Permafrost, Phillips, Springman & Arenson (eds)
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Numerical simulation of the interaction processes between snow cover and alpine permafrost

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ABSTRACT: The occurrence of permafrost strongly depends on atmospherical, topographical and soil specific factors such as mean annual air temperature, solar radiation, snow cover and soil texture. For a better understanding of the interconnection between these individual factors in the snow cover – permafrost system, a numerical model was developed: the one-dimensional model SNOWPACK, which simulates the local snow cover from the Swiss Automatic Snow and Weather Stations (IMIS), was extended to the underlying soil by including specific soil characteristics. The soil-specific parameters of this new model were calibrated with laboratory measurements. Simulations concerning the influence of soil grain-size on temperature development were conducted. A long-term simulation of the influence of increasing mean annual air temperatures on mean annual soil-surface temperatures shows both a strong linear dependency and soil-specific sensitivity. In this paper, the calibration of the new model and the first simulation results are presented.

1 INTRODUCTION

The interaction between atmosphere, snow cover and permafrost is part of a complex system of interconnected processes, in which each process affects soil temperatures in a more or less direct way. In comparison with high-latitude lowlands, conditions in low-latitude cold-mountain areas are characterized by 1) pronounced topographic and microclimatic complexity, 2) often well-drained but highly variable ground materials on steep slopes, and 3) a relatively thick and strongly differentiated winter snow cover (Etzelmüller et al. 2001). As a consequence, experience and modeling results from high-latitude lowlands (e.g. Smith & Riseborough 2002, Zhang et al. 2001) cannot be directly applied to alpine conditions.

The rules of thumb for the distribution of the Alpine permafrost show a correlation between soil temperatures, aspect and altitude (Haeberli 1975). This dependency can be traced back to the main permafrost-governing factors, which are mean annual air temperature, solar radiation input and the insulation effect of the snow cover (Hoelzle et al. 1993). The snow cover plays a central role, due to its physical properties. Thus, thick snow cover in winter months insulates the underlying ground from the cold atmosphere (Keller & Gubler 1993), whereas thin snow cover in autumn decreases soil temperatures due to the high albedo of the snow. The role of the snow cover in the permafrost system was also investigated by means of the distribution of the soil temperatures in avalanche slopes (Haeberli 1975, Lerjen 2001). Ground temperatures in the avalanche runout zone, at the foot of the slope, which has long-lasting snow, are lower than ground temperatures in the starting zone, in which snow is evacuated early (Harris & Corte 1992).

Ground temperatures are not only affected by topographical and meteorological factors, but also by soil-specific factors such as the soil grain-size and content of water and ice. On the blocky surface of the Murtèl rock glacier in the Engadin, Swiss Alps, Mittaz et al. (2000) measured a lack of energy in the energy balance, which was attributed to unmeasured air movements through the voids and the associated advective heat exchange. Outcalt et al. (1990) point out that the water content in the voids of fine-grained soils affects soil temperature by the latent-heat transport during freezing and thawing processes.

A numerical scheme based on the SNOWPACK model (Bartelt & Lehning 2002, Lehning et al. 2002) was created for a better understanding of the interaction processes. SNOWPACK is a one-dimensional mass and energy balance model, which was developed at SLF to simulate snow cover characteristics at the locations of the Swiss Automatic Snow and Weather Stations (IMIS). This model was extended to the underlying soil by including specific soil characteristics into additional soil elements.

Additional laboratory measurements were carried out for 1) a better understanding of the influence of soil grain size on water content and temperature in the soil and 2) the calibration of the soil parameters of the model. Under defined climatic conditions in the climate chamber of the SLF, temperature and humidity of three soil samples of different textures were measured continuously.

In the context of the work outlined here, the influence of different soil types on the heat transport processes in the soil as well as the influence of changing mean annual air temperatures on the mean annual soil-surface temperatures were investigated.

In this paper, the new coupled soil model is presented, the laboratory measurements and the calibration of the model are described and initial results of model runs concerning the influence of soil texture and changing climate on permafrost are shown.

2 METHODS

2.1 *Laboratory experiments*

The soil-specific parameters in the model are volumetric content of air, water, ice and soil. For their calibration, laboratory experiments were carried out in the climate chamber of the SLF. The temperature and moisture in three samples of different soil textures were measured continuously under well-defined climatic conditions (air temperature, humidity and radiation). A cyclical variation of air temperature between 8 to -8°C and humidity of 40 to 60 percent were provided as ambient climatic conditions.

Three soil samples, each of 0.25 m^3, were collected for the experiments. The samples were different in grain size but not in their parent rock characteristics. Figure 1 shows the samples of different grain size, which can be scaled by comparison with the pencil. The first fine-grained sample contained 10% silt, 30% sand and 60% gravel with a maximum diameter of 42 mm (Fig. 1A), the second intermediate sample consisted of 4% silt, 10% sand and 86% gravel with a maximum diameter of 86 mm (Fig. 1B) and the third coarse sample contained only blocks of a mean diameter of 80 to 250 mm (Fig. 1C). The samples were put in three 0.43 m deep boxes, which were well insulated on the sides and on the bottom.

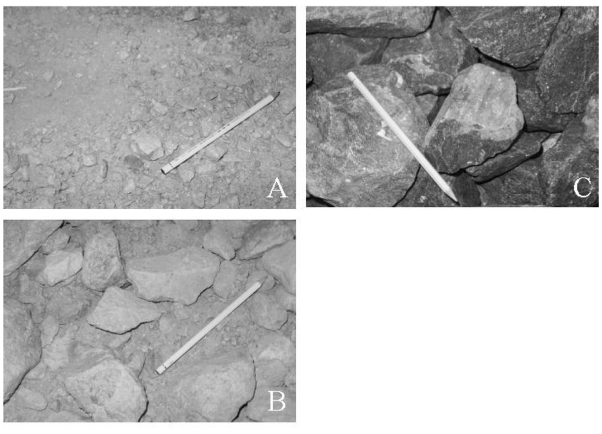

Figure 1. Soil samples of different grain size: (A) fine grained, (B) intermediate, (C) coarse blocky.

Temperatures were measured close to the surface and at 0.06 m intervals in depth in each box. The temperatures were measured continuously with plastic coated thermocouples (type k).

The moisture of the samples was measured using the method of time domain reflectometry (TDR), where the dielectric number of the sample is measured, using an aluminium TDR probe. The dielectric number can be related to the water content, using the empirical formulation of Topp et al. (1980), who found a third-order polynomial relationship between dielectric number and volumetric water content.

In the fine-grained and the intermediate sample, moisture was measured hourly at the same depths as the temperatures, using an aluminium TDR probe of 0.3 m in length, described in Schneebeli et al. (1998). The volumetric content of water was assumed to be negligible in the coarse blocky sample. One measurement with the TDR probe was compared to the results of the thermogravimetric method for each sample, where the water content is measured by the loss of weight after drying the sample at 105°C.

2.2 *Model*

Within the 1-D mass and energy balance model SNOWPACK, snow cover is simulated as a three-component material (air, water, ice), taking into account snow settlement, transport of mass and temperature in the snow cover, metamorphosis of the snow crystals, phase change processes and the exchange of mass and energy between the snow and the atmosphere (Fierz & Lehning 2001, Lehning et al. 2001, 2002).

A version of the SNOWPACK model called SNOWPACK_ECO, which accounts for the influence of different soils and soil-specific parameters, has been developed since 2000. The new model simulates both the soil and the snow cover above, using a meteorological input file and a soil input file. In the soil input file, the soil is characterized as a four-component material (air, water, ice and soil) with additional information about density, heat conduction and specific heat of the soil component.

The laboratory experiments, described in the section above, were simulated by adapting the soil specific parameters of the model, to calibrate the new coupled model.

The effective heat conductivity of the soil as a whole used in the model was calculated from the heat conductivities of water, air, ice and the mineral phase, which were specified in the soil input file. The model parameters were adapted by varying the volumetric content of water and air in the simulations, which finally leads to a direct change in the effective heat conductivity.

The measured rock density of 2853 kg/m^3, assumed heat conductivity of about 2.5 W/mK and specific heat of the mineral phase of about 879 J/kgK, corresponding to a mixture of granite and about 10% of soil (Incropera & DeWitt 1996), were fixed parameters in these simulations.

Besides studying the snow cover – soil interaction, the new version of SNOWPACK is also being used to study other processes, such as the transfer of radiation in the snow cover with regard to the underlying vegetation and studies on the chemical solute transports in the system.

3 RESULTS

3.1 *Laboratory experiments: effect of soil grain size on water content and temperature*

The effect of different soil textures on temperature development and moisture content was studied within the laboratory experiments. The temperature measurements were compared to the simulated temperatures by adapting the volumetric contents of water, air, soil and ice. An example of a laboratory measurement and the respective simulation is shown in Figure 2. The upper part shows the climatic parameters air temperature Ta (dotted line) and relative humidity Rh (black line). In the lower part, the measured (thick line) and calculated (thin line) temperatures at 0.25 m depth of the fine-grained sample (a) and the coarse blocky sample (b) are plotted. The example shows that coarse blocky material reacts more immediately to the changing air temperatures on the surface and reaches colder minimum temperatures than the fine-grained material. The water content used for the simulations was successively reduced to a final volumetric water content of 0.016, attaining a simulated temperature, which reproduces the measured temperature well (Fig. 2). The same was found in the intermediate sample, where the volumetric water content was reduced to 0.012.

The measured parameters are listed in Table 1 for the three samples (fine-grained, intermediate, coarse blocky) together with the parameters used for the simulation. The volumetric water content, measured with a TDR probe, is compared to the volumetric content of water determined by the thermogravimetric method in Table 2. The deviation of these values were 5% for the fine-grained sample and 44% for the intermediate sample, can be explained by the higher inhomogeneity of the intermediate sample, which is associated with higher inaccuracy of the measurement with the TDR probe.

The remaining deviation between measured and simulated temperatures (Fig. 2) in the fine-grained soil can be explained by the freezing-point depression of the soil freezing characteristics (Spaans 1994), which is not yet implemented in the model; phase change in the model thus occurs at the zero point.

The deviation between simulated and measured temperatures in the coarse blocky soil can be explained by air movements in the climate chamber, which were unaccounted for, and the associated advective heat fluxes between the blocks. Altogether, SNOWPACK_ECO reproduces the measured temperatures quite

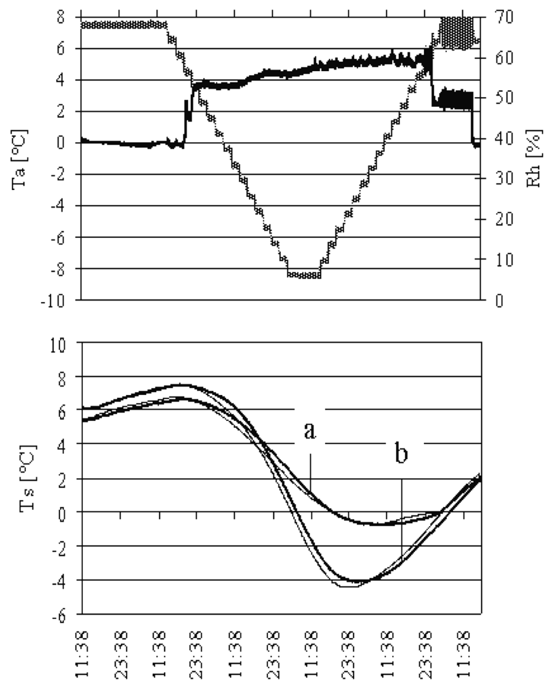

Figure 2. Laboratory measurements: The upper figure shows the climate variables air temperature (Ta, dotted line) and relative humidity (Rh, black line). The lower figure shows measured (thick line) and simulated (thin line) soil temperatures at 0.25 m depth in the fine-grained (a) and the coarse blocky (b) sample.

Table 1. Measured parameters and those used for the temperature simulations of the three soil samples: Volumetric content of water θ_w and air θ_a.

	Fine grained		Intermediate		Coarse blocky	
	θ_w	θ_a	θ_w	θ_a	θ_w	θ_a
Measured	0.087	0.350	0.083	0.380	–	0.480
Simulated	0.016	0.420	0.012	0.460	–	0.480

Table 2. Comparison between measured volumetric content of water using TDR method and thermogravimetric methods in the fine-grained and the intermediate sample.

	θ_w-TDR	θ_w-gravimetric
Fine-grained	0.087	0.074
Intermediate	0.083	0.041

accurately after adjustment of the water content in the fine-grained and the intermediate soil samples. Further model development will allow the heat conductivity of the soil to be adapted automatically during the calculation process.

3.2 *Simulation: temperature changes in different soil types*

The new model was applied to initial simulations of the influence of different soil types on soil temperature development. The simulations were performed over a period of three years, after which the influence of the initial conditions was negligible.

The meteorological input data chosen for these simulations were generated from measurements taken in Davos, Weissfluhjoch (2540 m a.s.l.), in the year 1993/94. In the winter of that year, the measured snow heights were very similar to the average snow heights for that altitude (SLF 1995). The radiation, which was originally measured in a test site on horizontal ground, was reduced to simulate conditions in a steep (40°) northerly exposed slope. The snow height was also reduced respectively by a factor of 0.3.

A 20 m thick layer of granite rock was also defined as soil input-data. The three input files for the different soil types are only different in their volumetric content of air, water, ice and soil. The corresponding soil parameters are listed in Table 3. Further parameters were set corresponding to a mixture of soil and granite particles, which are expressed by a particle density of about 2630 kg/m^3, heat conduction of about 2.5 W/mK and specific heat of the soil of about 879 J/kgK (Incropera & DeWitt 1996).

Figure 3 shows the simulated snow height (upper picture) and the simulated surface temperatures (lower picture) for the three soil types. The influence of the snow height on the surface temperature is obvious: at the beginning of the snow period, the snow height is not thick enough to insulate the underlying ground from air temperatures. At the end of the snow period, with the start of snow melt, ground surface temperatures show a zero curtain (Harlan & Nixon 1978). In the lower picture of Figure 3, the effect of different soil texture on the ground surface temperature is shown: the temperature of the fine-grained soil in spring is about 4°C warmer than the temperature of the coarse blocky soil and even 5°C warmer than the temperatures of the rock ridge. This effect is caused by the water content of the fine-grained soil, which on the one hand increases the mean heat capacity of the fine grained material, and which on the other hand causes a longer freezing period due to the latent-heat fluxes and the associated zero curtain. In the model, the advective heat fluxes due to air movements are not yet implemented.

Table 3. Initial simulations: volumetric content of ice θ_i, water θ_w, air θ_a, soil θ_s of three different soil/rock types.

Soil/rock	θ_i	θ_w	θ_a	θ_s
Coarse blocky	–	–	0.48	0.52
Fine grained	–	0.08	0.36	0.56
Rock ridge	–	–	–	1.00

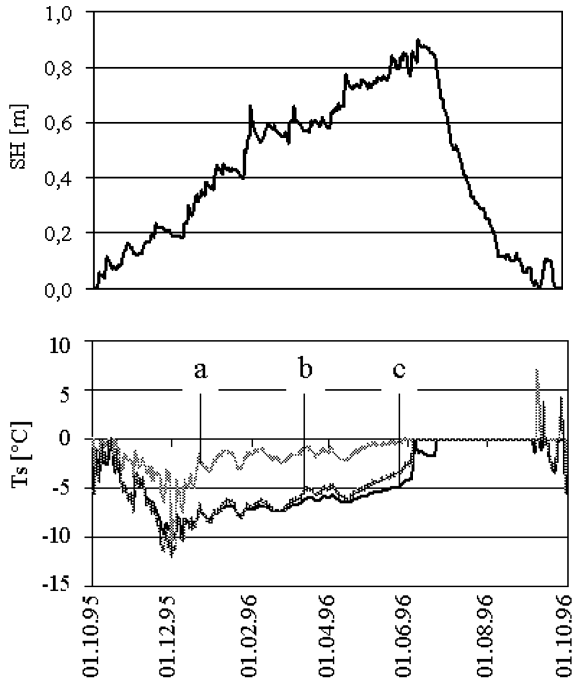

Figure 3. Simulated snow height (SH) in a steep northerly exposed slope and simulated soil surface temperatures (Ts) for (a) a fine-grained soil, (b) coarse blocky soil and (c) a rock ridge.

Therefore, the simulated temperatures in the coarse blocky soil and the rock ridge are rather similar.

3.3 *Simulation: increasing the mean annual surface temperatures by increase of the mean annual air temperature*

In another series of simulations, the influence of increasing mean annual air temperatures on mean annual soil surface temperatures of different soil types was investigated. The soil/rock types: rock ridge, fine-grained and coarse blocky were characterized by the same parameters as in the simulations in the section above (Table 3). Furthermore, the same meteorological input data (as described in the section above) were used. The mean annual air temperatures were increased successively in the simulation by steps of 0.5°C. Figure 4 shows the effect of increasing air temperatures by 1°C and 3°C on the snow height (upper graph): snow height decreases asymmetrically with an offset at the end of the snow period of three months.

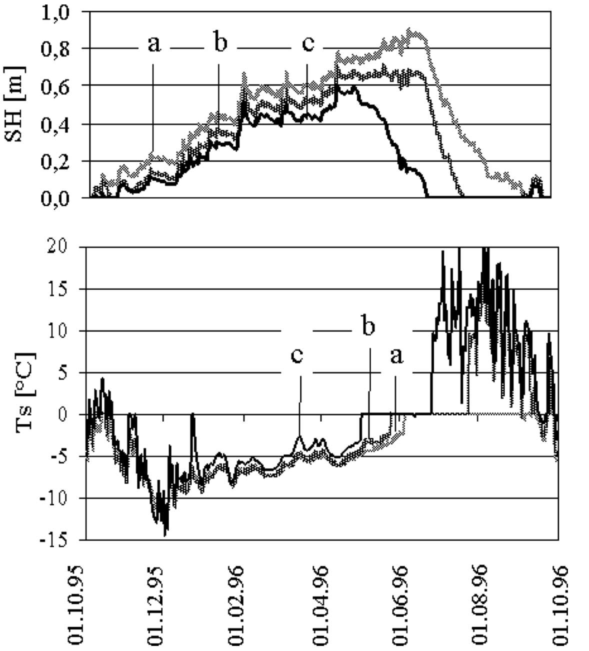

Figure 4. Simulations of the snow cover (SH) under increased mean annual air temperatures of (a) 0°C, (b) 1°C and (c) 3°C show an asymmetric decrease. The lower graph shows the corresponding soil surface temperatures (Ts).

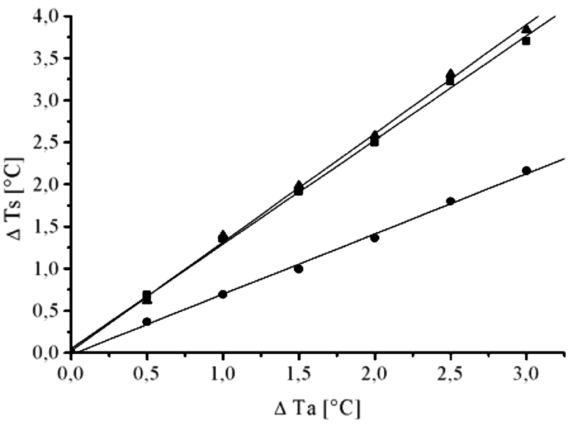

Figure 5. Correlations between the increase in the mean annual air temperature (ΔTa) and the increase in the mean annual soil surface temperature (ΔTs) show a strong linear dependency for a fine-grained soil (circles), a coarse blocky soil (triangles) and a rock ridge (squares). The lines indicate linear fits to the experimental data.

This affects the underlying ground accordingly: the lower graph shows the resulting increase in soil surface temperatures and an offset at the beginning of the zero curtain of two months.

The effect of increasing mean annual air temperatures on mean annual soil surface temperatures is shown in Figure 5, obviously, there is a strong linear dependency between the increase in the mean annual air temperature and increase in the mean annual soil surface temperature for the three soil types. The

Table 4. Parameters characterizing the linear fits in Figure 5: $\Delta Ts = A + B*\Delta Ta$, with correlation parameter R and standard deviation sd.

	A [°C]	B [−]	R	sd
Coarse blocky	0.054	1.237	0.999	0.060
Fine grained	−0.020	0.716	0.999	0.043
Rock ridge	0.024	1.291	0.999	0.059

parameters characterizing the linear fits of the temperature dependencies are listed in Table 4. The linear temperature dependency of the fine-grained soil type is not as steep as those of the rock ridge and coarse blocky soil type. Hence, the reaction of fine-grained soils (containing water) on air temperatures is dampened in comparison with the rock ridge and coarse blocky soils, which also can be seen from Figure 3.

4 CONCLUSIONS

For a better understanding of the interaction between factors affecting the snow cover – permafrost system, a numerical model was developed by coupling the SNOWPACK model to a ground heat flux model. This new model was tested by simulating the laboratory measurements, where humidity and soil temperatures of three samples of different grain sizes were investigated under well-defined climatic conditions. These simulations demonstrate that the measurements can only be reproduced accurately by the model with the adjustment of a significant water reduction. This can be justified by the fact that the laboratory measurements do not show a clear zero curtain. The soil moisture of the samples, hence, is supposed to be negligible. This contravenes the results of the TDR measurements. The TDR probe used for these measurements is not well adapted to measurements in loose material due to its unflexible fork shaped construction. The TDR, thus, could not be well embedded into the soil samples of the laboratory experiments, and the measurements, therefore, could not be made accurately.

First simulation results show that – for equal climatic forcing and snow cover characteristics – the soil surface temperatures of a partially saturated fine-grained soil are 4°C warmer than those of coarse blocky soils and even 5°C warmer than those of rock ridges. This effect is assumed to be the result of the water content of the fine-grained soil and the corresponding deviation of the mean heat conductivity and the exchanges of latent heat fluxes. Further simulations indicate that increasing mean annual soil temperature is linearly dependent on increasing mean annual air temperature. This linear dependency exists in all three different soil types but is represented by different gradients and intercepts.

The effect of variable climate sensitivity is also assumed to be related to the variable mean heat conductivities of the different soil types.

From the current state of the work, it can be stated that the SNOWPACK_ECO model has turned out to be an appropriate tool for the investigation of the influences of climate and soil texture on permafrost. Advective heat fluxes were not implemented in the model presented in this paper. Thus, the influence of air movements in coarse soils could not be considered. Also, specific freezing characteristics (freezing-point depression and corresponding changes in latent heat fluxes) of the soil have not yet been implemented. Further development of the model will enable the investigation of effects of advective and related latent heat fluxes in different soil types.

ACKNOWLEDGEMENTS

We would like to thank Sarina Eisenring, who helped in setting up and performing the laboratory measurements, P. Föhn for the support in meteorological aspects of changing climate, and to R. Meister for preparing the meteorological input parameters.

This work was partly funded by the Swiss National Science Foundation (Nr. 21-65263.01).

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