An Advanced Snow Parameterization for Models of Atmospheric Circulation

Ekaterina E. Machul'skaya[1,2], Vasily N. Lykosov[1,3]

[1] *Institute for Numerical Mathematics, Russian Academy of Sciences, Moscow, Russia*
[2] *Hydrometeorological Centre of Russian Federation, Moscow, Russia*
[3] *Moscow State University, Russia*

1 Introduction

Numerous observational studies and climate model simulations have shown that snow cover affects atmospheric circulation, air temperature, and the hydrologic cycle. Snow cover, especially fresh snow, has a much higher albedo than bare ground or liquid water, so that solar radiation absorption is significantly reduced, often as much as 50%. The induced radiative cooling is reinforced by the high thermal emissivity of the snow cover, which increases static stability in the atmospheric boundary layer and consequently reduces turbulent fluxes. This effect is enhanced by a reduced roughness of snow-covered vegetation when compared to snow free conditions.

Snow extent is related to a number of feedbacks, the most obvious being the snow albedo feedback: a positive temperature bias (for instance, as a result of a global climate change) leads to larger snow melt, faster snow cover depletion, which leads to a decrease of surface albedo. This allows more absorption of solar radiation and therefore reinforces further warming.

To represent land surface processes in atmospheric models different schemes have been developed, including soil-vegetation-atmosphere transfer schemes that incorporate snow models of the different complexity (e.g. Sellers et al., 1996, Bonan, 1996, Verseghy, 1991, Desborough and Pitman, 1998, Gusev and Nasonova, 1998, Volodin and Lykosov, 1998, Volodina et al., 2000).

At the moment many time series of different meteorological and hydrological characteristics have been accumulated from different field experiments and regular observations. It makes possible thorough evaluation and intercomparison of snow models to understand what snow processes must be represented in the coupled land surface schemes and atmospheric models.

The present study reports results of comparative analysis of the snow depth simulation obtained with two land surface schemes, namely the land surface scheme TERRA of the COSMO model (Doms et al., 2005) and one (Volodina et al., 2000) of the global circulation model of the Institute for Numerical Mathematics (INM) (Moscow, Russia). This intercomparison is done by means of the meteorological and hydrological data sets that were continuously collected at Valdai water-balance research station (Russia, European part) in 1966–1983 and at Yakutsk meteorological research station (Russia, East Siberia) in 1937–1984.

2 Brief description of models

The land surface scheme of the COSMO model has 7 layers in the soil (the depth of the 7th layer is 4.86 m, and there is one additional climatological layer at the depth of 14.58

m) and one layer to describe the snowpack properties, namely snow temperature, snow water equivalent depth and snow density. The temperature profile in the soil is predicted by the heat conduction equation and then adjusted against liquid/frozen water content (freezing/melting), and the snow temperature is calculated following the heat conduction and energy budget at the snow surface. When snow temperature rises upon the melting point, it is set to the melting point value and the excess of the heat is spent to melt the snow. This amount of the melted water immediately appears on the soil surface, and snow water equivalent depth decreases. Snow density varies accordingly to an empirical formula that accounts for the snow age, i.e., the old snow density is greater than the fresh snow density. It is taken that the fresh snow has a density of 250 kg/m^3.

In the land surface scheme of the INM model, it is possible to use an arbitrary number of soil layers (in the current study it was fixed at 32), the lowest layer locates at the depth of 10 m. In the snow model, constructed on the basis of studies on snow dynamics (e.g., Bengtsson, 1982; Colbeck, 1978; Glendinning and Morris, 1999; Pomeroy et al., 1998), an arbitrary number of layers in the snowpack is also used (in this study, 5 layers). The temperature profile in the soil and in the snow is also computed by the heat conduction equation and then adjusted against liquid/frozen water content. This adjustment is carried out not only in the soil, but also in the snow: any layer of the snowpack can contain the liquid water up to water holding capacity. This liquid water can refreeze, if the layer temperature falls under the freezing point. When the liquid water content of the layer becomes greater than water holding capacity of the snow, this water percolates into underlying layer. Snowmelt starts, i.e., snow water equivalent depth decreases, only when liquid water content of the lowest snow layer is greater than water holding capacity, and water from this layer percolates to the soil surface.

Besides the water refreezing and percolation processes, in the INM snow model the other processes are implemented — gravitational compaction and metamorphosis of the snow (Marshall et al., 1999) and the solar radiation penetration through the snowpack (Jordan, 1991). The density of each snow layer is analytically calculated accordingly to content of snow, liquid and frozen water in the layer. The fresh snow density depends on the air temperature and can vary from 65 to 145 kg/m^3 (Hedstrom and Pomeroy, 1998). Further, to describe effects of the gravitational compaction of snow, a semi-empirical formula (Marshall et al., 1999) is employed.

After implementing all of these physical processes into the INM snow model, the computational cost increased of 7 per cent, when compared with the first version of this model that was similar to the present COSMO snow model.

3 Data

Two observational data sets were used for numerical experiments. The first data set contains long-term systematical observations that were collected in 1966–1983 at a grassland site at the Valdai water-balance research station (57.6N, 33.1E) in the forest zone of Russia. This data has been used as forcing and evaluation data for the land surface simulations during the frame of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS), Phase 2(d) experiment. The forcing data with 3-hour temporal resolution contains measurements of the downward shortwave and longwave radiation, precipitation rate, air temperature, pressure and specific humidity at the 2 meter height and horizontal components of the wind speed at the 10 meter height. The evaluation data contains, among other parameters, time series of the snow water-equivalent depth that were measured every 10 days in winter and more often in spring.

The second data set is similar to the first one, but was collected at the Yakutsk meteorological station (East Siberia) in 1937–1984. Due to the lack of observations of the solar radiation at this station, to estimate the incoming shortwave and longwave radiation, some empirical formulae, containing information on the cloudiness, air temperature, humidity and pressure, station's latitude and longitude, were used.

4 Results and discussion

In general, both models reasonably represent the water-equivalent snow depth (SWE) and the onset of intensive snow melting.

For Yakutsk, the models under consideration have shown close results. The moment of complete disappearance of the snow cover is represented very close to observations, but the simulated SWE is systematically overestimated by both models during the late winter and spring. SWE, simulated by the INM model, is a little bit more close to the observed SWE than SWE, simulated by the TERRA (Fig. 1).

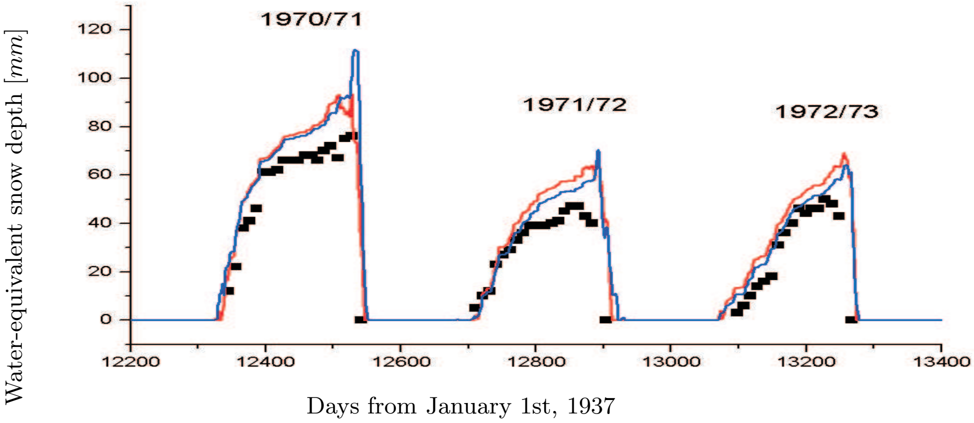

Fig. 1: Observed (black symbols) and simulated by TERRA and INM models (red and blue lines, respectively) water-equivalent snow depth, Yakutsk.

For Valdai, there are more differences in results of modeling. In the TERRA model, snow melts much earlier than in the INM model and than in reality. As summarized in Table 1, the correlation coefficient between time series of observed and simulated by TERRA and INM models snow water equivalent depth is 0.71 and 0.90, respectively. Mean errors in the time of the snow complete ablation are -17 (7) days in the TERRA model versus -1 (1) day in the INM model.

Table 1: (a) The correlation coefficient (r) between time series of observed and simulated by the TERRA and INM models snow water equivalent depth and (b) mean error ME (± standard deviation SD) in the time of the snow complete ablation at the Valdai station.

	(a) r	(b) ME ± SD,days
TERRA	0.71	-17(±7)
INM	0.90	-1 (±1)

In Fig. 2, time series of SWE, observed and simulated by both models for the 9 first years starting from 1967, are shown. It should be noted that within this study the first year of

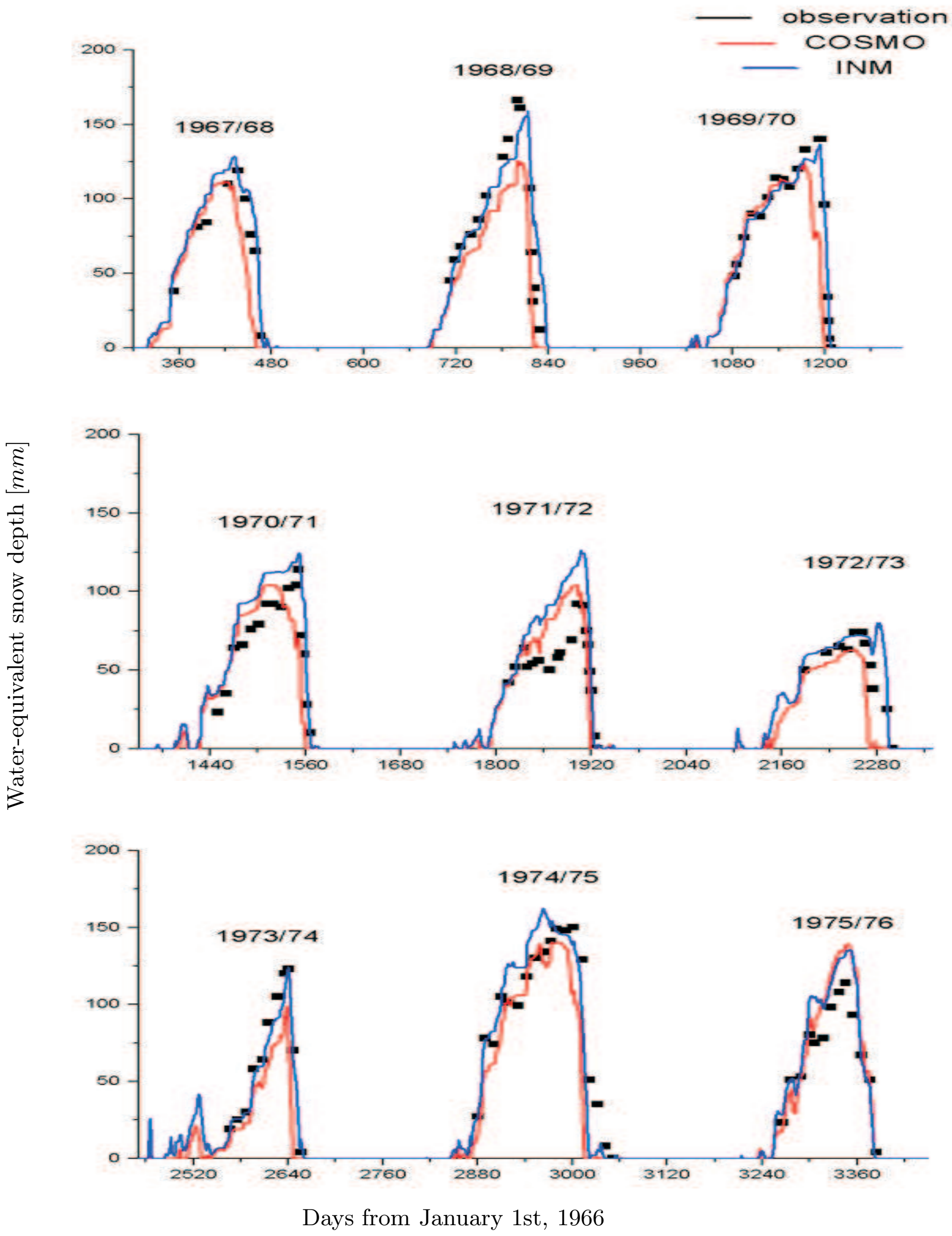

Fig. 2: Observed (black symbols) and simulated by TERRA and INM models (red and blue lines, respectively) snow water-equivalent depth, Valdai, 1967-1976.

integration, 1966, is considered as a spin-up period and is not included into analysis of the results. For the last 8 years, the pattern of difference between observed and simulated SWE is the same. The discrepancy between results of snow depth simulation by TERRA and INM models is more noticeably in the late winter and particularly during the spring.

This discrepancy can be explained by difference in the models descriptions of physical processes in snow. It is known that there is a delay between the onset of snowmelt at the snow surface and decrease of the SWE. Before the melted water can leave a snowpack, the cold content, i.e., negative heat stored in snow, must be overcome, and the snow saturation must be increased to its irreducible liquid saturation. The percolation rate of melted water depends on the hydraulic conductivity of the snow, but also very strongly on the degree of saturation of the snow. Even when the entire snowpack is at the freezing point and is saturated to its irreducible liquid content, the first amount of the melted water may need many hours to percolate from the snow surface to the snowpack base. Hence a snowpack can undergo many repeated cycles of the day-time snowmelt and night-time refreezing of liquid water, before any melted water leaves the snowpack.

It should be noted that the adequate prediction of the melting rate of the snow and time of its complete ablation is of particular importance for the weather forecasting since these processes determine the moment, after which the ground temperature starts to rise above the freezing point value. This, in turn, affects the air temperature, too. Figure 3 shows how surface temperatures are affected by snow melting process on the time scale of several days before and after snow ablation. Unfortunately surface temperature measurements with sufficient time resolution are not available (monthly mean values only), so we just have a possibility to intercompare the surface temperature evolution simulated by the models under consideration. One can see that during 10 - 20 days when snow in TERRA is completely melted and in INM it is not, there is a noticeably difference between daily mean values of the surface temperature.

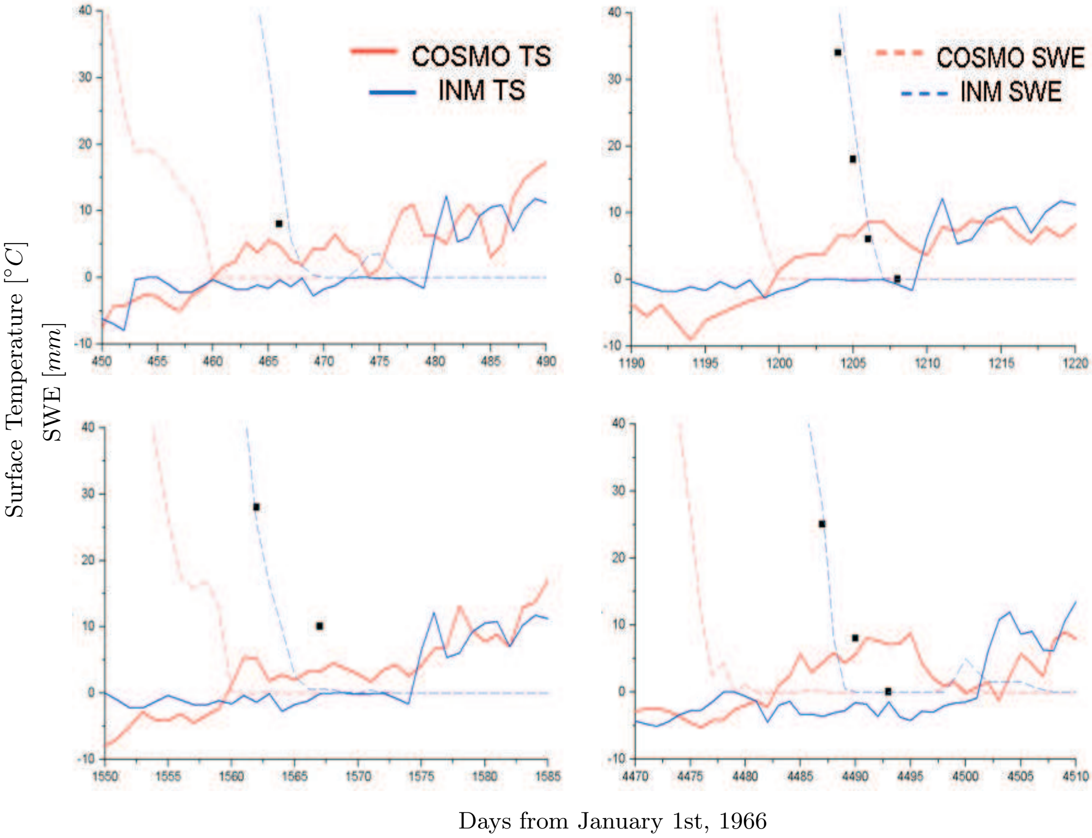

Fig. 3: Observed (black symbols) SWE and simulated by TERRA and INM models (red and blue lines, respectively) SWE (dashed lines) and surface temperature (solid lines), for 4 different years at Valdai.

In Yakutsk, in comparison with Valdai, the snow ablation is more rapid, at least, in those years when the snow depth observational data is available. The period of intensive melting lasted in these years a few days. Probably, this is the cause why in Yakutsk the aforementioned differences in the models results do not appear. In Valdai, the spring snow temperature many times passes through the freezing/melting point and that is why liquid water content noticeably influences the results. It should be noted that Valdai is situated in mid-latitudes of European part of Russia and the spring atmospheric conditions of this region are more close to the atmospheric conditions of Europe than to the strongly continental conditions of Yakutsk. Therefore, one can expect that processes related to liquid water in snow could be important for European territory, as well as for Valdai.

Together with the liquid water percolation and refreezing, the gravitational compaction and penetration of the solar radiation (which are also parameterized in the INM snow model) can affect the snow depth and the melting rate, too. An analysis has shown that processes of the snow metamorphosis and compaction due to gravity have a little impact on SWE in Valdai. Processes of the shortwave radiation penetration essentially delay the snow ablation. When the solar radiation, incoming onto the snow surface, does not penetrate into the snowpack, the whole amount of solar energy is spent to melt the top snow layer. In the case of penetrating radiation, the amount of incoming energy is distributed between some layers, and specific amount of energy is lesser in this case.

It is very useful to use a long-term continuous observational data, because during numerical experiment a great number of different meteorological conditions and situations can occur. Thus it is possible to determine the contribution of different physical processes to the modeling results and to understand the relative importance of each of them.

5 Summary and Outlook

In conclusion, some recommendations for the further development of the COSMO snow model, derived from results of the above presented analysis, can be suggested. Namely, the implementation of new parameterizations of the snow processes, particularly, taking into account transport of the snow liquid water and penetration of the solar radiation, can improve quality of simulation of the snow water equivalent depth.

It should be noted also that the Valdai observational data set includes data related to the snow density and albedo, as well as to the snow cover fraction. It is known that fractional snow cover, snow albedo, and their interplay have a considerable effect on the energy available for ablation (Slater et al., 2001; Luce et al., 1998). The scale of these processes (10–100 m) is much smaller than the grid resolution of most LSMs (10–100 km) (Pomeroy et al. (2003)). In both COSMO and INM models, the snow albedo is obtained from empirical formulae, and snow cover fraction linearly depends on SWE, when SWE is lesser than some critical value. Thus, the observational albedo and snow cover fraction data allows to further evaluate the COSMO snow model and to understand to what extent the adequate simulation of these variables is important, in order to improve the prediction of processes of the snow accumulation and ablation.

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