Improvement and Validation of the Multi-Layer Soil Model

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1 Introduction

The basic version of the new multi-layer soil model at DWD was described by Schrodin and Heise (2002). Meanwhile, this model has also been implemented in the global model GME of DWD. The LM and the GME versions are kept as similar as possible. The new soil model was tested in quasi two-dimensional simulations with the Rhône-AGG dataset (Boone et al., 2001) covering the major part of the Rhône catchment area, and in three-dimensional runs with GME. The quasi two-dimensional runs (see below) led to a couple of modifications to the original formulation, which will be described in this text.

2 Layer structure and boundary values

Thermal part

In the thermal part of the soil model 7 active layers are used. The depths of the lower levels of these layers follow an exponential increase: 0.01, 0.03, 0.09, 0.27, 0.81, 2.43, and 7.29 m, respectively. An inactive layer with a lower boundary at 21.87 m follows. In this inactive layer the annual mean near surface air temperature is prescribed as a constant boundary value. At a depth of 7.29 m the annual temperature amplitude is quite small. This can be shown by the general solution of the equation of heat conduction:

$$T(z) = \overline{T} + \Delta T_{z=0} \frac{\rho c \omega D^2}{2\lambda} e^{-z/D} e^{i(\omega t - z/D)} \tag{1}$$

Using the annual angular velocity $\omega = 0.2 \cdot 10^{-6} s^{-1}$ and reasonable estimates for heat capacity $\rho c = 2 \cdot 10^6 J/(m^3 K)$ and heat conductivity $\lambda = 1W/(mK)$, the penetration depth of the temperature wave is $D = \sqrt{2\lambda/(\rho c \omega)} = 2.25m$. With these values the annual temperature wave reduces to $0.04 \Delta T_{z=0}$ at a depth of 7.29 m. Therefore, we may safely use a boundary temperature constant in time below this depth. The alternative approach, i. e. a flux boundary condition (vanishing heatflux at the lower boundary), creates a large dependence of model results on barely known initial conditions in rather thick layers.

Hydrologic part

In the hydrologic part basically the same layer structure as in the thermal part is prescribed. But only the upper 6 layers are active. At the lower boundary of the 6th layer (in a depth of 2.43 m) only the downward gravitational transport is accounted for. This transport contributes to the runoff. The main reason for this treatment, different to the treatment in the thermal part, is the lack of adequate global or regional climatological data sets for the average soil water content. Existing data sets are either not really reliable, or at least they depend on the special soil model used for the determination of the data set.

3 Revised treatment of the snow melt process

The handling of the snow melt process in the operational model versions is described in detail by Heise and Schrodin (2002). It is characterized by a two step formulation. In the first step a snow surface temperature exceeding $T_0 = 273.15K$ is reduced to T_0, the temperature of the uppermost soil layer is increased accordingly. Only if the snow temperature is equal to T_0 and the soil surface temperature exceeds T_0, in the second step melting occurs. With the implementation of the freezing/melting process of soil water/ice in the multi-layer version of the soil model, the energy excess given by a snow surface temperature exceeding T_0 would be consumed to melt available soil ice in the uppermost soil layer. This could retard the melting of the snow deck considerably. To overcome this problem, the following formulation was introduced, if the preliminary snow surface temperature $T_{snow,p}$ exceeds T_0: Assuming a linear temperature profile between the snow surface and the soil surface, the energy content E_1 of the snow deck is

$$E_1 = \rho_w c_{ice} W_{snow,1} 0.5(T_{snow,p} + T_s) \qquad (2)$$

where ρ_w is the density of water, c_{ice} is the specific heat of ice, $W_{snow,1}$ is the water equivalent of the snow deck, and T_s is the temperature at the soil surface.

The temperature excess $T_{snow,p} > T_0$ is used for a partial melting of the snow deck reducing the snow water content $W_{snow,1}$ to $W_{snow,2}$ by reducing $T_{snow,p}$ to T_0.

$$W_{snow,2} = W_{snow,1} + \Delta W \qquad (3)$$

where $\Delta W < 0$ is the change of the snow water content by melting.

After the melting step the energy equation reads

$$E_2 = \rho_w c_{ice} W_{snow,2} 0.5(T_0 - T_s) - (\rho_w L_f + \rho_w c_{ice} T_0)\Delta W \qquad (4)$$

where L_f is the latent heat of fusion.

Using energy conservation, i.e. $E_1 = E_2$, the change of snow water equivalent by melting is

$$\Delta W = W_{snow,1} \frac{0.5(T_{snow,p} - T_0)}{0.5(T_s - T_0) - \frac{L_f}{c_{ice}}}. \qquad (5)$$

4 Tests using data of the Rhône-AGGregation Exeriment

The Rhône-AGGregation Experiment (Rhône-AGG, Boone et al., 2001) provides a test bed for different land surface schemes (SVAT models). A dataset of meteorological forcing parameters is provided for the four year period from August 1985 to July 1989. The investigation domain covers the main part of the Rhône catchment with a maximum extension of 530 km in north-south and 280 km in east-west direction, respectively, in south-eastern France. The domain has a strongly heterogeneous topography extending from the mountaineous region of the French Alps to the maritime region at the river outlet into the Mediterranean Sea. 1471 gridpoints with a resolution of 8x8 km^2 are used to cover the catchment area.

A hydrological model is used to calculate river routing from the surface and sub-surface runoff calculated by the respective SVAT models that finally is compared with the observed river discharges and routing tables. As a large number of SVAT models have participated in the Rhône-AGG (Boone et al., 2003), the intercomparison with other model results provides a powerful validation tool for our own model.

The very first tests with the Rhône-AGG data set revealed a serious problem with the snow melt process. During summer a large amount of snow was not melted in the higher regions of the Rhône catchment area. To solve this problem, a time-dependent snow albedo was introduced to replace the rather high constant value (0.7) used before. Now the snow albedo α_s is computed as a weighted mean of the albedo of 'fresh' snow $\alpha_{s,max} = 0.7$ and of a minimum value $\alpha_{s,min} = 0.4$ for 'old' snow, using a time-dependent weighting function $0 \leq f_s \leq 1$:

$$\alpha_s = \alpha_{s,max} \cdot f_s + \alpha_{s,min} \cdot (1 - f_s) \tag{6}$$

The change of f_s with time depends on snowfall and aging:

$$f_s(t) = f_s(t - \Delta t) + \Delta t \left[(\frac{\Delta f}{\Delta t})_{snowfall} + (\frac{\Delta f}{\Delta t})_{aging} \right] \tag{7}$$

The snowfall component uses the actual snowfall R_{snow} normalised with a 5 mm in 24 hours snowfall ($= R_{norm}$):

$$(\frac{\Delta f}{\Delta t})_{snowfall} = R_{snow}/(24h \cdot R_{norm}) \tag{8}$$

The aging component combines a constant effect $-1/\Delta t$ with a reduction of the aging due to snowfall:

$$(\frac{\Delta f}{\Delta t})_{aging} = MIN \left[0., \left(-1/\Delta t + (\frac{\Delta f}{\Delta t})_{snowfall} \right) \cdot f_s \right] \tag{9}$$

Initialisation of the weighting function should only be necessary, when no snow exists and snow fall sets in. In this case it should be set to one.

In the following the results of the new DWD multi-layer soil model (TERRA-ML) including the effect of a time dependent snow albedo are compared with model results from three other SVAT models: the first run of the ECMWF model, the NOAA hydrological model (NOAH), and the ISBA model from Meteo France.

The model results are discussed in monthly and area averaged values for the 3 year period from August 1986 to July 1989 (the first year of the data is regarded as a spin-up period for the SVAT models) to get an overview of the general results.

Figure 1 shows latent and sensible heat flux, ground heat flux and evaporation from bare soil. The energy fluxes are generally in the range of the results of the other models, except for a slightly weaker sensible heat flux during summer and a slightly stronger ground heat flux in that period. Evaporation from bare soil (lower right) is about 10 kg/m^2/month stronger than in the other models. Considering the hydrological components (Figure 2), some distinct features can be detected. The early summer peak in sub-surface runoff, which originates from the melting of snow in the high alpine region is smaller in TERRA-ML compared to the other models, indicating that snow melting is still underestimated. This is supported by the total amount of snow water equivalent (bottom right), which indicates a continuous increase of residual snow in the summer season over the 3 year period, i.e., in the high regions of the Alps some considerable amount of snow doesn't melt during the summer period. Sub-surface runoff shows its peaks mostly at the same times as in the other models, but generally the drainage values are smaller. Since soil moisture (lower left) is comparable to the lowest of the other model results, stronger sub-surface runoff may run the model in a too dry soil state.

Comparison of the river discharge calculated at CNRM by their hydrological model 'MOD-COU' from the runoff values provided by the different SVAT models has shown that monthly

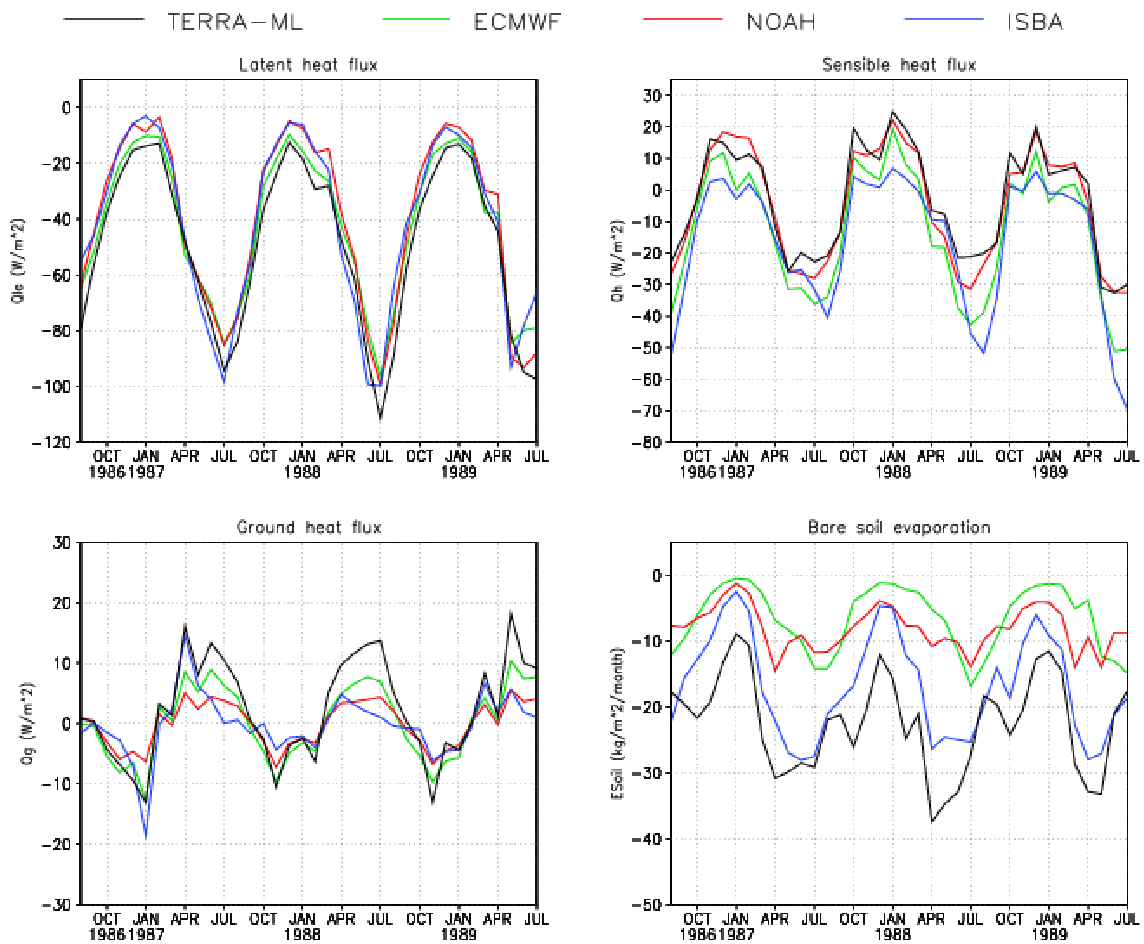

Figure 1: Time series of monthly mean average output parameters for the Rhône-AGG during the period Aug. 1986 - July 1989 for 4 different models. Latent heat flux, sensible heat flux, ground heat flux are given in W/m^2, evaporation from bare soil in kg/m^2/month. TERRA-ML denotes the new multi-layer soil model of DWD.

statistics of river runoff compares fairly well to observations at the gauging station of Viviers with a correlation coefficient of about 0.92 while daily statistics does not correlate significantly (Boone et al., 2003). This problem of daily runoff, although not of highest concern for a meteorological model, will be further studied.

Even though the use of a time dependent albedo alleviated the snow accumulation problem, an additional change to the model was required to finally get rid of it: The minimum and maximum snow densities were reduced from 500 kg/m^3 and 800 kg/m^3 to 250 kg/m^3 and 400 kg/m^3, respectively. This simple change completely solved the snow accumulation problem by reducing the heat transport from the snow to the soil (results are not shown here). For the time being the completion of these new results still require a second iteration with the hydrological model to be done at CNRM. This will also give a new estimate of the daily runoff in comparison to the measurements.

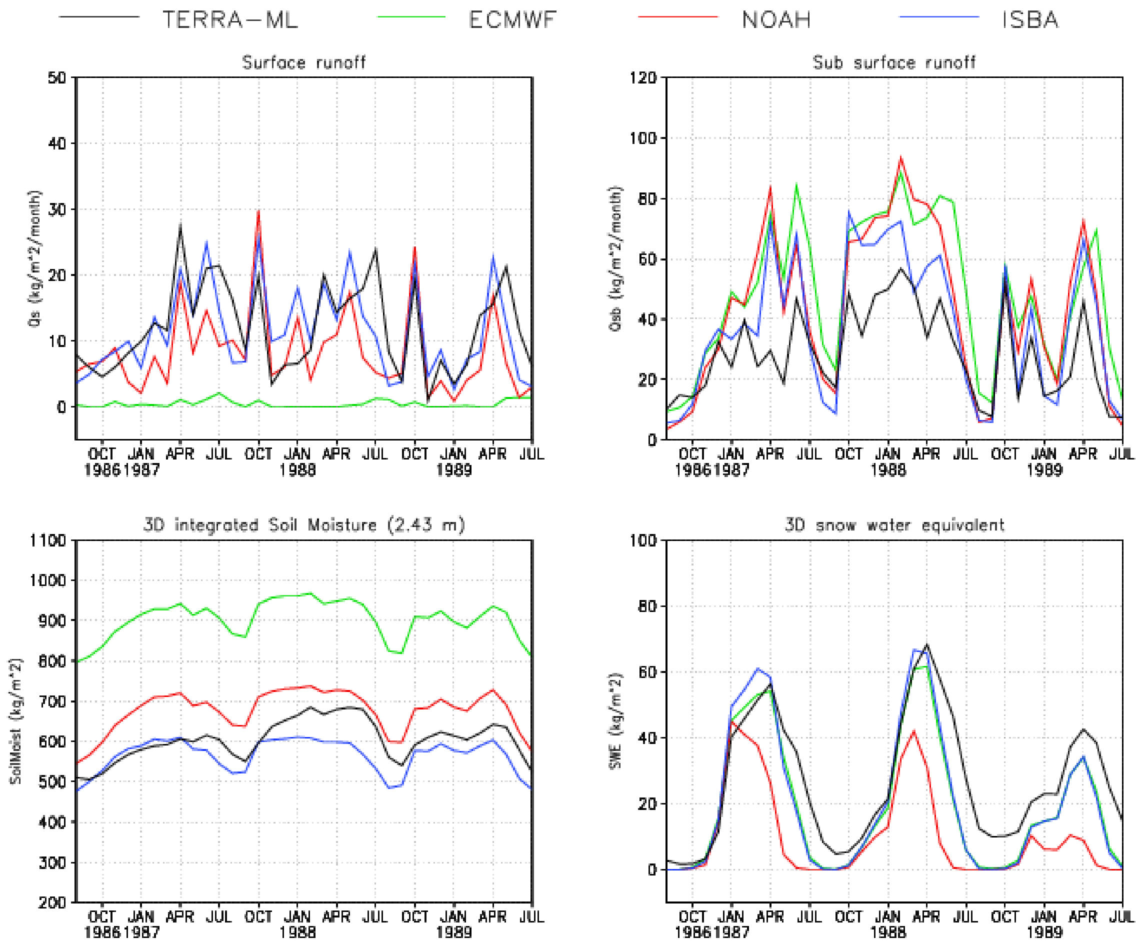

Figure 2: As Figure 1, but for the hydrological parameters surface and sub-surface runoff in kg/m^2/month, soil moisture and snow water equivalent in kg/m^2.

5 Summary

After extensive testing and associated modification the new multi-layer soil model has attained a stable state. The extension of the thermal part of the model down to an active depth of more than 7 m relieves the users from providing time dependent temperature boundary conditions. Similarly, avoiding a flux boundary condition (vanishing heatflux at the lower boundary) reduces the problem of providing adequate initial conditions. For the hydrologic part a compromise for the treatment of the lower boundary was found which takes into account the lack of reliable climatological data sets of soil water content. The use of the data sets of the Rhône-AGG proved to be a valuable tool for testing the model. This led to considerable improvement especially in the formulation of the snow melt process. A one year assimilation run with GME, which will start in the near future, will provide an additional thorough test for the model.

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7 References

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