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for

Small-Scale Modelling

Technical Report No. 2

***The Multi-Layer Version of the
DWD Soil Model TERRA_LM***

by

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September 2001

DOI: 10.5676/DWD_pub/nwv/cosmo-tr_2

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Editors: G. Doms and U. Schättler, Deutscher Wetterdienst, P.O. Box 100465, 63004 Offenbach, Germany
Printed at Deutscher Wetterdienst, Offenbach am Main

The Multi-Layer Version of the DWD Soil Model TERRA_LM

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Abstract

For the calculation of soil surface temperatures and temperature profiles inside the soil a multi-layer version TERRA_LM shall replace the 'Extended Force Restore'(EFR) method. The multi-layer version is based on the numerical solution of the heat conduction equation (HCE method). The EFR method uses two soil layers only, however with soil-type dependent thicknesses. In the HCE method, the number of the layers as well as their thicknesses can be specified as the case requires.

The advantages of the HCE method over the EFR method are

(a) physical improvement:

As a consequence of the rather thick upper soil layer in the EFR method the treatment of freezing/melting of soil water/ice was not successful. Therefore, the freezing/melting process was not implemented in the operational soil routine TERRA. This process will be included in the updated version TERRA_LM.

(b) organisational simplifications:

In the thermal part of the soil model the thicknesses of the soil layers are no longer dependent on soil type.

The soil layers for the treatment of the soil water transport in the hydrological part of the soil model can be chosen identical to the soil layers for the heat transport.

In an additional chapter, a simplified version of the numerical treatment of melting of a snow cover is presented.

1. Background

The following short description of the 'Extended Force-Restore' method (EFR method) refers to Jacobsen and Heise (1982).

The method is based on the solution of two coupled linear differential equations for the mean temperatures T_1 and T_2 of two layers,

$$T_1 = \frac{1}{2}(T_s + T_m), \quad T_2 = \frac{1}{2}(T_m + T_u),$$

where T_s is the soil surface temperature, T_m is the temperature at the lower boundary of the upper soil layer whose thickness is Δz_1 , and T_u is the constant temperature (climate value) at the lower boundary of the second soil layer whose thickness is Δz_2 .

The prognostic equations for the mean temperatures are

$$\frac{(\rho c \Delta z_1)}{2} \frac{\partial}{\partial t} T_1 = -(G_s - G_m), \quad (1)$$

$$\frac{(\rho c \Delta z_2)}{2} \frac{\partial}{\partial t} T_2 = -(G_m - G_u). \quad (2)$$

G_s is the soil heat flux at the surface represented by the atmospheric forcing (the sum of radiative fluxes and turbulent sensible and latent heat fluxes), G_m and G_u are the heat fluxes at the lower boundary of the first and the second soil layer, respectively, ρ is the density, and c is the specific heat which accounts for a constant mean water content (mean of air dryness point and pore volume). The thickness of the soil layers depends on the thermal characteristics of the soil. For the soil types used in LM/GME, the thickness of the upper layer Δz_1 varies for a rather dry soil between 0.07 m and 0.11 m, the thickness of the lower layer, Δz_2 , varies between 0.25 m and 0.37 m. The thickness of the layers also depends on the water content that is time dependent. However, in operational implementation of the EFR method, the layer thicknesses are determined using a constant value of the water content that is used for the determination of c .

The hydrological part of the soil model is formulated as a multi-layer model already, the soil layer thicknesses being independent of soil type. Operationally we use two active layers with thicknesses of 0.1 m (upper layer) and 0.9 m (lower layer), which are different from those of the thermal part. Therefore, a simple treatment of the interaction between hydrological and thermal processes in the actual soil model TERRA is not possible.

This deficiency can be avoided by using the HCE method for the calculation of soil surface temperatures and temperature profiles in the soil.

The heat conduction equation reads

$$\frac{\partial T}{\partial t} = \frac{1}{(\rho c)} \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right). \quad (3)$$

At the upper boundary, the soil heat flux $G_s = -(\lambda \partial T / \partial z)_s$ is specified. At the lower boundary, a constant value T_u (climate value) is used. The volumetric heat capacity ρc is determined depending on the soil type and the actual water and ice contents. The heat conductivity λ is dependent on soil type and on soil water content.

For the solution of Eq. (3) the implicit finite differencing scheme is used which reads for the time index n

$$\frac{T_k^{n+1} - T_k^n}{\Delta t} = \frac{1}{(\rho c)_k} \frac{\partial}{\partial z} \left(\lambda \frac{\partial T_k^{n+1}}{\partial z} \right)_k. \quad (4)$$

The vertical discretisation at grid levels z_k results in a three-diagonal linear system

$$A_k T_{k-1}^{n+1} + B_k T_k^{n+1} + C_k T_{k+1}^{n+1} = D_k \quad (5)$$

which can be solved by an economic numerical procedure. To prevent high frequency oscillations the mean temperature of the uppermost soil layer is presently used as the soil surface temperature.

2. Comparison of EFR and HCE method

In this section, the reaction of the soil surface temperature on different forcing is shown for both the EFR and the HCE method. The results presented have been obtained by time integration to quasi-stationarity.

For harmonic forcing G_s , the temperatures T_s and T_m predicted by the EFR method agree with the respective analytical solution of the HCE. For this idealised condition of harmonic forcing, *Figure 1* shows the diurnal variation of soil surface temperature by the EFR method (t_EFR) in comparison to the analytical solution of the HCE equation (t_ANA) and to the two numerical solutions with the following vertical grid structures:

- a) 100 layers of constant thickness of 0.005 m (t_100L),
- b) 5 (active) layers with thicknesses 0.02, 0.02, 0.04, 0.08, 0.16 m (t_5L).

Figure 1 demonstrates that for the special case of harmonic forcing the differences in the results are small. The deviations between all temperature curves shown do not exceed 1 K at any time step. Apart from very small under- and overshooting, even the five layer version results (t_5L) cannot be distinguished from the other ones. These results confirm that for the case of harmonic forcing the numerical results of the EFR method and of the HCE method are equivalent.

As the next step, both methods are supplied with a modified forcing: harmonic forcing in the first half of the diurnal period, corresponding to the mean diurnal variation between 6 a.m. and 18 p.m. local time, and in the second half a constant forcing corresponding approximately to the mean situation between 18 p.m. and 6 a.m. To simulate more complex and realistic situations, this forcing is superimposed by a high frequency noise to test the

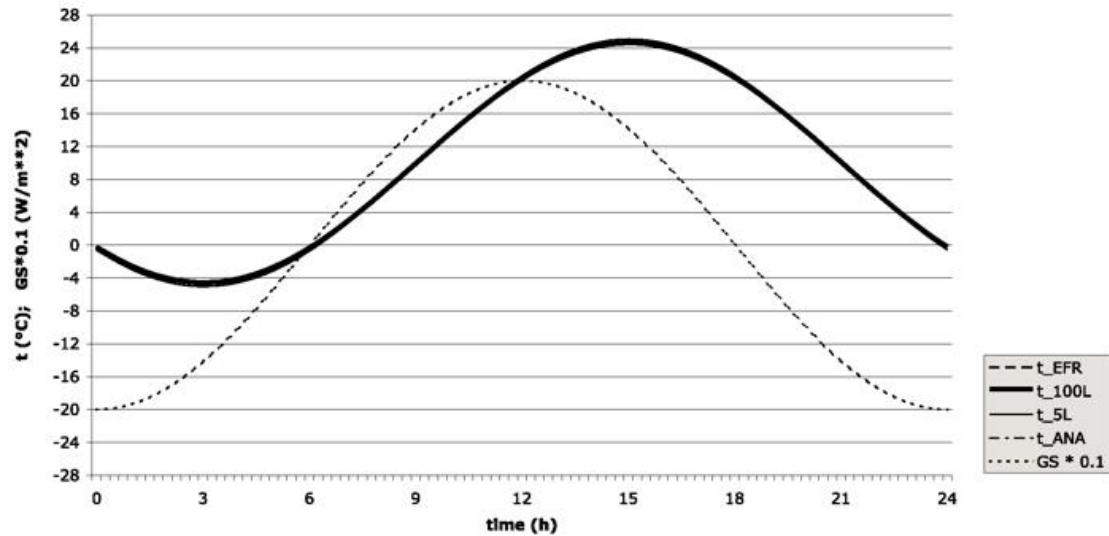


Figure 1: Soil surface temperature using the EFR method (t_{EFR}) and the HCE method (t_{XL}) compared with the analytical HCE solution t_{ANA} ($X=100$: 100 layers, $\Delta z = 0.005m$; $X = 5$: 5 layers whose thicknesses increase with depth).

ability of the different methods to provide a quick feedback in soil surface temperature. As no analytical solution is available now, the results of the HCE method with 100 layers are used as a reference. In *Figure 2*, the high frequency reaction to this type of forcing is shown. The results with the 5 layer version agree well with those of the 100 layer version.

This fast feedback of the soil surface temperature in the HCE method is caused by the choice of layers of small thickness close to the soil surface. On the contrary, the EFR method uses a thickness of the upper layer of about 0.1 m which results in a smooth feedback in the mean temperature of this layer and therefore also in the soil surface temperature. Again the EFR method agrees reasonably well with the 'true' simulation of the HCE method with 100 levels.

In a further test both methods are driven by a low frequency forcing with abrupt changes in three hour intervals to test the influence of a sudden but persistent change in solar radiation at the soil surface, caused for example by convective clouds. *Figure 3* shows that the EFR method simulates the temperature feedback with some delay especially at the points of extreme changes in the forcing at 9 a.m. and at 12 a.m. However, the results do not significantly differ in comparison to the results of the HCE method.

In summary these results demonstrate the quality of the EFR method operationally used in the DWD model suite. Indeed, if no freezing or melting processes inside the soil are considered, the EFR method is the most economic procedure to simulate the diurnal temperature variation with high quality.

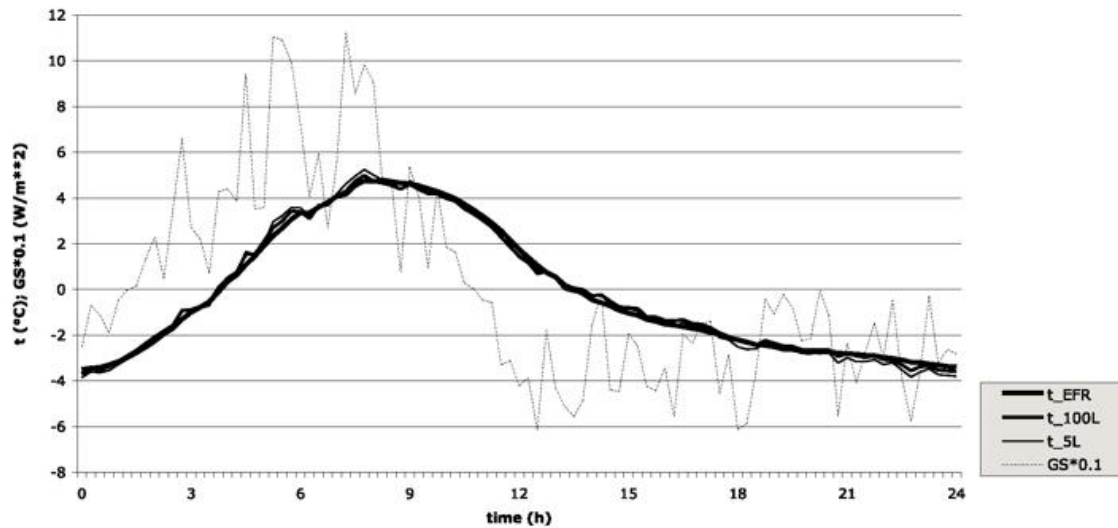


Figure 2: Soil surface temperature calculated with the EFR method (t_{EFR}) and the HCE method (t_{XL}) for high frequent forcing GS ($X=100$: 100 layers, $\Delta z = 0.005m$; $X=4$: 4 layers whose thicknesses increase with depth).

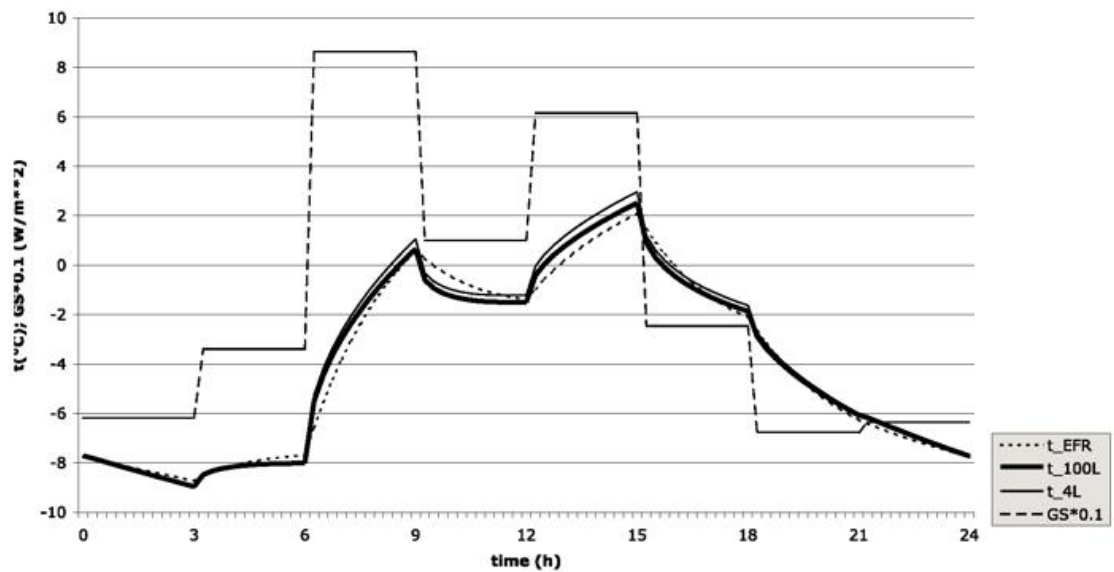


Figure 3: Soil surface temperature calculated with the EFR method (t_{EFR}) and the HCE method (T_{XL}) for low frequent forcing GS ($X=100$: 100 layers, $\Delta z = 0.005m$; $X=4$: 4 layers whose thicknesses increase with depth).

3. The influence of freezing/melting of soil water/ice on soil surface temperatures

The process of freezing/melting of soil water/ice inside the soil is frontal in nature. Treating this process in discrete model layers results in averaging the front over the respective layer thickness. In the present operational models of DWD the upper layer in the hydrological part has a thickness of 0.1 m. The large amount of water/ice available in such a thick layer results in a remarkable suppression of temperature changes if phase transitions occur. In the worst case the diurnal cycle of the temperature can be totally suppressed for a period of several days.

This was the case for the Europa-Modell after it had become operational. Therefore, the freezing/melting process was switched off in that model. In the 4th generation model suite GME/LM the respective code was not included.

The neglect of freezing/melting processes also results in systematic errors. When crossing the melting point $t_0 = 273.15K$ the soil temperatures decrease/increase too rapidly. This leads to temperatures being too cold/warm for a considerable time.

Using the HCE method, the freezing/melting process can be included, and the deficiencies can be reduced by the use of high grid resolution, especially close to the soil surface. It will be shown, however, that for some short periods the temporal behaviour of soil temperature significantly depends on the grid resolution.

In section 3.1, the diurnal variation of the soil surface temperature is shown including freezing/melting of soil water/ice at t_0 . A second approach (section 3.2) replaces t_0 by taking into account the influence of soil texture on the melting/freezing temperature as a function of soil water content.

3.1 The influence of the freezing/melting process at 273.15 K on the soil surface temperature

If the temperature T_{pre} resulting from the solution of the heat conduction equation (3) is crossing t_0 in any soil layer, a part of the existing soil water/ice will freeze/melt. The available energy for this phase change process is

$$\Delta E = (\rho c) \Delta z (T_{pre} - t_0), \quad (6)$$

where $\Delta E < 0$ for freezing and $\Delta E > 0$ for melting.

The maximum possible change of liquid water $W_{l,max}$ and of ice $W_{i,max}$, respectively, can be calculated from

$$\Delta W_{l,max} = -\Delta W_{i,max} = \frac{\Delta E}{L_f \rho_w}. \quad (7)$$

L_f is the heat of fusion, ρ_w is the density of water. The actual change of ice content ΔW_i is given by

$$\begin{aligned}\Delta W_i &= -MIN\{-\Delta W_{i,max}; W_i\} \quad \text{if } \Delta W_{i,max} < 0 \quad , \\ \Delta W_i &= MIN\{\Delta W_{i,max}; W - W_i\} \quad \text{if } \Delta W_{i,max} > 0 \quad ,\end{aligned}$$

where W is the actual total water content (sum of liquid water and ice) and W_i the ice content at the previous time step.

The effect on the temperature is included by using

$$T = t_0 + (\Delta W_i - \Delta W_{i,max}) \frac{(L_f \rho_w)}{(\rho c \Delta z)} \quad (8)$$

to compute the final temperature T at the current time step.

For the whole period of melting or freezing inside a soil layer this procedure causes a final layer mean temperature of t_0 at the end of each time step. Additionally Eq. (8) considers the case that no phase transition occurs. In this case $\Delta W_i = 0$, and the energy ΔE will be completely used to change the soil temperature T .

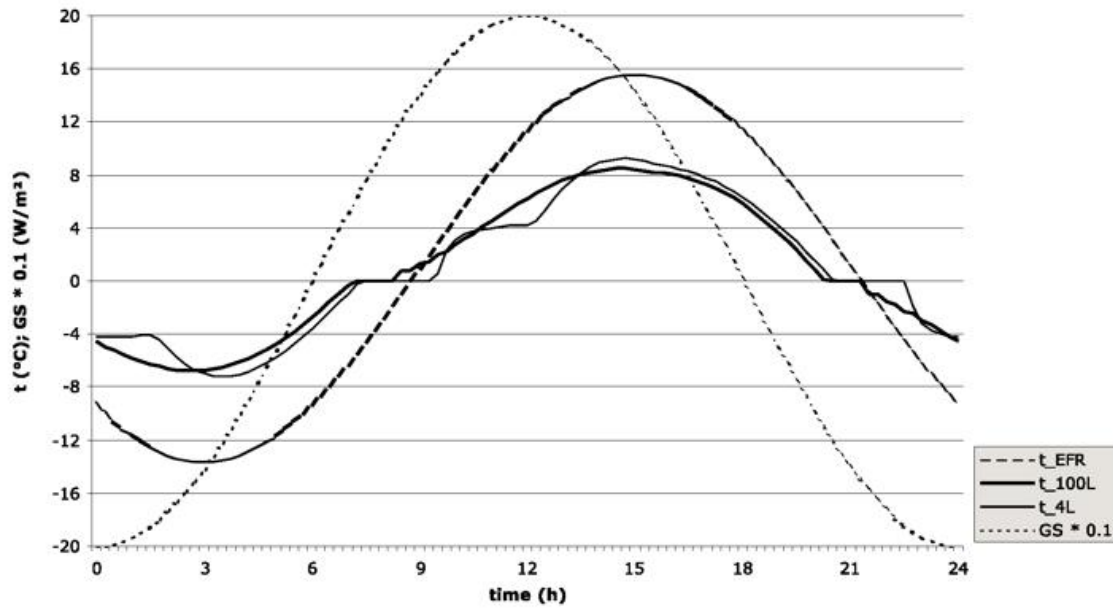


Figure 4: Influence of soil freezing/melting at 273.15 K in the HCE method (t_{XL}) on the diurnal variation of soil surface temperature compared to the EFR method (t_{EFR}) without freezing/melting for harmonic forcing GS ($X=100$: 100 layers, $\Delta z = 0.005m$; $X=4$: 4 layers whose thicknesses increase with depth).

Figure 4 shows an example of the soil surface temperature behaviour with due regard for freezing/melting using the HCE method for two different grid resolutions. A comparison is made with the results using the EFR method, which, as already mentioned, is formulated with no regard for freezing/melting. Again the numerical solution of the 100-layer version of the heat conduction equation with constant layer thickness of 0.005 m is used as reference. Compared to the EFR method, the diurnal variation of the soil surface temperature is significantly damped. The extent of the effect is proportional to the amount of liquid water/ice available for freezing/melting.

The soil surface temperature behaviour for a version with only 4 active layers (layer thicknesses 0.02, 0.04, 0.08, 0.16 m) is also shown in *Figure 4*. Because of their greater thicknesses these four layers need more time to freeze/melt than the 0.005m layers of the 100-layer version. This is the reason for the pronounced step-like curve of the soil surface temperature in the 4-layer version compared to the 100 layer version. This effect can be minimized by using high grid resolution close to the soil surface. On the other hand, the lower limit of layer thickness is a function of the time step and has to take into account economic demands.

3.2 The soil type dependent melting/freezing and its influence on the soil surface temperature

Warrach (2000) uses a relation for the maximum of the volumetric water content $W_{l,max}$ in the soil based on a suggestion by Flerchinger and Saxton (1989). This relation reads

$$W_{l,max} = W_s \left[\frac{L_f(T - t_0)}{Tg\Psi_s} \right]^{-1/b} . \quad (9)$$

W_s is the pore volume, T is the temperature, g is the gravitational acceleration, Ψ_s is the air entry potential at saturation, and b is the pore-size distribution index (Brooks and Corey, 1966).

After Cosby et al. (1984) the air entry potential Ψ_s and the pore-size distribution index b are determined by the soil type,

$$\Psi_s = \Psi_0 \cdot 10^{1.88-1.3f_s} , \quad (10)$$

$$b = 2.91 + 15.9f_c . \quad (11)$$

Ψ_0 is -0.01 m, and f_s and f_c are the fractions of sand and of clay in the soil, respectively. The following table shows for the soil types of the LM the fractions f_s and f_c (the remaining part of the soil fractions is assumed to be silt), the air entry potential Ψ_s calculated with Eq. (10) and the pore-size distribution index b calculated with Eq. (11).

| | f_c | f_s | $\Psi_s(m)$ | b |
|------------|-------|-------|-------------|-------|
| sand | 0.90 | 0.05 | - 0.0513 | 3.705 |
| sandy loam | 0.65 | 0.10 | - 0.1084 | 4.50 |
| loam | 0.40 | 0.20 | - 0.2291 | 6.09 |
| loamy clay | 0.35 | 0.35 | - 0.2661 | 8.47 |
| clay | 0.15 | 0.70 | - 0.4842 | 14.04 |

Eq. (9) can be transformed to calculate a freezing point temperature as function of the water content $W_{l,max}$ of the previous time step,

$$T_* = t_0 \left[1 - \frac{g\Psi_s}{L_f} \left(\frac{W_s}{W_{l,max}} \right)^b \right]^{-1}. \quad (12)$$

The temperature T_* is the equilibrium temperature where no freezing/melting is observed. If this equilibrium temperature in any soil layer is crossed by the solution T_{pre} of the HCE, freezing or melting occurs. As in section 3.1, the energy difference, that is proportional to the temperature difference $T_{pre} - T_*$, is used to melt ice or to freeze liquid water, that is

$$\Delta E = (\rho c) \Delta z (T_{pre} - T_*). \quad (13)$$

Using modified formulations for ΔW_i ,

$$\begin{aligned} \Delta W_i &= -MIN\{-\Delta W_{i,max}; MIN(-(W - W_{l,max} - W_i), W_i)\} \quad \text{if } \Delta W_{i,max} < 0 \quad , \\ \Delta W_i &= MIN\{\Delta W_{i,max}; MAX((W - W_{l,max} - W_i), 0.)\} \quad \text{if } \Delta W_{i,max} > 0 \quad , \end{aligned}$$

the final temperature T can be calculated through the relation

$$T = T_* + (\Delta W_i - \Delta W_{i,max}) \frac{(L_f \rho_w)}{(\rho c \Delta z)} \quad (14)$$

that is analogous to Eq. (8).

The concept of a water content and soil type dependent freezing/melting temperature accounts for a more continuous behaviour of the soil temperature during freezing/melting. This is demonstrated in *Figure 5*. For the soil types (a) sand, (b) loam and (c) clay the quasi-stationary diurnal variation of the soil surface temperature (driven by a periodic harmonic forcing) for water content dependent freezing/melting (solid curve) is compared to freezing/melting at constant temperatures t_0 (dashed curve). The calculations are performed with a multi-layer version with layer thicknesses of 0.01, 0.03, 0.06, 0.12, 0.24, 0.48 m.

The total water content was set to 50% of the pore volume in each layer. For the soil type sand (a) the differences in the behaviour of temperatures are the smallest. With decreasing soil particle sizes lower temperatures are necessary to initiate freezing. Furthermore, for the soil type clay (c) even a water content of 50% of pore volume is not sufficient to allow any freezing at temperatures between 0°C and -10.5°C.

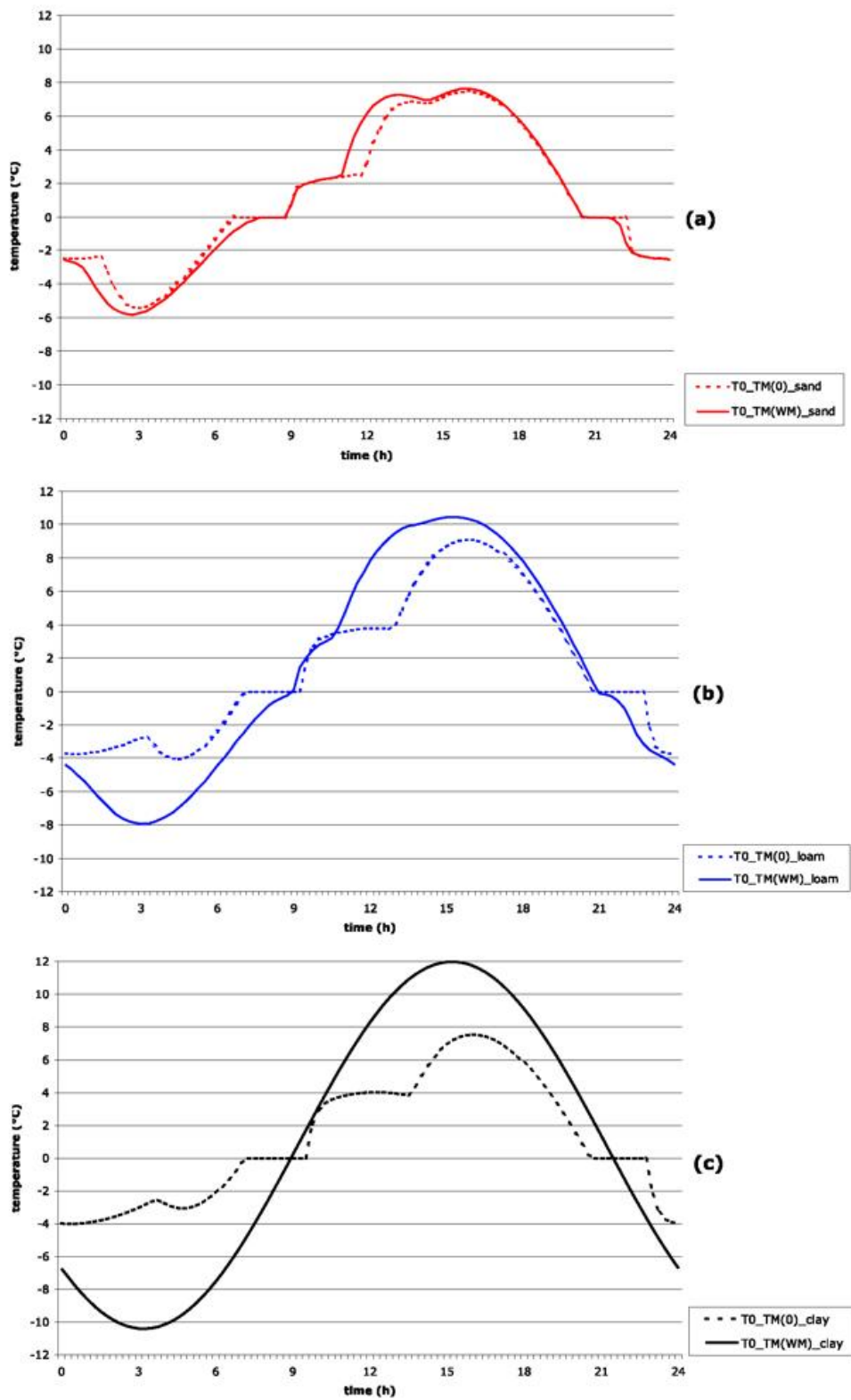


Figure 5: Diurnal variation of the soil surface temperature for soil types (a) sand, (b) loam and (c) clay. Total water content: 50% of pore volume. $TO_TM(0)$: freezing/melting at $0^{\circ}C$, $TO_TM(WM)$: freezing/melting as function of liquid water content.

The local minimum of the soil surface temperature for the soil type sand in *Figure 5a* at 3 p.m. occurs because melting takes place in the layer between 4 and 10 cm which is supported by a downward directed heat flux causing a reduction of the soil surface temperature. However, when ice is completely melted the temperature in this layer can increase. This significantly reduces the downward directed flux and allows the soil surface temperature to increase again.

The method of simulation of the freezing/melting temperature described above produces results between the extrema of 'no freezing/melting', as in the EFR method, and of 'freezing/melting at t_0 ', as described in section 3.1.

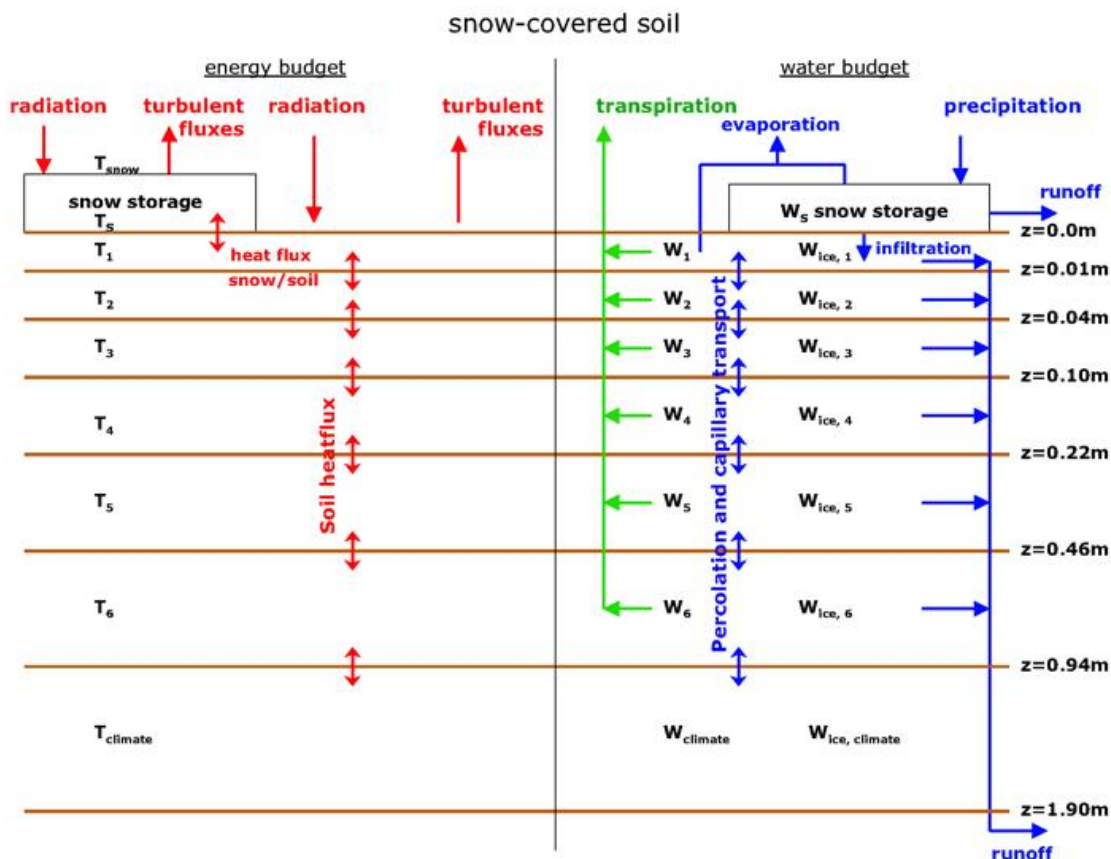


Figure 6: The multi-layer grid of the soil model TERRA_LM: General structure and physical processes considered in case of a snow covered soil.

4. A suggestion for fixing the vertical soil layer grid for the multi-layer HCE method

Because of computational limits, a maximum of six active soil layers can be afforded at present in the operational model LM. Experiments with different vertical layer distributions have shown that the uppermost layer should be of thickness of 0.01 m. Furthermore, the LM is nested in the Global Model GME with the lower boundary of the second hydrological layer in 1.0 m. For this reason, the following distribution of layer boundaries (layer bottom,

so-called half levels) for the thermal as well as for the hydrological part, is suggested:

$$z_k = 0.01, 0.04, 0.10, 0.22, 0.46, 0.94, 1.90 \text{ m}.$$

This distribution is built up by the formula

$$z_{k+1} = z_k + 0.03 \cdot 2^{(k-1)} \quad \text{with} \quad z_1 = 0.01 \text{ m}.$$

The layer limited by the half levels at 0.94 m and 1.90 m is the so called 'climate layer' with the values of temperature, liquid water content and ice content kept constant during a model run. Figure 6 shows an updated version of the layer structure published in COSMO Newsletter No. 1 (Doms and Schättler, 2001) for a snow covered soil.

Numerical experiments have shown that six active layers are sufficient for numerical weather prediction models. The results become useless if the the number of active layers in this distribution is reduced to less than four. Therefore, six soil layers are sufficient also for simulations over longer time periods with temperature waves penetrating deeper into the ground. Further experiments have shown that with additional layers close to the soil surface the results are not different remarkably, even if freezing and melting occurs.

5. An updated version for computation of melting of snow cover

The operational version for the treatment of melting snow required a rather complicated programming. In order to simplify this part of the model, the method was changed slightly (Heise and Schrodin, 2001). Now only two cases are distinguished:

Case (a)

The soil model calculates a preliminary temperature of the snow cover $T_{snow,p} > t_0$ and a preliminary soil surface temperature $T_{s,p} < t_0$. The reduction of $T_{snow,p}$ to $T_{snow} = t_0$ is simulated by redistribution of the heat content between the snowpack and the uppermost soil layer according to

$$\frac{T_{snow} + T_s}{2} (\rho c \Delta z)_{snow} + T_{so} (\rho c \Delta z)_{so} = \frac{T_{snow,p} + T_{s,p}}{2} (\rho c \Delta z)_{snow} + T_{so,p} (\rho c \Delta z)_{so} \quad (15)$$

with $T_{snow} = t_0$ and the unknown temperatures T_s and T_{so} .

Additionally we assume

$$T_{so} - T_{so,p} = T_s - T_{s,p} = \Delta T_s. \quad (16)$$

Combining (15) and (16) results in

$$\Delta T_s = [T_{snow,p} - t_0] \left[1 + \frac{2 \cdot (\rho c \Delta z)_{so}}{(\rho c \Delta z)_{snow}} \right]^{-1}.$$

If T_s exceeds t_0 , possible melting is postponed to the next time step.

Case (b)

If the preliminary temperature $T_{so,p}$ in the uppermost soil layer exceeds t_0 , the redistribution of energy is simulated, now reducing T_{so} to t_0 . Then Eq. (16) becomes

$$T_s = T_{s,p} - T_{so,p} + t_0 . \quad (17)$$

Replacing T_s in the budget equation (15) with T_s given by (17) results in

$$T_{snow} = T_{s,p} + T_{snow,p} - t_0 + 2[T_{s,p} - t_0] \frac{(\rho c \Delta z)_{so}}{(\rho c \Delta z)_{snow}} .$$

If $T_{snow} > t_0$, a melting step is performed. The energy available for melting is

$$E_{avail} = \frac{T_{snow} - t_0}{2} (\rho c \Delta z)_{snow} ,$$

and the energy required for melting the whole snowpack is

$$E_{total} = L_f \rho_w W_s ,$$

where W_s is the snow water equivalent. If $E_{avail} < E_{total}$, the melted fraction of snow ΔM_s is

$$\Delta M_s = \frac{E_{avail}}{E_{total}} W_s .$$

In case more energy is available than is required for melting the whole snowpack, we have $\Delta M_s = W_s$, and the soil surface temperature has to be recomputed through

$$T'_s = T_s + \frac{E_{avail} - E_{total}}{(\rho c \Delta z)_{so}} . \quad (18)$$

6. Conclusions and Outlook

Preliminary tests have shown that the HCE method is superior to EFR method if in the current soil model the freezing/melting process is to be included. The additional computational cost seems comparatively small. Furthermore, the HCE method can rapidly react to high frequency changes of the atmospheric forcing. A great advantage of the multi-layer version is the formulation of hydrological and thermal processes with exactly the same layer distribution. This simplifies the formulation of feedback processes between the thermal and hydrological parts as soil temperature and soil water interpolations are unnecessary.

The new multi-layer version of the soil model is currently implemented into the LM and a corresponding interface is written for the interpolation program GME2LM. Details on the implementation and on the evaluation of the scheme for real data cases will be published in a forthcoming issue. The new version is planned to become operational in winter/spring 2002.

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COSMO Newsletters

Newsletter No.1, February 2001.

COSMO Technical Reports

No. 1, Dmitrii Mironov and Matthias Raschendorfer (2001): *Evaluation of Empirical Parameters of the New LM Surface-Layer Parameterization Scheme. Results from Numerical Experiments Including the Soil Moisture Analysis.*

No. 2, Reinhold Schrodin and Erdmann Heise (2001): *The Multi-Layer Version of the DWD Soil Model TERRA_LM.*

COSMO Technical Reports

Issues of the COSMO Technical Reports series are published by the *Consortium for Small-Scale Modelling* at non-regular intervals. COSMO is a European group for numerical weather prediction with participating meteorological services from Germany (DWD, AWGeophys), Greece (HNMS), Italy (UGM, ARPA-SMR) and Switzerland (MeteoSwiss). The general goal is to develop, improve and maintain a non-hydrostatic limited area modelling system to be used for both operational and research applications by the members of COSMO. This system is initially based on the Lokal-Modell (LM) of DWD with its corresponding data assimilation system.

The Technical Reports are intended

- for scientific contributions and a documentation of research activities,
- to present and discuss results obtained from the model system,
- to present and discuss verification results and interpretation methods,
- for a documentation of technical changes to the model system,
- to give an overview of new components of the model system.

The purpose of these reports is to communicate results, changes and progress related to the LM model system relatively fast within the COSMO consortium, and also to inform other NWP groups on our current research activities. In this way the discussion on a specific topic can be stimulated at an early stage. In order to publish a report very soon after the completion of the manuscript, we have decided to omit a thorough reviewing procedure and only a rough check is done by the editors and a third reviewer. We apologize for typographical and other errors or inconsistencies which may still be present.

The report series is also open for contributions from external users of the LM system at various universities and research institutes.

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