J1.6 - PARAMETERIZATION OF FROZEN SOIL PHYSICS IN MAPS AND ITS EFFECT ON HYDROLOGICAL CYCLE COMPONENTS

Tatiana G. Smirnova

Cooperative Institute for Research in Environmental Sciences (CIRES)
University of Colorado/NOAA Forecast Systems Laboratory
Boulder, Colorado

John M. Brown and Stanley G. Benjamin

NOAA Forecast Systems Laboratory
Boulder, Colorado

1. INTRODUCTION

The Mesoscale Analysis and Prediction System (MAPS) is a four-dimensional data assimilation system (implemented operationally at NCEP as the Rapid Update Cycle or RUC) running in real time (Benjamin et al., 1997, 1998). The forecast component of MAPS includes a multilevel soil/vegetation scheme for the prediction of soil temperatures and volumetric water content (Smirnova et al., 1997). In January of 1997 a snow physics parameterization was added to this soil/vegetation model. This enhancement accounts for the presence of snow on the ground and its melting and subsequent runoff and infiltration of water into the soil (Smirnova et al., 1998). Soil temperature, soil moisture and snow cover, as predicted by the soil/vegetation/snow model, are carried forward from the previous forecast to initialize the next forecast in the MAPS cycle. This continuous cycling is desirable because it allows the effects of abnormally wet or dry soil conditions to positively influence forecasts of the planetary boundary layer through surface fluxes.

However, seemingly subtle aspects of the climatology of the soil model, and especially the climatology of hydrological cycle components, such as soil moisture, root zone drainage, surface runoff and snow cover, can dramatically affect atmospheric predictions. Further, in the cold season the existence of frozen moisture in soil considerably changes the processes of heat and moisture transfer inside soil, and also affects all components of the hydrological cycle. This motivated us to further improve the soil/vegetation model by searching for ways of incorporating the effects of frozen soil physics into our soil model.

2. PARAMETERIZATION OF PROCESSES IN FROZEN SOIL

Frozen soil plays a significant role in the hydrology of many regions, decreasing infiltration into the soil and causing large runoff rates from otherwise mild rainfall or snowmelt events. Significant runoff over saturated and unprotected soils may cause extreme erosion that may threaten agricultural productivity and construction projects. The need to control runoff and erosion and to determine sensitivity of these processes to soil properties and types of crops and vegetation covering the ground surface has generated much attention to modeling of freezing and thawing processes among hydrologists and soil scientists. Many methods to predict the depth and permeability of frozen soil as a function of the interrelated processes of heat and moisture transfer within the soil have been developed (Harlan,1973; Fuchs et al.,1978; Jame and Norum, 1980; Flerchinger and Saxton, 1989). Many of the models have a high degree of sophistication and accuracy in predicting soil freezing depths and profiles of temperature, water and ice in the soil. However, the nonlinearity and complexity of frozen-soil physics, particularly the coupling of thermal and hydrological processes, complicates the inclusion of parameterizations of frozen soil physics into meteorological forecast models, especially those running operationally. We have therefore developed a computationally efficient and very simplified parameterization of processes in frozen soil for incorporation into MAPS (Smirnova et al., 1999).

This method considers the latent heat of phase changes in soil by substituting an apparent heat capacity for the volumetric heat capacity of unfrozen soil in the heat transfer equation. The apparent heat capacity has an additional term responsible for phase changes inside the soil that can be defined from the freezing characteristic curve for each soil type. (The freezing characteristic curve is an empirical relation, unique to each soil type, that prescribes as a function of temperature the fraction of total water content existing in liquid form.) The apparent heat capacity increases abruptly by several orders of magnitude when ice formation begins. This happens because the release of energy from the freezing of liquid water slows down the propagation of cooling into the soil. The increase of heat capacity is larger if the temperature is closer to the freezing point, and after all available water in the soil is frozen, it reduces back to values close to the volumetric heat capacity in unfrozen soils.

Thermal conductivity at temperatures below freezing also is replaced by apparent thermal conductivity, which includes the contribution of latent heat of fusion. The mechanism of heat transport by the ice-water phase transformations is clearly described in Fuchs et al. (1978): "As liquid water moves toward a colder region in the partially frozen soil, it decreases the matric potential of the warmer soil layer which it leaves.... this lowers the freezing point temperature of the warmer layer and causes the melting of some ice and thus the removal of latent heat of fusion. The liquid water which penetrates the colder layer increases the matric potential and elevates the freezing point. This leads to new ice formation and release of latent heat of fusion in the colder layer of soil." Obviously, latent heat is transported in the same direction as sensible heat - from the warm to the cold layers of soil. Therefore, phase changes inside soil increase apparent thermal conductivity at temperatures close to the freezing point; this slightly reduces the damping effect of the significantly larger apparent heat capacity noted above.

Corresponding author address: Tatiana G. Smirnova, NOAA/ERL/FSL, R/E/FS1, 325 Broadway, Boulder, CO 80303, e-mail: smirnova@fsl.noaa.gov

The effect of ice presence in soil on water transport is also considered by changing the formulations of hydraulic and diffusional conductivities. According to experimental data (Jame and Norum, 1980), the presence of ice in soil disrupts the established flow paths and therefore reduces the water flow speed, and the impeding factor is assumed to be a function of the total ice content. This experimental data showed that this factor may increase exponentially from 1 for ice-free conditions to 1000 when volumetric ice content is greater that 20%. The impeding factor was incorporated into the formulations of hydraulic and diffusional conductivities used in MAPS, and without ice in the soil they transform into the formulations used in MAPS previously, as described in Smirnova et al. (1997). If the volumetric ice content in a layer of soil is higher than the porosity minus some threshold value (set equal to 0.13), there is no flow of liquid water in this layer. If this layer is the top one, the liquid water provided by snow melting or rain cannot infiltrate into the soil and is then forced to go into the surface runoff.

3. ONE-DIMENSIONAL EXPERIMENTS

3.1 Effect of frozen soil physics on soil parameter profiles

The MAPS frozen-soil physics parameterization was first tested off-line in a one-dimensional (1-D) setting before incorporation into the MAPS/RUC forecast scheme. The goal here is to test if our significantly simplified parameterization is still able to simulate the main feature of the freezing or melting processes inside soil, and to see if it could provide improvements in the evolution of hydrological components, such as soil moisture and snow depth, in the continuous cycling of these variables in MAPS.

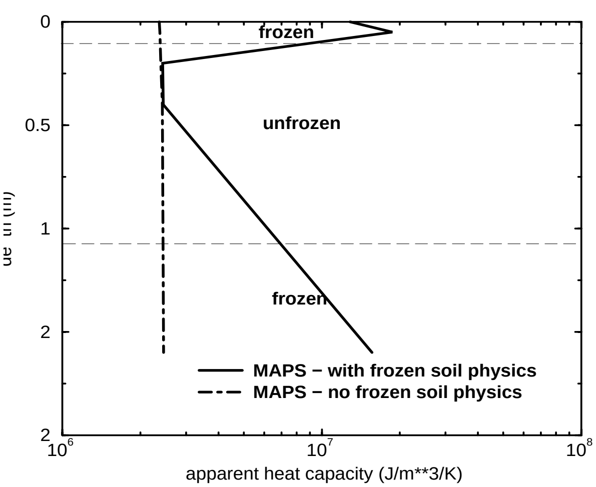

Figure 1. Profiles of apparent heat capacity simulated by MAPS 1-D land-surface models, 15 April 1981, Valdai, Russia.

The dataset most suitable for this 1-D testing was from an observation site at Valdai, which is located in a climatic zone of Russia with significant seasonal variations and persistent snow cover from November until April. This dataset includes continuous atmospheric forcing data for 18 years. The Valdai dataset has been used for the most recent phase of the ongoing, internationally based Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) phase 2d which focused attention on the processes of the cold season, considered to be of great importance for global climate simulations (Schlosser et al., 1998). The MAPS 1-D model participated in the PILPS phase 2d intercomparison, along with many other 1-D land-surface process models.

The MAPS results from the Valdai experiment demonstrate reasonable performance of frozen soil physics parameterization and its significant impact on the hydrological regime of the Valdai catchment during the cold season, and, in particular, in spring and fall when thawing and freezing of the soil moisture occur.

Figure 1 demonstrates the comparison of apparent heat capacity profiles with and without frozen soil physics parameterization when multiple melted and frozen layers were present, typical for spring meltout in the Valdai catchment. Within the melted layers the values of the apparent heat capacity are very close to each other in both versions of MAPS. However, below the freezing point the two versions of MAPS are quite different, and in the MAPS version with parameterization of frozen soil physics apparent heat capacity increases abruptly by one order of magnitude, which is an obvious improvement in representing soil properties when ice formation begins.

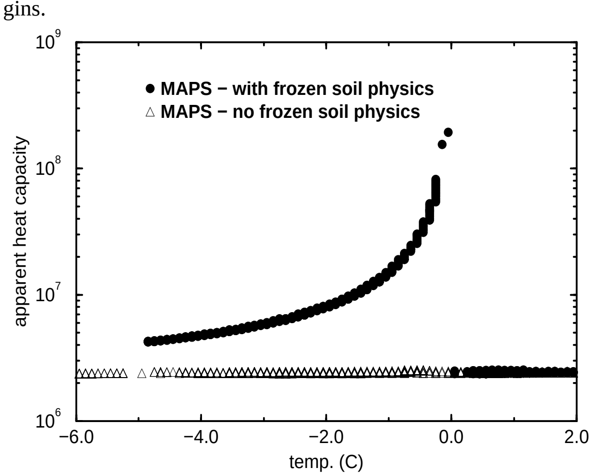

Figure 2. Apparent heat capacity as a function of temperature, 9-16 April 1966, Valdai, Russia.

If we look at apparent heat capacity as a function of temperature (Fig. 2), we can define the range of temperatures over which the energy of the water phase changes is important. For temperatures above freezing, apparent heat capacity is temperature-independent and the same with both versions of MAPS. At below freezing temperatures there is an interval from 0^oC to -2^oC when the apparent heat capacity is dominated by the latent heat conversion term. The increase of heat capacity is greater if the temperature is closer to 0^oC, when the fraction of water in the liquid phase is high. In this range the heat capacity depends on the soil temperature only. Below -2^oC it decreases to values close to those without frozen soil physics parameterization. Here heat capacity depends again on the soil type and the amount of water and ice in the soil. Thus, the functional form of the apparent heat capacity determines a well-defined freezing-thawing zone within the soil profile. In this zone large values of apparent heat capacity significantly slow downward propagation of, for example, the diurnal temperature wave compared to the situation with unfrozen soil.

The dependency of apparent thermal conductivity on the soil temperature (Fig. 3) reveals similar features as apparent heat capacity. When temperatures fall below zero, thermal conductivity increases due to additional transport of latent heat inside the freezing soil, but this occurs over a narrower range of soil temperatures. The most abrupt increase of thermal conductivity happens between 0^oC and -0.5^oC. In this subzone the damping effect from increased heat capacity is partially compensated for by the increased thermal conductivity, so that cooling or heating of soil occurs at a rate higher than predicted from apparent heat capacity only. Therefore, it is important to consider the latent heat of fusion contribution to both soil parameters, especially for regions having frequent freezing-thawing cycles.

The results from the MAPS frozen soil physics parameterization are consistent with the experimental data described, for example, in Fuchs et al. (1978). They also indicate that the parameterization implemented in MAPS is able to capture the main features of freezing processes inside soil in the Valdai experiment.

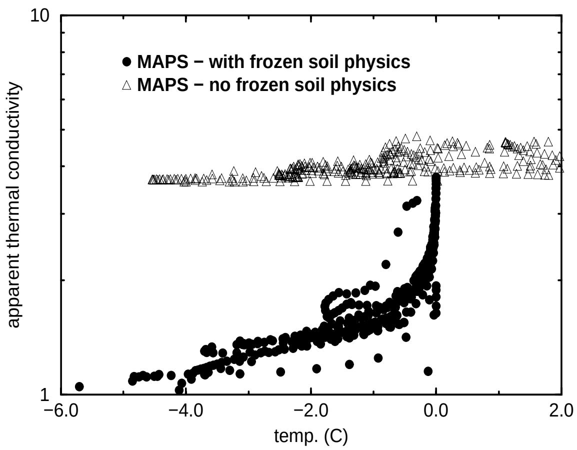

Figure 3. Apparent thermal conductivity as a function of temperature, 9-16 April 1966, Valdai, Russia.

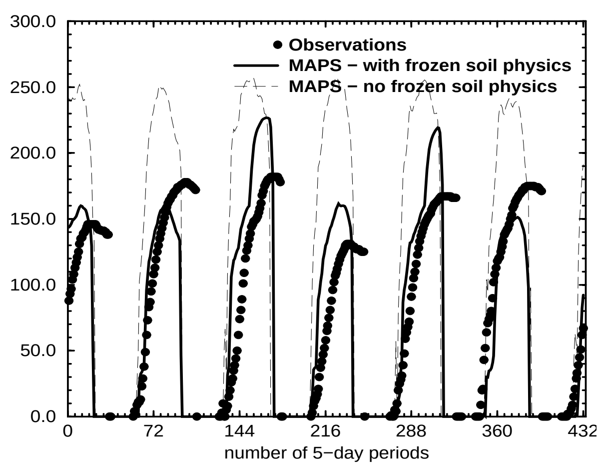

Figure 4. Observed and MAPS simulations of freezing depth in soil (cm) for Tulun, Russia, 1978-1983.

3.2 Simulation of freezing depth

Additional testing of the MAPS frozen soil model has been conducted using the data from six stations located in the different climatic regions of the former Soviet Union. These data, provided by Adam Schlosser (pers. comm.) and described by Robock et al. (1995), contain information about the freezing depth on the sites over a 6-year period. This is very useful for verification of the simulated rate of temperature-wave propagation in freezing soil.The model freezing depth is determined by linear interpolation of temperature between the levels to find the depth of the 0^oC isotherm. The deepest level at which temperature turns from below freezing to above freezing is considered to be the freezing depth in the model. It is defined with less accuracy if located in the deeper layers of soil domain due to low vertical resolution of the model and also due to larger effect of uncertainty of the definition of the bottom soil temperature. However, even this crude estimate of the freezing depth is informative in regard to the performance of the frozen soil physics algorithm.

It is of interest to consider the performance of the frozen soil model in a moist climate with persistently cold winters (for example, Tulun, Russia), and in a dry climate with frequent freezing-thawing cycles in winter (for example, Uralsk, Kazakhstan). In the first case, the contribution of the latent heat conversion term into the rate of temperature wave propagation may be significant because of the large amount of water to be frozen. In the second, the effects of frozen soil physics also should be important because the soil is subjected more often to the dynamics of freezing and thawing.

A comparison of simulated freezing depths provided by the two versions of MAPS against observations for Tulun is presented in Fig.4. The disregard of thermodynamical processes in the freezing soil significantly overestimates the cooling of deep soil layers - the soil is frozen up to 2.5 m against 1.3-1.8 m in reality, and the variations between the years are negligible. The implementation of frozen soil physics improves performance. The slowing of the downward propagation of the temperature wave due to latent heat conversions in the fall makes the slope of freezing depth curve closer to the observed. The depth of freezing wave penetration is reduced to more realistic values, and simulated interannual and intraannual variability is well correlated with the observations. Similar features are noted in Uralsk, Kazakhstan, with dryer and warmer winters (Fig. 5). In both cases the incorporation of frozen soil physics appears to be very important.

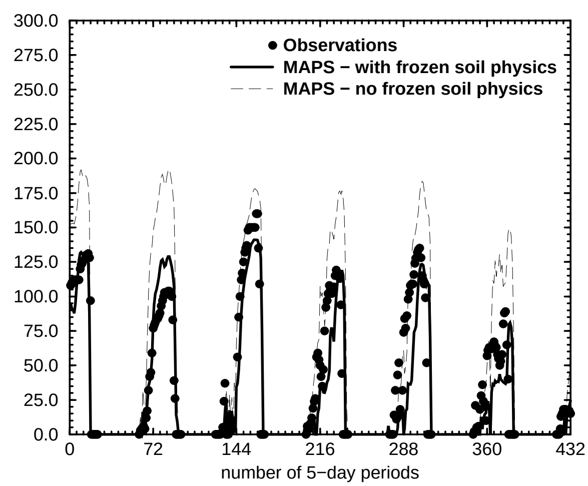

Figure 5. Observed and MAPS simulations of freezing depth in soil (cm) for Uralsk, Kazakhstan, 1978-1983.

Experiments were also conducted for four other stations, and, overall, the model with frozen soil physics demonstrated improved performance, although the potential for improvements depends on the amount of stored water in the soil and also on the winter thermal regime.

3.3 Effect of frozen soil physics on the long-term averages of hydrological cycle components

The performance of the frozen soil physics parameterization in MAPS is also studied from a climatological viewpoint for the Valdai 18-year PILPS 2d period. The annual cycles over this period are averaged for different variables. The soil moisture in the top 1-m layer averaged over the 18-year period (Fig. 6) verifies fairly well against observations, demonstrating moist conditions from October until April and drying out in the summer. The soil moisture simulation in winter is less accurate than in the warm season if hydraulic properties take no account of frozen soil. The spring maximum associated with the snow melting process is reflected in both versions of MAPS, but it is more realistic with frozen soil physics because of the reduced capability to infiltrate melted water into the still frozen soil. Due to a surface runoff increase, the total runoff is higher with frozen soil physics when melting of snow occurs. The surface runoff in midwinter is quite small, and the underestimated storage of water in the top meter of soil is explained by the higher drainage of soil water through the lower boundary without frozen soil physics. However, when temperatures rise above the freezing point in late spring, this deficiency is offset fairly quickly by the overestimated amount of infiltrated water from snow melt, and the two models both perform with sufficiently good accuracy (Fig. 6).

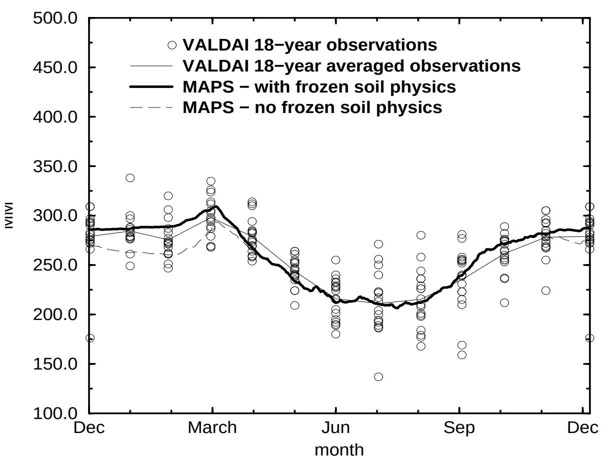

Figure 6. Annual variation of soil moisture content in the top 1-m layer in MAPS simulations over an 18-year period for Valdai, Russia.

4. CONCLUDING REMARKS

An off-line one-dimensional testing of the MAPS soil/snow/vegetation scheme with a parameterization of frozen soil physics and a full energy budget has been undertaken on the data from several Russian stations. The model has demonstrated good performance in capturing the main features of the thermodynamical processes when the ice formation in soil begins. The improvements in representing properties of the freezing soil are the most significant in climate simulations for stations located in the areas of moist climates or in the areas where the soil experiences frequent freezing and thawing. The climatology of hydrological cycle components is affected by the soil processes in the cold season and especially during the transition period from the cold to warm season. Spring surface runoff and water storage in soil in the winter may be simulated with better accuracy by reducing the hydraulic conductivity of soils containing ice. Further improvement of the model results may be achieved by more accurate estimation of the frozen water amount in soil layer, which is currently diagnosed from the freezing characteristic curve using the temperature of the soil layer obtained from the previous time step.

5. REFERENCES

Benjamin, S.G., J.M. Brown, K.J. Brundage, D. Devenyi, D. Kim, B.E. Schwartz, T.G. Smirnova, T.L. Smith, and A. Marroquin, 1997: Improvements in aviation forecasts from the 40-km RUC. *7th Conference on Aviation, Range, and Aerospace Meteorology*, Long Beach, CA, Amer. Meteor. Soc., 411-416.

Benjamin, S.G., J.M. Brown, K.J. Brundage, B.E. Schwartz, T.G. Smirnova, and T.L. Smith, 1998:The operational RUC-2. *16th Conference on Weather Analysis and Forecasting*, Amer. Meteor. Soc., Phoenix, AZ, 249-252.

Flerchinger, G. N., and K. E. Saxton, 1989: Simultaneous heat and water model of a freezing snow-residue-soil system: I. Theory and development. *Trans. of the Amer. Soc. of Agric. Eng*, **32(2)**, 565-571.

Fuchs, M., G. S. Campbell and R. I. Papendick, 1978: An analysis of sensible and latent heat flow in a partially frozen unsaturated soil. *Soil Sci. Soc. of Amer. J.*, **42(3)**, 379-385.

Harlan, R. L., 1973: Analysis of coupled heat-fluid transport in partially frozen soil. *Water Resour. Res.*, **9(5)**, 1314-1323.

Jame, Y.-W., and D. I. Norum, 1980: Heat and mass transfer in a freezing unsaturated porous medium. *Water Resour. Res.*, **16(4)**, 811-819.

Robock, A., K. Ya. Vinnikov, and C. A. Schlosser, 1995: Use of midlatitude soil moisture and meteorological observations to validate soil moisture simulations with biosphere and bucket models. *J. Climate*, **8**, 15-35.

Schlosser, C. A., A. Slater, A. Robock, A. J. Pitman, K. Ya. Vinnikov, A. Henderson-Sellers, N. A. Speranskaya, K. Mitchell, A. Boone, H. Braden, P. Cox, P. DeRosney, C. E. Desborough, Y.-J. Dal, Q. Duan, J. Entin, P. Etchevers, N. Gedney, Y. M. Gusev, F. Habets, J. Kim, E. Kowalczyk, O. Nasonova, J. Noilhan, J. Polcher, A. Shmakin, T. Smirnova, D. Verseghy, P. Wetzel, Y. Xue, and Z.-L. Yang, 1998: Simulations of a boreal grassland hydrology at Valdai, Russia: PILPS Phase 2(d), Submitted to *Mon. Wea. Rev.*

Smirnova, T. G., J. M. Brown, and S. G. Benjamin, 1997: Performance of different soil model configurations in simulating ground surface temperature and surface fluxes. *Mon. Wea. Rev.*, **125**, 1870-1884.

Smirnova, T. G., J. M. Brown, and S. G. Benjamin, 1998: Impact of a snow physics parameterization on short-range forecasts of skin temperature in MAPS/RUC. *Twelfth Conference on Numerical Weather Prediction*, Phoenix, AZ, Amer. Meteor. Soc., 161-164.

Smirnova, T. G., J. M. Brown, and S. G. Benjamin, 1999: Seasonal variations of hydrological cycle components in the Mississippi River basin from a MAPS version with snow and frozen soil physics. Submitted to *J. Geophys. Res.*