A MULTI-LAYER SNOW COVER MODEL FOR NUMERICAL WEATHER PREDICTION AND CLIMATE MODELS

Sascha Bellaire[1] and Michael Lehning[1,2]

[1]*WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland*

[2]*Labaratory of Cryospheric Sciences, School of Architecture and Civil Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland*

ABSTRACT: The seasonal snow cover strongly influences boundary layer processes such as turbulence and radiation. Therefore, knowledge of the current state of the snow cover on the ground is of paramount importance for numerical weather prediction (NWP) and climate models. This is especially true since the horizontal resolution (up to 1 km) of NWP models strongly increased in recent years. Currently, most NWP models use simplified – typically one snow layer – snow cover schemes, which are in general not capable to simulate snow cover formation, evolution and melt with adequate accuracy. Within the framework of the COSMO consortium (Consortium for Small-scale Modelling) we are developing a new multi-layer snow cover module for the regional weather forecasting and climate model COSMO and the global model ICON (Icosahedral Nonhydrostatic). The snow cover model consists of six snow layers with increasing but constant thickness for the upper part (top 29 cm) of the snow cover and a variable amount of snow layers (minimum = 2) in the lower part of the snow cover. Preliminary results indicated an improvement of the snow surface temperature with only minor effects on the near surface air temperatures, when compared to the single layer counterpart at the location of a network of high-alpine weather stations.

KEYWORS**:** snow cover modelling, numerical weather prediction, climate modelling

1. INTRODUCTION

The seasonal mountain snow cover can lead to hazardous situations (e.g. avalanches, flooding), provides water resources during the melt phase and constitutes an important factor for global and regional weather and climate. Forecasting the snow cover evolution in complex terrain provides valuable information to assist with avalanche danger assessments as well as runoff estimations relevant for hydropower development and flood prevention. Furthermore, knowing the evolution and spatial distribution of the seasonal mountain snow cover allows for a better estimation of the surface albedo or turbulent fluxes of heat and moisture relevant for accurate weather and climate modelling. As a result, the boundary layer develops differently over snow with consequences for the dynamics of the whole atmosphere. Therefore, knowledge of the current state of the snow cover on the ground is of paramount importance for numerical weather prediction (NWP) and climate models. This is especially true in complex topography when running forecasts with fine horizontal resolution, where the spatial heterogeneities of the snow cover is large, and where a high-quality snow analysis is difficult to obtain.

Forecasting the evolution of a mountain snow cover requires an accurate modeling of the snow surface temperature. In general, the surface temperature is defined by the surface energy balance and controls the balance between atmospheric heat fluxes – short wave and long wave radiation as well as turbulent fluxes and heat conduction into the snow cover. Heat conduction from the surface, through the snow cover, to the snow/soil interface depends on the surface temperature, the snow cover layering, i.e. density, as well as the current temperature distribution as well as phase changes happening in the snow. Therefore, it has been shown that single layer models are typically not capable of reproducing the complex heat flow within a snow cover (e.g. Etchevers, 2004). A single snow layer would possess homogenous thermal properties. However, due to the often strongly varying atmospheric forcing, e.g. a daily cycle or clouds, the snow temperature profile is highly nonlinear, which changes not only the temporal dynamics of energy exchange but also its total amount.

Currently, most NWP and climate models, including COSMO, use simplified – typically one snow layer – snow cover schemes, which are in general not capable to model the complex processes relevant for snow cover formation and evolution. Although more sophisticated land surface schemes exist, e.g. CLM (Community Land Model; Oleson et al., 2013) or SURFEX (e.g. Vionnet et al., 2012; Masson et al. 2013), which include multi-layer snow cover schemes, it is often not feasible to simply swap the land surface scheme used by a NWP model. This is especially true for an operational weather service where numerical stability and reliability of the forecast is of paramount importance. Intensive testing is required prior to such a drastic step.

Although a multilayer snow cover parameterization scheme (Volodina et al. 2000, Machulskaya 2015) has been tested in COSMO and ICON, it has shown unresolved difficulties especially for operational applications. In collaboration with the COSMO consortium we therefore are developing a new multi-layer snow cover scheme for both models. In this paper we present the current status of this project, first initial results as well as future plans.

2. DATA

Forecasted data were mainly compared with data from a network of automated weather (Fig.1.) stations (N = 112) located between 1500 m and 3000 m a.s.l. across the Swiss Alps (Intercantonal Measurement and Information System: IMIS; Lehning et al., 1999). The IMIS stations were designed to provide additional meteorological and snow cover data for avalanche services and are therefore located at representative locations across the Swiss Alps. For this study we used measured surface temperature as well air temperature resampled to hourly values for direct comparison with the hourly output of the NWP model.

3. METHODS

In the following we first describe the general setup of the COSMO model used for this study. We then introduce the proposed multi-layer snow cover scheme (MLS) followed by a brief description of the numerics for solving the 1-dimensional heat equation as well as a description of the calculation of the radiative (short-wave) and turbulent fluxes.

3.1 COSMO model setup

We used the numerical weather prediction model COSMO. The COSMO model (formerly ‘LM’, Doms and Schaettler, 2002) is currently in operational use by different international weather forecasting services (e.g. Germany, Switzerland, Italy, Poland, Romania, Greece, Israel and Russia). COSMO is a non-hydrostatic limited-area model developed and maintained by the COnsortium for Small scale MOdelling (COSMO, www.cosmo-model.org). For our study, we chose the model setup corresponding to operational Version of COSMO operated by the Swiss meteorological office (MeteoSwiss) with a horizontal resolution of 7.7 km (COSMO-7). For the COSMO simulations we chose a domain with an extent of approximately 700 km x 700 km (Fig. 1). The domain includes most of the Alps spanning from France in the West over Italy and Switzerland to Austria in the East. Boundary conditions were taken from the COSMO-7 analysis. We carried out 72-hour forecasts starting 16 February 2017 at 00UTC. For comparison with the observations forecasted data from the closest (Euclidean distance) grid point was extracted.

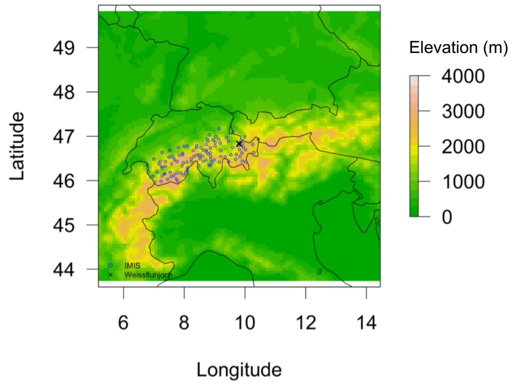

Figure 1.: Surface heights of the COSMO model domain used in this study (7 km horizontal resolution). Open blue circles indicate the location of the IMIS stations (N = 112). Black cross shows the location of the experimental site Weissfluhjoch above Davos, Switzerland (Eastern Swiss Alps).

3.1 Multi-layer snow cover scheme - Layering

The proposed multi-layer snow cover scheme (MLS) consists of six snow layers with increasing but constant thickness for the upper (top) part of the snow cover and a variable amount of snow layers (minimum 2) in the lower part of the snow cover. Whereas the layer thickness of these layers is a least 1 cm. The thickness of the upper layers is defined as (top down), 1 cm, 2 cm, 3 cm, 5 cm, 7 cm and 11 cm, respectively (total 29 cm). Therefore, with the current MLS scheme a snow cover with a snow depth ≥ 31 cm can be simulated. For grid cells with a snow depth of smaller < 31 cm the single layer snow cover scheme is used.

The multi-layer soil model of the land-surface scheme TERRA consists of 8 soil layers, i.e. 7 active layers for which for example the heat flux and water transport is calculated and 1 so-called climate layer, where the annual mean surface temperature is subscribed as a boundary condition.

3.2 MLS – Solving the 1D heat equation

The one-dimensional heat equation is solved for a combined column of snow and soil layers (total 16 layers) with varying thickness. A set of linear equations results, which is then solved using the Thomas-Algorithm (Conte and deBoor, 1972).

3.3 MLS – Upper boundary condition

The temperature of the upper boundary, i.e. top snow layer, is mainly controlled by the surface energy balance. Most NWP models including COSMO calculate grid cell representative fluxes of radiation and turbulence, which control the energy exchange of the atmosphere with the surface. That means for example, in case a grid cell includes e.g. forest, the albedo is typically lower compared to an albedo of snow-covered ground. Furthermore, the surface or ground temperature depends on the fractional cover, i.e. snow, forests settlement etc. and can therefore vary significantly from the snow surface temperature especially when the horizontal resolution of the model is larger and the fraction of the snow cover is comparably small.

In order to assess the sensitivity of these gird cell representative fluxes on the snow surface temperature calculation we estimate the net. short wave radiation and turbulent fluxes independently. Therefore, we estimate an albedo as a function of current atmospheric conditions such as:

$$\alpha = c_1 + c_2 \times P_R + c_3 \times T_1 + c_4 \times T_0 \qquad (1)$$

with P_R being the precipitation rate (mm h^{-1}), and T_1 the temperature of the first atmospheric level (K), the current snow surface temperature T_0 (K) as well as the coefficients c_1 = 3.1, c_2 = 176.1, c_3 = -0.01 and c_4 = 0.004.

In addition, Schlögel et. al (2017) recently developed stability correction functions for snow covered areas which show better performance than standard methods in complex snow cover alpine terrain. Transfer coefficients were therefore calculated using the suggested universal multivariate parameterization. Turbulent fluxes of sensible and latent heat were estimated using the bulk method taking into account the air temperature and specific humidity of the first atmospheric level as well as the temperature and the specific humidity of the snow surface. For the specific humidity at the snow surface we assume saturation.

4. RESULTS

Here we present initial results of the performance of the multi-layer scheme (MLS) in comparison to the current single layer scheme (SLS) for the surface temperature (4.1) as well as for the air temperature (4.2). In section 4.3 we show the sensitivity of surface temperature as well as air temperature to the choice of different parameterization of turbulent fluxes and net. short-wave radiation in a so-called point validation.

Table 1: Averaged mean bias (ME) and mean absolute bias (MAE) of the 72-hour forecast for all IMIS stations (N = 112) for the surface temperature and air temperature. ME and MAE are given for the forecast using the single layer scheme (SLS), the multi-layer scheme (MLS) using the same forcing as used by the SLS scheme as well as for the MLS scheme using alternative formulations for the net. short-wave radiation and turbulent fluxes (MLS_{NEW}).

	Surface Temperature		Air Temperature	
	ME	MAE	ME	MAE
SLS	5.6	6.3	-1.6	2.2
MLS	1.1	7.5	-1.9	2.5
MLS_{NEW}	-1.1	4.7	-6.1	6.3

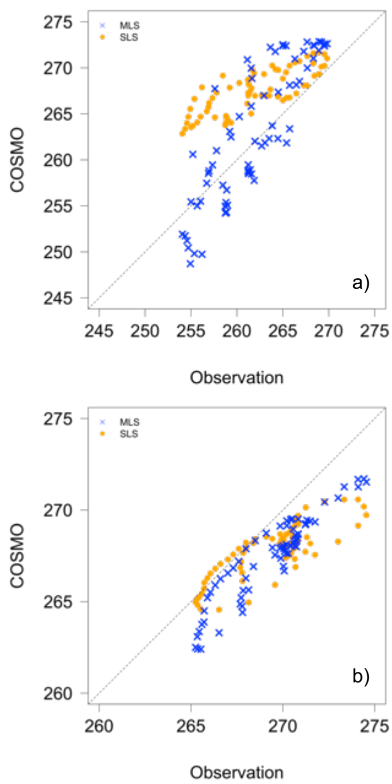

Figure 2: Mean measured (IMIS) and forecasted (COSMO; closest grid point) a) snow surface temperature as well as b) air temperature for 112 automated weather stations of the IMIS network. Shown are the surface and air temperatures for a 72-hour forecast in February 2017 with the single layer snow cover scheme (SLS, orange circles) as well as the multi-layer scheme (MLS; blue crosses). Dashed line shows the 1-to-1 relationship.

4.1 Snow surface temperature

A comparison of measured (IMIS) and forecasted (COSMO; 72-hours; closest grid point) snow surface temperature for the location of 112 IMIS stations is shown in Figure 2a. Performance measures, i.e. the mean error (ME) and mean absolute error (MAE) are given in Table 1. The single layer snow scheme (SLS) overestimates the snow surface temperature (ME = 7.0 K; MAE = 6.3 K). The multi-layer scheme (MLS) performs better, i.e. the ME is about 4 times smaller, at the location of the IMIS stations, but still overestimates the surface temperature (ME = 1.1 K; MAE = 7.5 K).

4.2 Air temperature

In order to assess the effect of an improved snow surface temperature on the atmosphere we compared the measured air temperature at the location of the IMIS stations to the forecasted air temperature of the first atmospheric level (Fig. 2b). Note that the first atmospheric level is approximately at a height of 10 m. Measurements at the IMIS stations are typically taken at 6.5 m, corrections for this difference were not made. However, due to the difference between station elevation and model grid point, we applied a wet-adiabatic lapse rate of 0.65 °C/100 to the forecasted data. Compared to the simulation with the SLS scheme the MLS scheme shows similar performance, but tends to be slightly cooler. Overall, both schemes show a cold bias at the location of the IMIS stations. The mean errors for the SLS and MLS scheme were -1.6 K (MAE = 2.2) and -1.9 K (MAE = 2.5), respectively.

4.3 Atmospheric coupling

In order to test the sensitivity of the multi-layer scheme to the choice of flux calculation we used alternative formulations for the net. short-wave radiation, i.e. a different albedo parameterization (Eq. 1) as well as for the turbulent fluxes by using an alternative formulation for the transfer coefficients. A comparison of measured and forecasted surface as well as air temperature for a single IMIS station named Boveire - Pointe de Toulesis (Western Swiss Alps) is shown in Figures 3a und 3b. Note that the corresponding grid cell to this location has no forest cover, i.e. the fractional snow cover is 1.

The surface temperature for this specific location was overestimated by the SLS scheme (ME = 6.6 K; MAE = 7.3 K). Although the MLS scheme using the same fluxes shows better performance (ME = -1.6 K) it shows strong variation indicated by a large mean absolute error of 10.6 K. On the other hand, the forecasted surface temperature using the alternative flux parametrizations provides the best results for this specific location, i.e. a mean error of -2.3 K and a mean absolute error of 4.9 K.

The air temperature forecast using the SLS scheme as well as the MLS scheme with the same forcing show a cold bias (ME = -1.3 K). If the MLS scheme with the alternative flux calculations is used the cold bias further increases to -4.0 K.

Note that the mean scores for the MLS scheme using the alternative fluxes for all IMIS stations of the surface temperature and the air temperature were found to be ME = -1.1 K, MAE = 4.7 K and ME = -6.1 K, MAE = 6.3 K, respectively.

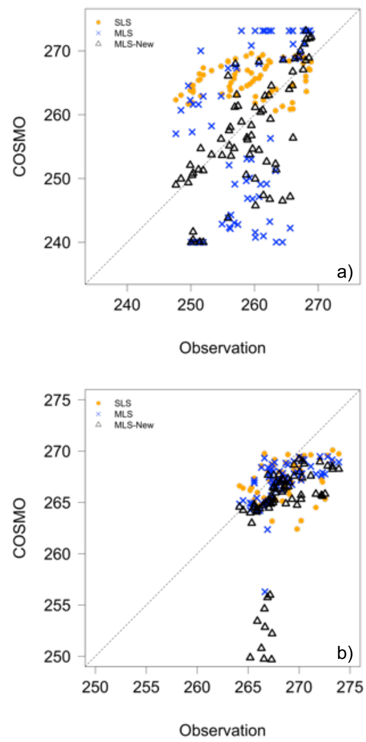

Figure 3: Comparison of a) surface temperature and b) air temperature for the location of a single IMIS station named Boveire - Pointe de Toulesis (forest free). Additionally, shown are comparisons of measured surface and air temperature of a forecast using the MLS scheme with alternative formulations of net. short-wave radiation and turbulent fluxes (open black triangles). Dashed line shows the 1-to-1 relationship.

5. DISCUSSION

The question remains why an improved surface temperature using the MLS scheme with alternative flux calculations does not improve the air temperature. This is mainly due to the fact that the MLS scheme calculates the atmospheric forcing in a different way compared to the SLS scheme, i.e. different albedo as well as a different function for the correction of atmospheric stability, hence different turbulent fluxes. Therefore, the exchange between the surface and the atmosphere is based on wrong fluxes and conservation of energy and mass balance is violated.

A solution to this problem is not trivial since it involves fundamental changes to the model physics especial of the turbulent transfer scheme. However, a tile approach where the energy and mass balance are calculated for each tile separately, i.e. for snow, forest, water etc., would allow the formulation of alternative formulations for the surface fluxes. Such an approach is currently implemented and tested in the ICON model (Icosahedral Nonhydrostatic; www.dwd.de) and would allow using alternative formulation in order to derive more accurate snow surface temperatures essential for the snow cover evolution, especially during the ablation phase where the impact of the new MLS scheme is expected to be large.

6. CONCLUSIONS

We successfully implemented a new multi-layer snow cover scheme into the numerical weather prediction model COSMO. At this stage the scheme solves the one-dimensional heat equation for eight snow and eight soil layers. The scheme was validated in terms of surface temperature as well as air temperature with measurements from a network of alpine weather stations. Although, the new MLS scheme shows improved scores for the snow surface temperature it tends to be too cold – especially during the night – which will require adjustments to the parameterizations of the turbulent fluxes. Future work will include the consolidation of the surface atmosphere exchange as well as phase changes, water transport and settlement.

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