Soil freezing in LSPM SVAT Scheme

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Abstract

Soil moisture changes are generally due to external forcing (precipitation, evaporation etc.) as well as internal forcing (gravitational force, capillarity, transpiration etc.). Due to these forcings, freezing/thawing effects must be taken into account in modeling regions where air temperature goes below 0 °C for hours or even days.

The present work is devoted to the numerical modeling of the water phase change in the soil by means of the soil-atmosphere interaction model LSPM (Land Surface Process Model).

1. Introduction

It is well known that the fluxes between soil and atmosphere can trigger precipitation and convection, allow fog or dew development in the first surface layer, enable frost on vegetation, and strongly modify the soil water content and temperature (Luo et al., 2003).

A wrong or imperfect soil moisture estimation leads to errors in the boundary layer estimation (Viterbo et al., 1999). Moreover soil properties change during the freezing/thawing transient stage (hydraulic conductivity, thermal capacity etc.) leading to a variation in the hydrological balance components (Zheng et al., 2001, Niu et al, 2006).

The goal of this study is to improve the SVAT scheme LSPM (Land Surface Process Model), developed at the University of Turin (Cassardo et al., 1995) and now used operationally by the agro-meteorological regional service of Piedmont, by parameterizing the freezing/thawing in the soil.

To this end, comparisons with observations are made, highlighting the importance of the soil freezing/thawing for a correct estimation of the energy and hydrologic budgets in the surface layer. The improvement of the performances of such kind of models have a practical significance in many fields. In meteorology, the better estimation of the boundary layer development, linked to the atmospheric stability, leads to better performances of GCM or LAM in predicting two meter temperature and precipitation (Balsamo et al., 2004). In agriculture, irrigation techniques could be better planned. In hydrology, it would be possible to better estimate the runoff associated with rainfall and snowmelt on frozen soil.

2. The LSPM model (Land Surface Process Model)

The Land Surface Process Model (LSPM) is a diagnostic one-dimensional model developed at the University of Torino (Cassardo et al., 1995). It is a SVATs which can be used both as a stand-alone model or coupled with an atmospheric circulation model, behaving as its lower boundary condition. All specific details about its use and features are fully described in Cassardo (2006).

The LSPM domain is vertically subdivided into three main zones: the soil, the vegetation and the atmospheric layer within and above the vegetation canopy layer. Variables are mainly diagnosed in the soil and in the vegetation layers. The canopy itself is represented as a single uniform layer (big leaf approximation), whose properties are described by vegetation cover and height, leaf area index, albedo, minimum stomatal resistance, leaf dimension, emissivity and root depth. The soil state is described by its temperature and moisture content, and its main parameters are: thermal and hydraulic conductivities, soil porosity, permanent wilting point, dry heat capacity, surface albedo and emissivity. These variables are calculated by integrating the heat Fourier and the water mass conservation equations using a multi-layer scheme. The eventual presence of snow, considered as a single layer and characterized by density, albedo, water equivalent and ice content, is taken in account with specific routines.

Momentum, heat and water vapour fluxes between the soil (bare and vegetated, and eventually covered by snow) and the reference height, above the canopy, are computed using an electric analogue formulation, for which they are directly proportional to the gradients of the related scalars and inversely proportional to the adequate resistance.

As the LSPM is a diagnostic model, some observations in the atmospheric layer are needed as boundary conditions. These are: air temperature, humidity, pressure, wind speed, cloud cover, long- and short-wave incoming radiation, and precipitation rate. Usually these observations are measured values, sometimes with the reconstruction of some missing data using adequate interpolation techniques.

3. The freezing parameterization in LSPM

Three different parameterizations have been implemented in LSPM to describe freezing processes in the soil:

Energy vs temperature [Schrodin et al., 2001]

This parameterization (hereafter P1) is based on the imposition of the energy balance. The energy available for phase change is:

$$\Delta E = (\rho c)_s \Delta z (T - T_0) \tag{1}$$

where $(\rho c)_s$ is volumetric thermal capacity of soil, Δz is the depth of the considered soil layer and T_0 is the threshold temperature (0°C). The maximum possible change of liquid water (ice) $\Delta\eta_{l,max}$ ($\Delta\eta_{i,max}$) is:

$$\Delta\eta_{l,max} = -\Delta\eta_{i,max} = \frac{\Delta E}{L_f \rho_w} \tag{2}$$

where L_f is the latent heat of fusion and ρ_w is the density of water. Finally, the temperature at the current time-step is

$$T = T_0 + (\Delta\eta_i - \Delta\eta_{i,max}) \frac{L_f \rho_w}{(\rho c)_s \Delta z} \tag{3}$$

where $\Delta\eta_i$ is the actual change of ice content.

Thermal capacity vs temperature [Viterbo et al., 1999]

This parameterization (hereafter P2) is based on the modification of soil thermal capacity. The soil energy equation in the presence of soil water phase change is:

$$(\rho C)_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_T \frac{\partial T}{\partial z} \right) + L_f \rho_w \frac{\partial \eta_i}{\partial t} \tag{4}$$

where k_T is the soil thermal conductivity. The volumetric ice content is evaluated by this parameterization:

$$\eta_i = f(T)\sigma_v \eta_{fc} \qquad 5)$$

where σ_v is the vegetation cover, η_{fc} is the soil water content at the field capacity, and $f(T)$ is a function of temperature given by:

$$f(T) = \begin{cases} 0 & T > T_1 \\ 0.5\left[1 - sin\left(\frac{\pi(T - 0.5T_1 - 0.5T_2)}{T_1 - T_2}\right)\right] & T_2 \le T \le T_1 \\ 1 & T < T_2 \end{cases} \tag{6}$$

where $T = T_0 + 1$K e $T_2 = T_0$ -3K, and T_0 is the freezing point of water.

Thermal capacity vs temperature [Cassardo, 2006]

In this parameterization (hereafter P3) the ice water content η_i is given by:

$$\eta_i = f(T)\eta - \eta_{min} \tag{7}$$

where $\eta_{l,min}$ is the minimum quantity of water in soil and $\eta = \eta_l + \eta_i$.

4. The available data

Three different data sets have been used to test the different parameterizations of the water phase change in the soil.

The first set of data, called "synthetic data", has been created as a workbench in order to verify the correct estimation of the physical mechanisms taking place during the water phase change.

The other two sets of data came from two different experimental campaigns: Brookings (South Dakota, USA, [Fluxnet, 2009]), and Falkenberg (Germany, Europe, [EOL NCAR, 2009]). These two sets of data have been selected with the aim to verify the performance of the parameterizations P1-P3 mentioned above in reproducing the real physical phenomena.

4.1. Synthetic data

The synthetic data consist in an idealized year and are subdivided into three well distinct periods. The initial period, lasting about 30 days, consists of a period with daily mean temperature above 0°C characterized by continuous precipitation, in order to saturate the upper soil layer and achieve the numerical stability. The intermediate period, lasting about 280 days, is supposed to be dry (in order to avoid snow accumulation on the ground which might affect the ice behavior in the soil) with a mean air temperature well below 0°C, in order to have the freezing in the uppermost soil layers. The final period, lasting about 50 days, is characterized by an average air temperature above 0°C and continuous precipitation, in order to force the thawing of the subsurface ice formed in the intermediate period.

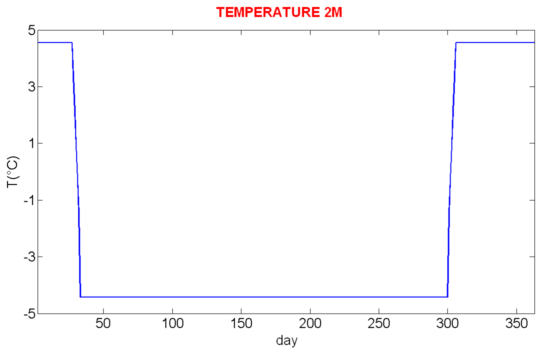

Figure 1: Daily mean 2m temperature used in the synthetic data.

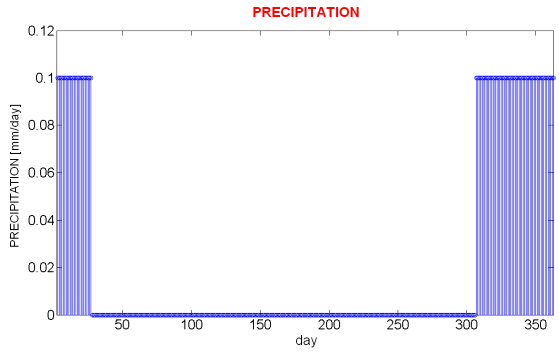

Figure 2: Daily mean precipitation used in the synthetic data

SYNTHETICAL DATA – LSPM setting		
6 layers (cm): 20, 20, 40, 80, 160, 320		
Δ*t* = 60 s	Initial η_w = 0.4 m³/m³	**Initial *T* = 1 °C**
Soil type: silty clay		
Soil porosity η_s [m³/m³]	Wilting point η_{wi} [m³/m³]	**Filed capacity η_{fc} [m³/m³]**
0.492	0.283	**-0.4**
Vegetation type: short grass		

Table 1: Model setting for the simulation with the synthetic data

The results show that the model is able to reproduce the physical process of freezing/thawing when each of the parameterizations P1, P2 and P3 is used. This can be seen by observing the decrease of the liquid water content η_w during the freezing period (Fig. 3) and the warming of the layer affected by freezing with respect to P0 parametrization (when freezing is not activated), due to the latent heat release. The warming of this layer is proportional to the quantity of ice present in the soil: this fact is not surprising, as the heating is linked to the latent heat release. In this sense, P2 and P3 simulate the warmest temperatures and the biggest ice quantity.

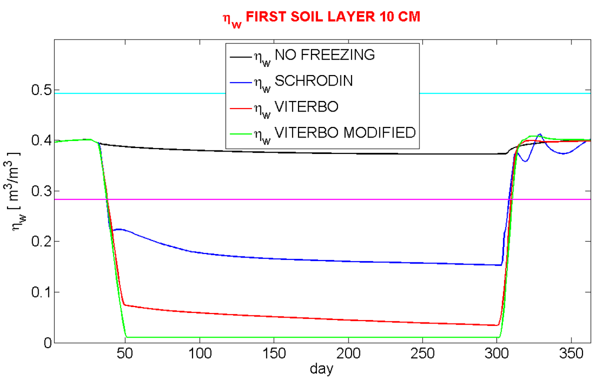

Figure 3: Soil moisture trend in the 10 cm soil layer The cyan line is the porosity η_s, the red line is the wilting point η_{wi}.

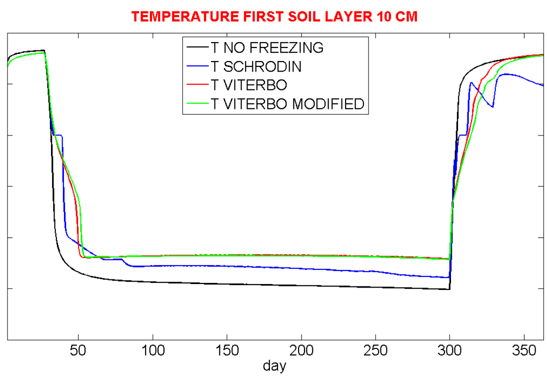

Figure 4: Soil temperature trend in the 10 cm soil layer.

4.2. Brookings campaign

The second part of the work is consistent in the comparison with the observations. The first dataset with which we compare the LSPM results using the parameterizations P0-P3 is that of Brookings.

This site is located in South Dakota, and the dataset contains 3 years of observations (Gilmanov et al., 2005), useful to drive the model LSPM and to compare its output with regards to soil water freezing/thawing. The 3 year period includes three winters and two springs. Figures 4 and 5 show the trend of the daily averaged 2m temperature and precipitation for the entire period.

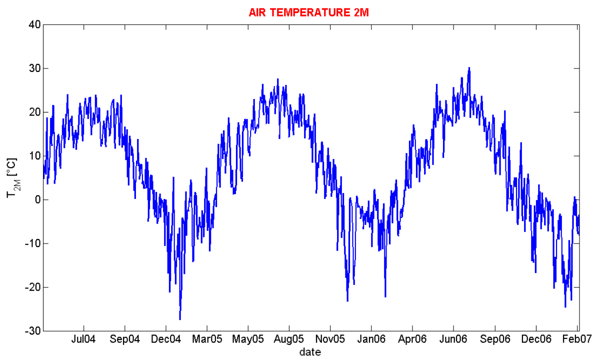

Figure 5 Brookins (South Dakota, U.S.A.) daily mean 2m temperature.

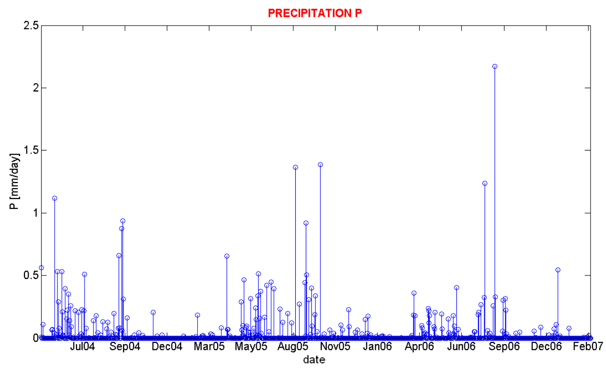

Figure 6 Brookins (South Dakota, U.S.A.) daily mean precipitation.

LSPM has been set as shown in table 2. Soil depths have been chosen according to the observed soil temperatures and moisture.

The simulation results show that all freezing parameterizations are able to simulate well the freezing/thawing periods. Moreover, as seen for the synthetic data experiment, P2 and P3 let a bigger ice production, resulting in a warmer winter layer.

BROOKINGS – LSPM setting		
Temperature: 7 layers (cm): 4, 8, 8, 24, 40, 88, 160 Moisture: 7 layers (cm): 5, 10, 10, 10, 20, 60, 120		
Δt = 60 s	Initial η_w = 0.4 m^3/m^3	Initial T = 1°C
Soil type: silt loam		
Soil porosity η_s [m^3/m^3]	Wilting point η_{wi} [m^3/m^3]	Filed capacity η_{fc} [m^3/m^3]
0.485	0.179	-0.36
Vegetation type: short grass		

Table 2: Model setting for the simulation with the Brookings campaign

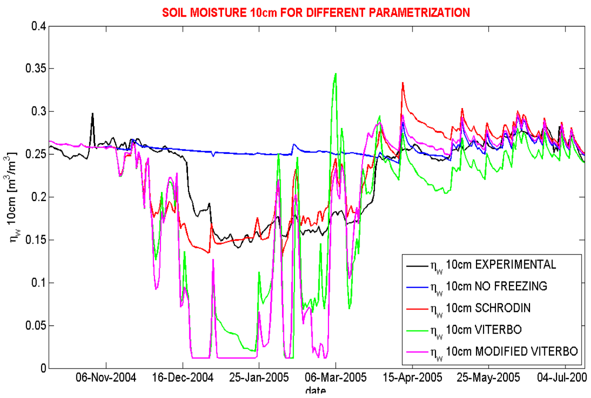

Figure 7: Daily averaged soil moisture trend in the 10 cm soil layer.

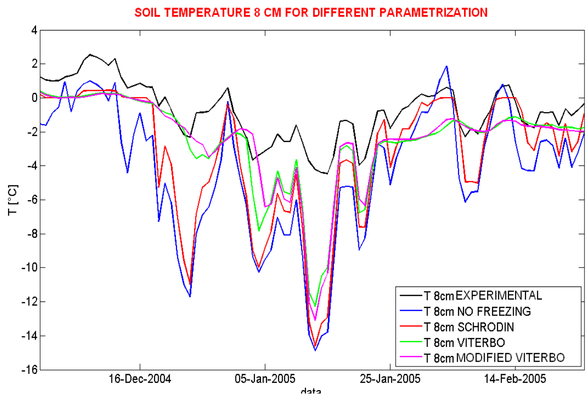

Figure 8: Daily averaged soil temperature trend in the 8 cm soil layer.

The comparison with the observed data (Figs 7 and 8) and the statistical analysis performed evaluating mean error (ME), fractional bias (FB), root mean square error (RMSE) and correlation coefficient (r), suggests that P1 estimates in a better way the soil liquid water content, while P2 and P3 describes better the trend of the soil liquid water content, and catch more precisely the onset and the offset of the freezing/thawing. Soil temperature has a higher correlation using P2 and P3.

It has to be noted that, probably, there is an underestimation of the snow depth, due to a precipitation underestimation during the winter time. In fact, in this location, precipitation was recorded using a rain gauge not provided by heating, which do not allow a correct observation of snowfall, one of the LSPM inputs. This probable underestimation of snowfall led to a related snow depth underestimation by LSPM, which could have affected the soil energy budget and hence the freezing/thawing.

4.3. Falkenberg campaign

The second dataset refers to Falkenberg, a site located in Germany. Here, the campaign lasted almost three years, including three winters and three springs. Figures 9 and 10 show the trend of the daily averaged 2m temperature and precipitation for the entire period and used to drive the model LSPM.

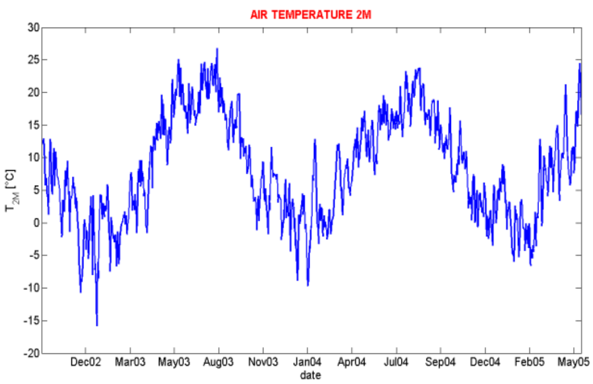

Figure 9: Falkenberg (EU, Germany) daily mean2m temperature

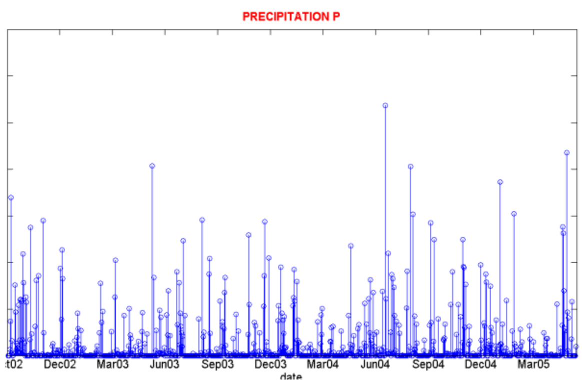

Figure 10: Falkenberg (EU, Germany) daily mean precipitation.

The LSPM settings to simulate this location are listed in Table 3. Soil depths have been chosen according to the observed soil temperatures and moisture.

FALKENBERG – LSPM setting		
Temperature: 8 layers (cm): 3, 4, 4, 8, 11, 30, 60, 120 Moisture: 7 layers (cm): 6, 4, 10, 10, 30, 60, 120		
Δt = 60 s	Initial η_w = 0.4 m^3/m^3	Initial T = 1°C
Soil type 0 - 30 cm: sandy clay loam		
Soil porosity η_s [m^3/m^3]	Wilting point η_{wi} [m^3/m^3]	Filed capacity η_{fc} [m^3/m^3]
0.370	0.04	-0.23
Soil type 30 - 60 cm: sandy clay loam		
Soil porosity η_s [m^3/m^3]	Wilting point η_{wi} [m^3/m^3]	Filed capacity η_{fc} [m^3/m^3]
0.360	0.03	-0.23
Soil type 60 - 120 cm: sandy loam		
Soil porosity η_s [m^3/m^3]	Wilting point η_{wi} [m^3/m^3]	Filed capacity η_{fc} [m^3/m^3]
0.340	0.11	-0.30
Vegetation type: short grass		

Table 3: Model setting for the simulation with the Falkenberg campaign.

The comparison with the observed data (Figs 11 and 12) and the statistical analysis based on mean error (ME), fraction bias (FB), root mean square error (RMSE) and correlation coefficient (r) suggests that, for this location, P2 and P3 have the best scores.

The instrumentation installed on Falkenberg is slightly different than those in Brookings, especially regarding precipitation measure. In fact in this case there is not a simple rain gauge, but is based on the principle of collection bucket weight. In this way it is possible to have observation even in case of solid precipitation, differing from the measurements made in Brookings and allowing a better estimation of snow accumulation during winter.

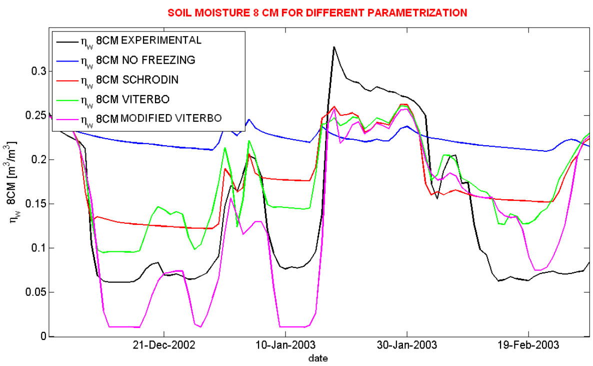

Figure 11: Daily averaged soil moisture trend in the 8 cm soil layer.

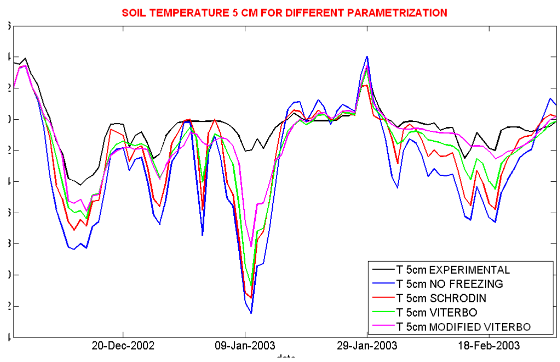

Figure 12: Daily averaged soil temperature trend in the 8 cm soil layer.

5. Conclusions

Water phase changes in the soil are very important for many reasons. In this work we have implemented and tested some freezing parameterizations in the LSPM scheme, searching the most performing one.

First of all, the new version of LSPM seems more able to catch the transient phase related to the soil water phase changes. All parameterizations show the impact of the latent heat release/absorption during the freezing/thawing phases on the soil temperature (Boone et al., 2000).

The statistical analysis highlighted the snow cover underestimation, problem due to the automatic precipitation monitoring, especially in the station located at Brookings, where precipitation has been observed by means of a traditional no-heated rain gauge. Thus, the statistics related to the dataset of Falkenberg can be considered more reliable. In the German site, the two parameterizations P2 and P3 of the freezing/thawing in the soil seem estimate better the experimental data, both regarding soil moisture as well as soil temperature.

We would like again to stress that the possible wrong estimation of the snow-cover, due both to data problems or to an eventual model parameterization failure, combined with the intrinsic non-linearity of the equations relative to the soil temperature and moisture, is a serious limitation for the numerical predictions. For this reason, the conclusions regarding the performances of the freezing/thawing inclusion in the LSPM model must be regarded as provisional. Further comparisons with more reliable observations, and especially with trustworthy winter precipitation data, will be needed. In particular, a guided campaign with forced and artificially created boundary conditions could be helpful for finding out the best parameterization.

In the future developments, another aspect that could be taken into consideration is the inclusion of more appropriate parameterizations for the soil property changes induced by the freezing/thawing phenomena, such as the thermal and hydrological changes of the soil due to the presence of ice (Penner, 1970, Parodi et al., 2003).

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