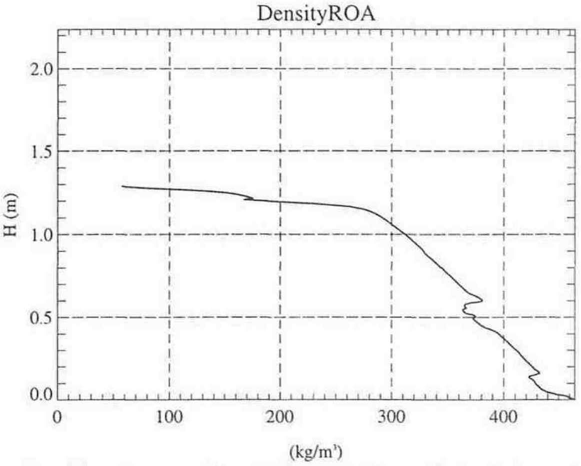

Fig. 4a: Density profile of March 6 at Rotschalp using Neumann boundary conditions.

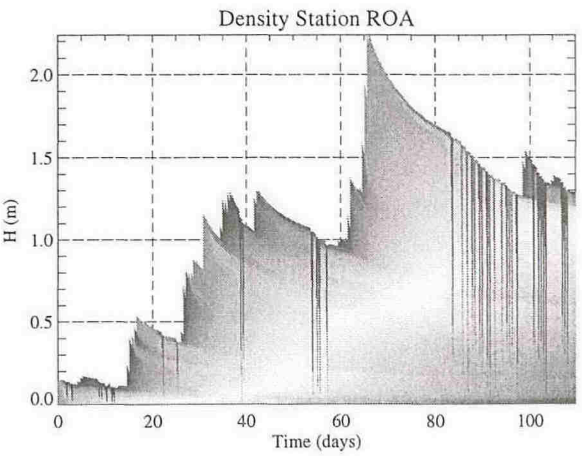

Fig. 4b: Density profile evolution at Rotschalp using Neumann boundary conditions.

3. CONCLUSIONS

A prototype of the presented new snowpack model, which is currently under development at the SLF, is already in operational use. It operates on the input data from automatic weather and snow stations and calculates important snowpack parameters such as formation of surface hoar, new snow depths, temperature and density profiles for over 40 stations in the Swiss Alps. The model is run hourly and supplements the information from the measurements, which are updated every 30 minutes. Since the model provides nowcasting results for a great variety of locations at altitudes of avalanche starting zones, the analysis reveals information on the spatial variability of the snowpack. This first prototype shows encouraging results but the evaluation work needs to be continued and extended.

Continuing development mainly focuses on an improved formulation of snow metamorphism. This is a crucial prerequisite to enable the modeling of weak layer evolution and to establish a link between snowpack metamorphism parameters and mechanical stability characteristics. In addition, a coupling of the operational Swiss weather forecast model to the snowpack model using appropriate downscaling procedures is in preparation. This will allow short term forecasts to be made. Major research work is also devoted to a formulation of wind erosion and accumulation. Especially for an assessment of the local variability of the snowcover in rugged terrain and on slopes, the description of windblown snow is essential.

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