Verification of SNOWPACK model in the Western Caucasus, Russia, for spatial assessment of snow cover stability

Elena S. Klimenko
Lomonosov Moscow State University, Russia

ABSTRACT: We applied physical model Snowpack, developed in Switzerland, to simulate the evolution of snow cover in the Western Caucasus, Russia during three winter seasons (2008-09, 2009-10, 2011-12). The model was forced by the data from three weather stations located at different altitudes (1605, 2010, 2130 meters) which included: air temperature and humidity, reflected shortwave radiation, wind speed and direction, temperature at the upper and lower surface of the snow cover, snow height. Model's output was compared with the field data on snow height, temperature and snow pit studies. The results are in a good agreement with the observations. We suppose that the lack of data on incoming longwave radiation and liquid precipitation is the major source of revealed errors. We conclude that applied configuration of Snowpack model (v. 3.11) adequately reproduces evolution of snow cover structure and properties in the conditions of the Western Caucasus.

KEYWORDS: snow cover evolution, physical modeling, snow properties, meteorological data

1 INTRODUCTION

Human activities in mountains of Western Caucasus are largely affected by snow cover and avalanche activity. Avalanche forecast is one of the key issues in snow science today. Currently a new complex method of snowpack stability assessment, which is an inherent part of avalanche forecast, is under development. The method aims at identification of weak layers in snowpack profiles and is intended to provide spatial patterns of unstable zones at avalanche sites as output. Thus it requires detailed information on snow structure and properties on avalanche slopes. For that we use a physically-based layered model of snow cover evolution as a part of our method.

Application of any detailed snowpack model at a new site requires its preliminary approbation due to a number of empirical formulations used in the model. The present paper describes results of verification of physical model Snowpack, developed in Switzerland by the SLF (Bartelt et al., 2002), in the climate conditions of the Western Caucasus, Russia. The model was forced and verified by the data from weather stations of Rosa Khutor ski resort. Its slopes are used as a test site for development of our method. The resort is going to receive the Olympics 2014.

2 RESEARCH AREA

2.1 Field site

Rosa Khutor ski resort occupies the northern slopes of Aibga Ridge located in the Western Caucasus, south of European part of Russia. It is an area of typical alpine relief with elevations ranging from 600 to 2400 m asl. The research site has a damp climate with warm summers and moderately mild winters. It is similar to the climate of Davos town vicinity, Swiss Alps, where Snowpack model was developed and initially verified. Temperature regime and frequent warm spells usually accompanied with rains should be mentioned as main similarities. Mean perennial temperature of January (the coldest month) at 1888 m asl is -5.8˚C (Zalikhanov, 1981) while the value of -9˚C was obtained from the measurements at Weissfluhjoch site, Davos (2540 m asl) (Akifieva, 1996). It implies a good precondition for Snowpack model application. The most significant difference is in the precipitation falling during snow accumulation season which is two times larger in our site than in Weissfluhjoch: 1820 and 750 mm correspondingly. Snowpack simulations were done for three locations on the northern slope of Aibga ridge – at 1605, 2010 and 2130 m asl (Figure 1).

2.2 Study years

Snowpack model was tested during three winter seasons 2008-09, 2009-10 and 2011-12 for which required meteorological data were available. The selected winters were characterized with largely different weather conditions (Table 1).

Corresponding author address: Elena S. Klimenko, Lomonosov Moscow State University, Moscow, Russia;
tel: +7 916 810 8234;
email: eklmnk@gmail.com

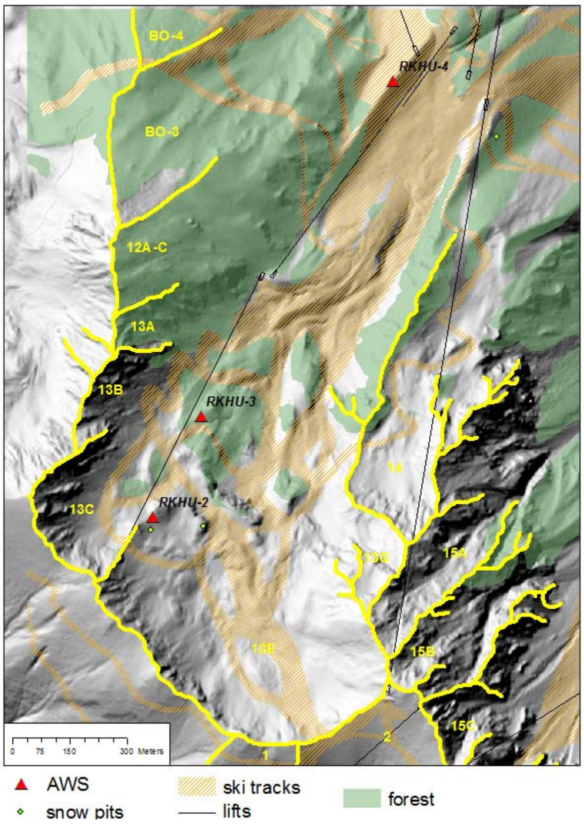


Figure 1. The research area of Rosa Khutor ski resort

Winter season 2008-09 had relatively high temperatures, numerous thawing periods and a significant amount of liquid precipitations. Warm winter was then superseded by a cold spring, which caused low snow melting rates. The season 2009-10 was relatively warm both in winter and in spring with frequent heavy snowfalls and many thaws. By contrast winter season 2011-12 was dominated by long periods with very low temperatures and the absence of thaws. Data collected during the seasons with significantly different conditions serve as a good basis for assessing the performance of Snowpack model.

Table 1. Comparison of weather characteristics of three seasons based on the data from weather station Aibga (2300 m asl) located in 2 km to the south-west from the highest of AWS. Time domain was defined by the period of snowpack presence

Season	2008-09	2009-10	2011-12
Cold days (T_{air}<0°C)	123	115	165
Warm days before snow melt (T_{air}>0°C)	84	98	15
Mean air temperature of the coldest month, °C	-11,9	-5,3	-17,9
Days with precipitations	132	101	95
Snowfalls	31	48	17
Precipitation sum, mm	1480	1650	950

3 FIELD DATA

Snowpack model was forced and verified by the data from three automatic weather stations (AWS) located at different altitudes – 1605, 2010 and 2130 m asl (Figure 1). The AWS recording interval was 30 minutes. The model input parameters (Table 2) included air temperature and humidity, wind speed and direction, reflected shortwave (SW) radiation, temperature at the upper and lower surfaces of the snowpack. Data on snow height were used for identification of snowfall start, duration and rate. It is a minimum data set necessary for Snowpack simulations. Field data (air temperature and humidity, snow height and temperature) were preprocessed to exclude spurious spikes and outliers and fill the data gaps. Air temperature was corrected for radiative heating of radiation shield. For assessment of model performance we used snow height and temperature measured at three levels inside snowpack along with results of snow pit studies done at 2110 m and 2140 m (snow density, snow grain type and size). Snow pit observations were carried out at 7-10 days intervals during the all seasons by the workers of the Avalanche Service of the resort.

Table 2. Names and characteristics of sensors used to collect meteorological and snow data

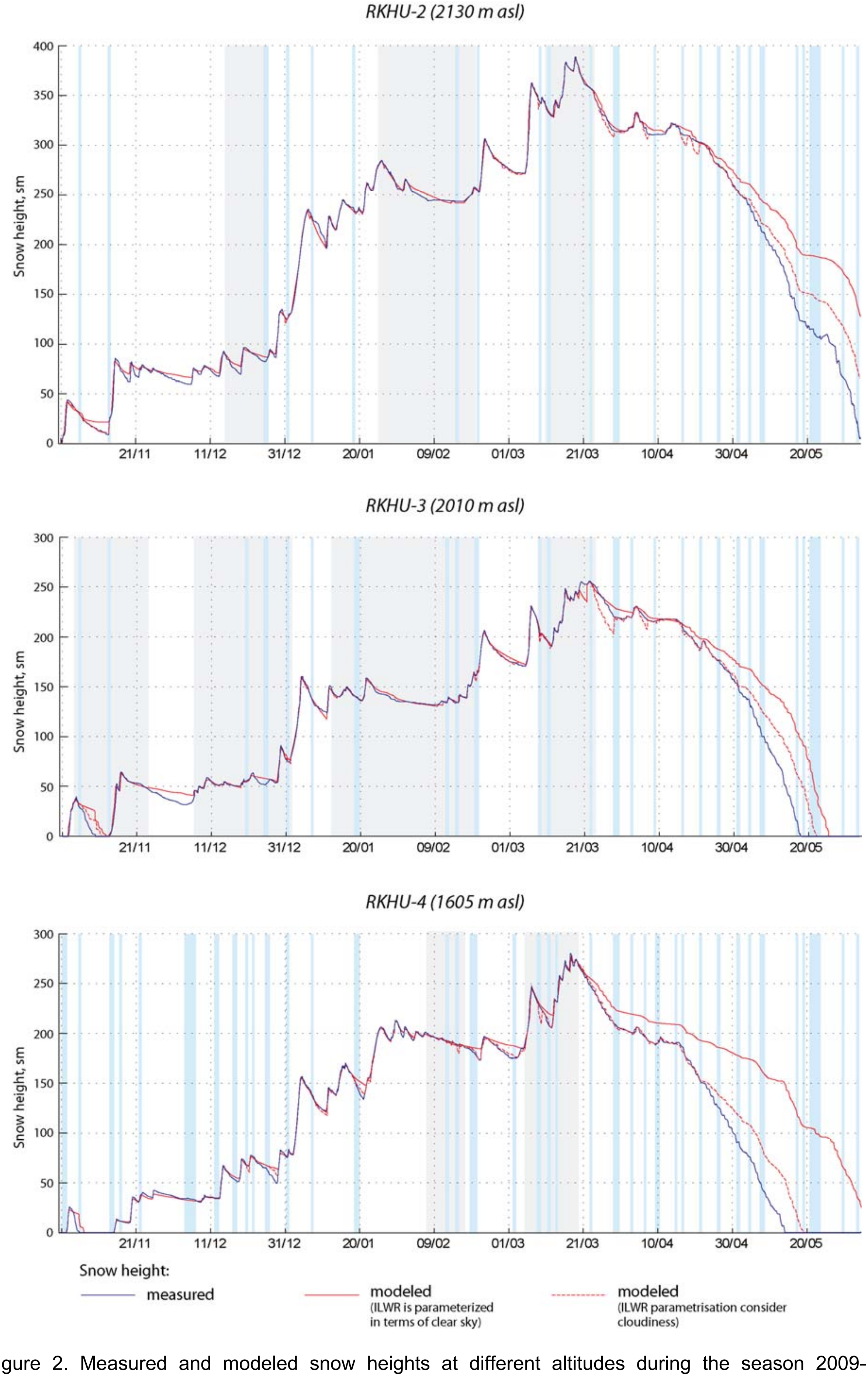
Parameter	Sensor	Precision
Air temperature	Campbell T107	± 0.1˚C
Air humidity	Rotronic Hygroclip	± 1%
Wind speed	RM Young 05103	± 0.3 m/s
Wind direction	RM Young 05103	± 3˚
Reflected SW radiation	Campbell CS300	± 5%
Snow surface temperature	IR Alpug	± 0.5˚C
Snow temperature	Campbell T107b	± 0.1˚C
Snow height	Campbell SR50A	± 0.1 sm

Since no data on precipitation, incoming SW and longwave (LW) radiation were available, the model was run with Dirichlet boundary conditions at the snow surface and empirical formulation of snow albedo (Lehning et al., 2002b).

4 COMPARISON OF SIMULATION RESULTS WITH FIELD DATA

4.1 Snow height

Snow height is a key parameter characterizing snowpack. It controls mass of


RKHU-2 (2130 m asl)

RKHU-3 (2010 m asl)

RKHU-4 (1605 m asl)

Figure 2. Measured and modeled snow heights at different altitudes during the season 2009-10

water stored in snow cover. Temporal dynamics of the snow height is an integral estimate for processes involved in snow accumulation, waste and compaction.

Applied configuration of Snowpack model accurately tracks the changes in snow height during snow accumulation periods of three simulation seasons at all altitudinal levels. Results for the season 2009-10 are presented in Figure 2. It allows us to conclude that empirical formulations for new snow density, snow viscosity, settling mechanism and wind erosion derived in Davos, Switzerland, and implemented in Snowpack model produce reasonable results under conditions of the Western Caucasus, Russia. Mean relative difference between simulated and measured snow heights is 3% (Figure 3).

However, during warm periods in winter and in spring the simulated snow height appears to be consistently overestimated. This discrepancy could be caused by underestimation of melt rate which is controlled by the incoming heat flux and settling rate.

The applied configuration of Snowpack model switches from Dirichlet-type of upper boundary conditions to Neumann-type when the surface temperature rises above -1.3 °C, so heat flux during warm spells and melting season is driven by measured and parameterized components of surface energy balance. LW radiation fluxes are major contributors to the energy balance at the snow surface in the conditions of the Western Caucasus since dense cloud cover is often observed and overcast conditions are not unusual. Yet it is one of the poorly resolved parameters in our study, since no field data were available and the parameterization implemented in applied version of Snowpack (v. 3.0) assumes clear sky conditions. Thus we suggest that calculated LW radiation fluxes can result in substantial underestimation of the energy supply to the snow surface which leads to reduced melting.

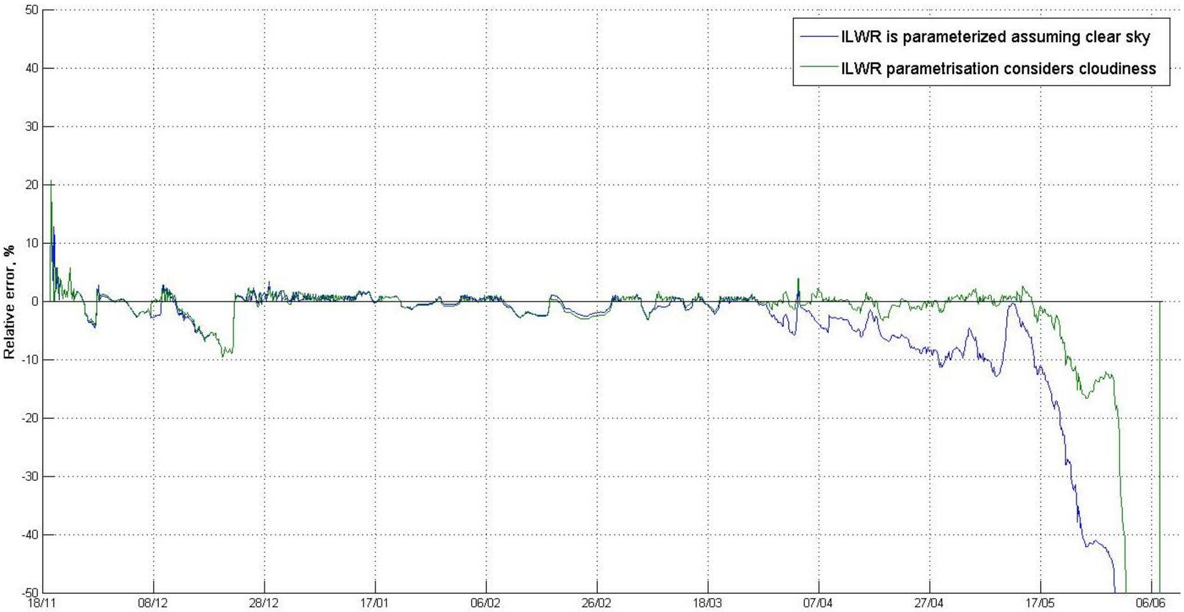


Figure 3. Relative difference between modeled and measured heights of snow cover at 2310 m asl during the season 2008-09

To test this hypothesis we ran the simulations using an updated version of Snowpack model (v. 3.11) in which a more flexible parameterization of LW radiation was implemented (Unsworth et al., 1975). The algorithm accounts for potential influence of the cloud cover by comparing theoretical and measured SW radiative fluxes. The estimated relative errors in snow height values produced by two applied versions of Snowpack are presented in Figure 3. The Unsworth parameterization appears to be a major improvement and reduces the relative difference between measured and modeled snow height by 60%, in several cases this difference is even negative. It is also evident that the effect of underestimated LW radiation fluxes is more pronounced at lower altitudes.

Another possible source of errors in estimation of snow height is in rate of snow settling. In the absence of precipitation data the model can not account for the influence of liquid precipitation on the rate snow melt and properties, which in turn affect the settling rate. The potential impact of liquid precipitation was assessed qualitatively by identifying the periods when rain events were probable (areas marked blue in Figure 2). The condition implied local temperature measured by the AWS above 1.2˚C and liquid precipitation observed at the weather station at the valley bottom (566 m asl). It is apparent that in some cases the positive differences between simulated and measured snow height values were caused by underestimation of snow settling rate. Thus precipitation data is of high importance for snow cover simulations using Snowpack.

4.2. Internal snow temperatures

Distribution of temperature in snow is a major control on energy fluxes between layers, which in turn has a dramatic effect on snow properties through metamorphism of grains. We validated the simulated snow temperature evolution by comparing it with measurements of snow temperature done at three levels above the ground: 0.2, 0.4 and 0.8 m. The results for the simulation site at 2010 m asl are presented in Figure 4.

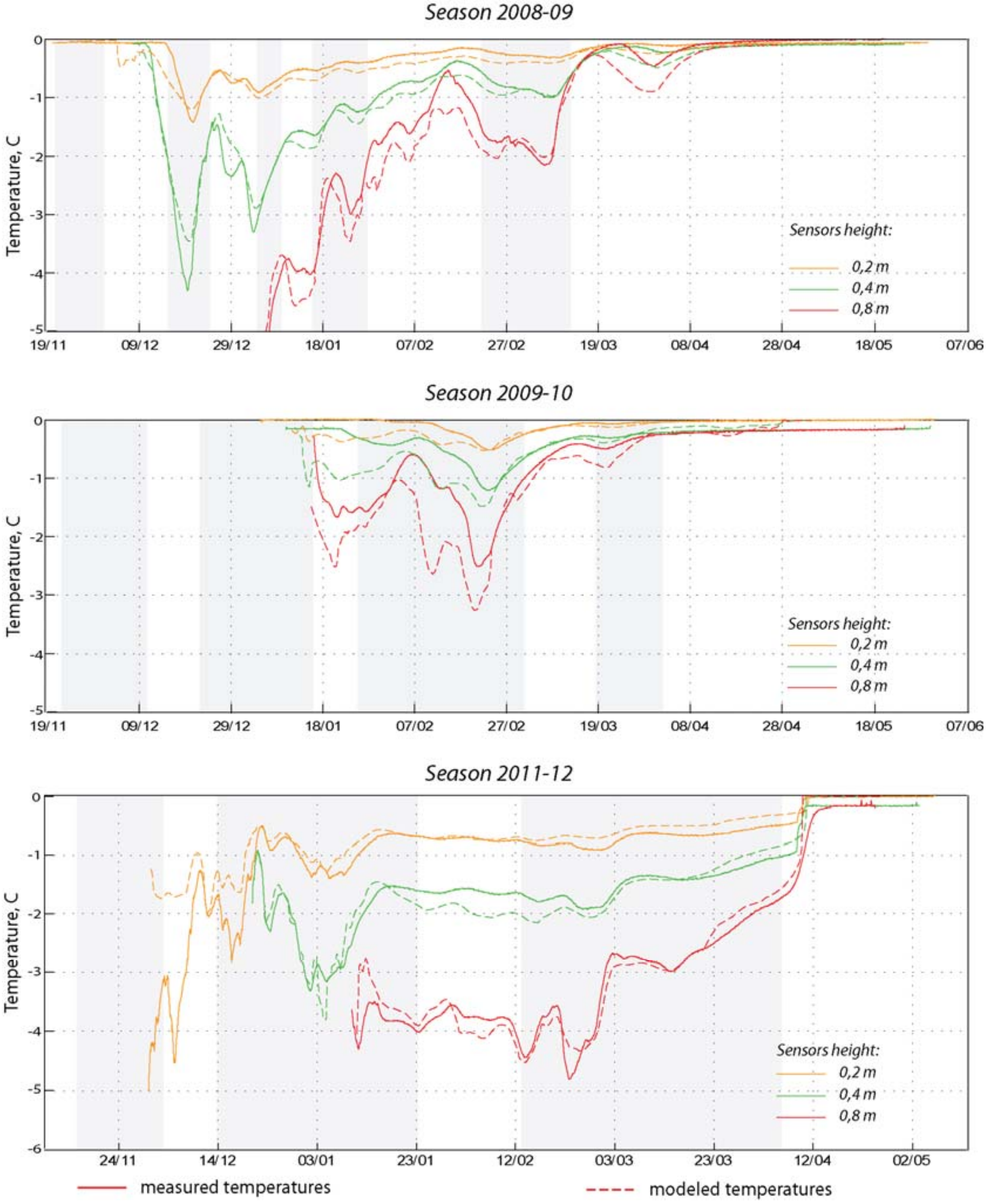


Figure 4. Measured and modeled snow temperatures at the altitude of 2010 m

A close correlation between simulated and measured values is observed with mean relative difference of 10% or less. The dominant tendency is underestimation of temperature by the model. We suggest that the reason is most likely to be in the poor parameterization of the LW radiation flux discussed in the previous section. Lack of data on liquid precipitation is another possible source of error. Rain on snow events have the potential for abruptly rising snow temperature due to release of latent heat of fusion during water refreezing. This effect is most obvious in the upper part of snow profiles and was particularly well pronounced during the warm winters of 2008-09 and 2009-10.

Another prominent feature is the small time lag between measured and modeled peaks in temperature. It is observed for both positive and negative spikes for all three years. Simulation results reveal consistently earlier spikes than the field data, which could be an indication of modeled snow thermal conductivity being too high. Errors in measurements as well as revealed uncertainties between modeled and observed snow height could also affect simulated snow temperature distribution.

We can conclude that Snowpack can produce adequate estimations of snow temperature in the conditions of the Western Caucasus even when such relevant for snowpack modeling data as LW radiation flux and precipitation is not available.

4.3 Layering and microstructure

Finally we assessed the model performance by comparing its output with data from snow-pit studies. By this we aim at understanding if simulated snowpack layering, physical and microstructural properties are typical for the research site. High spatial variability of snow cover and relatively large distance between snow pit sites and weather stations allow us to make only a qualitative comparison of snow characteristics: layered structure, grain types, ranges of density and grain size. We mainly consider the data of the coldest season 2011-12 since frequent rains during other years apparently had a profound effect on snowpack which could not be captured by the simulations.

Most layers described in the snow pits were found in the modeled snowpack profiles to the exclusion of several ice crusts which might be a result of rain on snow events in early winter. The snowpack was mostly composed by faceted crystals, rounded grains and wind-packed layers (Figure 5). However, the modeled rates of kinetic growth metamorphism producing faceted grains and depth hoar seem to be a little higher than those observed in the field.

In all seasons simulated snow cover had a number of very thin loose layers composed by faceted and depth hoar crystals which were formed due to abrupt local increases in temperature gradient just below snow surface. This is a result of steep drops in snow surface temperature (up to -20˚C) associated with rapid decreases in air humidity during calm cloudless nights. A number of similar weak layers was observed in the field which proves the high skills of the model.

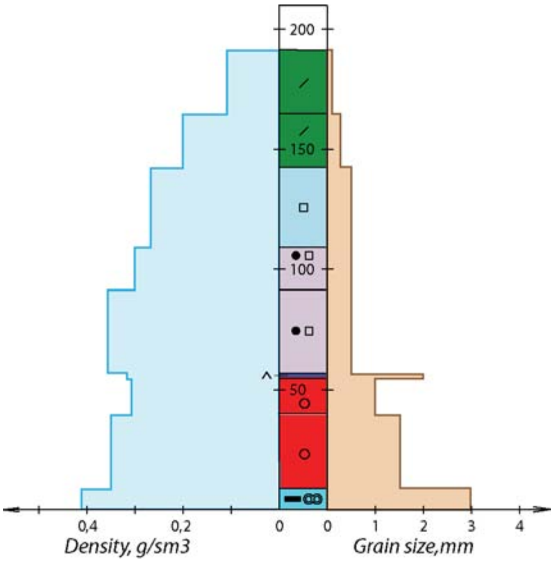


Figure 5. Snowpack profile typical for the cold season 2011-12, observed 5.02.12 at 2140 m asl

The range of simulated densities and grain sizes both for new and old snow layers is in a good agreement with the observed data during the whole winter 2011-12. Dry snow density is around 150 kg/m^3 for new snow layers and ranges from 200 to 450 kg/m^3 for old snow. During snow accumulation period grain sizes are generally less than 1 mm except for the snow layers which underwent melting and subsequent refreezing.

5 CONCLUSION

Detailed model of snow cover evolution Snowpack was tested in the climate conditions of the Western Caucasus, Russia, during three winter seasons. The simulation results were compared with measured snow height, temperature and observed profiles. A high general level of correspondence was found. Periodical underestimation of snow height and temperature (especially in spring) might be corrected by introducing the data on precipitation and incoming LW radiation. Most layers described in the snow pits are present in the modeled snowpack profiles. Thus, the applied configuration of Snowpack (v. 3.11) successfully reproduces evolution of snow cover in our field site and can be used as a part of our method of snow stability assessment on avalanche slopes.

6 AKNOWLEDGEMENTS

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7 REFERENCES

Akifieva K.V. Dynamics of snow regime in Weissfluhjoch site (Davos, Switzerland). 1996. Manuscript. Moscow, Archive of the Laboratory of Snow Avalanches and Mudflows.

Bartelt P.B., Lehning M. 2002. A physical SNOWPACK model for Avalanche Warning Services. Part I: numerical model. Cold Reg. Sci. Technol., 35(3): 123-145.

Lehning, M., P.B. Bartelt, R.L. Brown, C. Fierz and P. Satyawali. 2002b. A physical SNOWPACK model for the Swiss Avalanche Warning Services. Part III: meteorological boundary conditions, thin layer formulation and evaluation. Cold Reg. Sci. Technol., 35(3): 169-184.

Unsworth M. H., J. L. Monteith. 1975. Long-wave radiation at the ground. Quarterly Journal of the Royal Meteorological Society, 101 (430), 1029–1030.

Zalikhanov M.C. Snow and avalanche regime and development prospects of the Caucasus. 1981. Rostov, 376.