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A New Frozen Soil Parameterization in Land Surface Scheme

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Abstract—Lack of frozen soil parameterization in the Land Surface Models will result in great uncertainty of soil moisture simulation in the permafrost and seasonal frozen soil regions. In this paper, we incorporate a new frozen soil parameterization in the Land Surface Scheme—SiB2. A modified approximation Stefan solution is used to predict the frost/thaw depth, and then the soil temperature and moisture profiles are estimated by taking account the effects of frozen/thaw process. The model is validated using GAME-Tibet observations. It estimates the frost depth precisely and improves the soil moisture estimation significantly. The liquid water content and phase transition time are predicted reasonably.

INTRODUCTION

Frozen soil is obviously a dominant factor in land surface processes because of its effects on thermal and hydrological regimes and its large area extend. To incorporate frozen/thaw process in a Land Surface Scheme (LSS) is very important and essential. Lack of frozen soil parameterization in land surface models will result in great uncertainty of soil moisture simulation (Pitman *et al*., 1999), large diurnal temperature cycles and the resulting soil cooling in winter (Viterbo *et al*., 1999).

However, the frozen soil parameterization in land surface schemes is not given sufficient attention until recent years. Most of the literatures began to appear in later 90's. These parameterizations are different in detail, but summed up, they can be assorted into three categories. The first kind of them only account for the hydraulic and thermal properties of frozen soil, e.g. SSiB and SiB2 use a linear function to calculate the decreasing hydraulic conductivity when soil temperature is below 0°C (Sellers *et al*., 1996a; Xue *et al*., 1996); BATS assumes that soil moisture freezes uniformly between 0°C and –4°C and the thermal diffusivity of soil is limited to 1.4×10^{-6} m^2s^{-1} (Dickinson *et al*., 1993). The second kind of them calculate ice production rate based on the amount of heat consumed (released) and left to be consumed (released) in a unit volume of soil. The frozen soil parameterization in the BASE (Best Approximation of Surface Exchanges) (Slater *et al*., 1998) and the CCSR/NIES GCM (Takata and Kimoto, 2000) belong to this category. The originality of this method can be found in a coupled heat and moisture flow model, FROSTB (Berg *et al*., 1980; Shoop and Bigl, 1997). The third kind of frozen soil parameterization uses soil matric potential to define maximum liquid water content when soil temperature is below the freezing point. The frozen soil parameterization in the MAPS (Mesoscale Analysis and Prediction System) (Smirnova *et al*., 1999, 2000), the VIC (Variable Infiltration Capacity) model (Cherkauer and Lettenmaier, 1999), and the mesoscale Eta model (Koren *et al*., 1999) belong to this category. In this parameterization, liquid water content is a function of soil matric potential, and any additional water is ice (Fuchs *et al*., 1978; Flerchinger and Saxton, 1989).

It is natural to anticipate that the predictability of frost/thaw depth can improve the frozen soil parameterization. The Stefan solution, which is frequently used by permafrost scientists to predict frost depth and simulate heat transfer with water phase transition in frozen soil, is capable to implement this objective. The classic solution of Stefan problem can be documented as early as 1890's (Stefan, 1890). Recent literatures of modified solutions can be classified as numerical solutions (Li *et al*., 1996; Zhang and Stamnes, 1998), analytic solutions (Romanovsky and Osterkmap, 1997), and approximation solutions (Fox, 1992; Hinkel and Nicholas, 1995). All these solutions have their advantage in explicitly incorporating phase change in heat and moisture transfer and in predicting frost/thaw depth over time, but the numeric and analytic solutions usually need very fine resolution of soil layers (from <1 cm to a few centimeters). This can explain why only a few efforts have been made to couple Stefan solution with land surface or large scale water balance models (Fox, 1992), which usually employ a soil column of no more than 3 levels below surface. Too many soil layers and a numerical solution of coupled heat and moisture transfer in a land surface model result in large computation cost and difficult initialization of moisture and temperature profiles.

The paper presents a compromise method between the accuracy of Stefan solution in predicting frost/thaw depth and the simple structure of land surface models in manipulating soil column. In the method a modified approximation Stefan solution is incorporated in the framework of the land surface model—SiB2. We introduce the parameterization scheme in this paper and validate the model using the GEWEX Asian Monsoon Experiment (GAME)-Tibet observations.

FROZEN SOIL PARAMETERIZATION

Modifications on the governing equations of SiB2

SiB2 is a revised version of the Simple Biosphere Model (SiB) developed by Sellers *et al*. (1986, 1996a). It includes three soil layers: a surface soil layer, which acts as a significant source of direct evaporation when moist; a root zone, which is the supplier of soil moisture to the roots and accounts for transpiration; a deep soil layer, which acts as a source for hydrological baseflow and upward recharge of the root zone. This structure of the soil model in SiB2 is kept in the new frozen soil parameterization, but the three governing equations of water balance are modified to involve the soil freezing/thawing process.

The equations of water balances that incorporate ice content in the three soil layers can be expressed by

$$\frac{\partial \theta_{l,1}}{\partial t} + \frac{\rho_i}{\rho_l}\frac{\partial \theta_{i,1}}{\partial t} = \frac{1}{D_1}\left[\left(D_c + D_d - Ro_1\right) - Q_{1,2} - \frac{1}{\rho_l}E_{gs}\right] \tag{1}$$

$$\frac{\partial \theta_{l,2}}{\partial t} + \frac{\rho_i}{\rho_l}\frac{\partial \theta_{i,2}}{\partial t} = \frac{1}{D_2}\left[Q_{1,2} - Q_{2,3} - \frac{1}{\rho_l}E_{ct}\right] \tag{2}$$

$$\frac{\partial \theta_{l,3}}{\partial t} + \frac{\rho_i}{\rho_l}\frac{\partial \theta_{i,3}}{\partial t} = \frac{1}{D_3}\left[Q_{2,3} - Q_3\right] \tag{3}$$

where, $\theta_{l,j}$ and $\theta_{i,j}$ (j = 1, 2, 3) are the liquid water content and the ice content (m^3m^{-3}) of each soil layer, respectively; D_j (j = 1, 2, 3) is the thickness of each soil layer (m); $Q_{j,j+1}$ is the water flow between j and j + 1 layers (m s^{-1}); Q_3 is the gravitational drainage from recharge soil moisture store (m s^{-1}); D_c is the canopy drainage rate (m s^{-1}); D_d is the canopy throughfall rate (m s^{-1}); Ro_1 is surface runoff rate due to excess water infiltration in the surface soil (m s^{-1}), E_{gs} and E_{ct} are the evaporation rate from soil surface layer (m s^{-1}) and the canopy transpiration rate though the stomata (m s^{-1}), respectively.

Frost/thaw depth

Li and Cheng (1995) used Green's equation to solve the problem of time-cumulative heat transfer with phase transition and obtained the following equations to calculate the frost depth (ξ_f) and thaw depth (ξ_t) over time in a homogeneous soil column. The frost and thaw depth can be expressed in a similar equation to the approximation Stefan solution (The Institute of Geocryology, 1974).

$$\xi_f = \sqrt{\frac{2\kappa_f \tau_h \sum_{i=1}^{t}\left(T_f - T_g\right)}{L_f \rho_l \theta}} \tag{4}$$

$$\xi_t = \sqrt{\frac{2\kappa_t \tau_h \sum_{i=1}^{t}\left(T_g - T_f\right)}{L_f \rho_i \theta}} \tag{5}$$

where, κ_f and κ_t are the thermal conductivity of frozen and thawed soils

(W $m^{-1}K^{-1}$), respectively; τ_h is the time length (s) and τ_h = 3600 s in this study; T_f is the freezing point of water (K); T_g is the surface temperature (K); L_f is the latent heat of fusion (J kg^{-1}); θ is the total volumetric water content (m^3m^{-3}).

Frozen soil parameterization

To account for the great diurnal variation of surface temperature, the thermal transfer in the surface soil layer is solved by an analytic solution of thermal transfer equation.

$$T_{s,1} = T_0 - gD_1 + A\exp\left(-D_1\sqrt{\frac{\omega}{2V_g}}\sin\left(\omega t - D_1\sqrt{\frac{\omega}{2V_g}}\right)\right) \tag{6}$$

where, $T_{s,1}$ is the soil temperature of surface layer (K); T_0 is the mean temperature (K), initialized as the daily mean value of the last day; g is the thermal gradient (K m^{-1}); A is the amplitude of surface temperature variation; $\omega = 2\pi/l$ and l is the period; V_g is the heat diffusivity and

$$V_g = \frac{\kappa_f}{C_s} \tag{7}$$

where, C_s is effective volumetric heat capacity (J $m^{-3}K^{-1}$). When soil is frozen, C_s is modified to take into account the thermal effect of frozen soil

$$C_s{}' = C_s + L_f\rho_l\frac{\partial\theta_{l,1}}{\partial T_{s,1}}. \tag{8}$$

The liquid water changing rate $\partial\theta_{l,1}/\partial T_{s,1}$ is a function of $T_{s,1}$, which is derived form Li and Cheng (1995) and Nakano *et al*. (1982)

$$\frac{\partial\theta_{l,1}}{\partial T_{s,1}} = \left(-a^*b\right)\left(T_f - T_{s,1}\right)^{b-1} \tag{9}$$

where, a and b are two empirical coefficients associated with soil type.

Therefore, by substituting Eq. (8) into Eq. (6), $T_{s,1}$ can be resolved by a numeric method.

The soil temperature in the root zone and deep soil are predicted as a linear function of frozen depth. If $z < \zeta_f$, the soil temperature at a given depth z is

$$T_z = T_f + \left(T_0 - T_f\right)\left(1 - \frac{z}{\xi_f}\right). \tag{10}$$

If $z > \zeta_f$, the soil temperature at a given depth z is

$$T_z = T_f + \left(T_d - T_f\right)\left(\frac{z - \xi}{D - \xi_f}\right) \tag{11}$$

where, T_d is the temperature of the deep soil (K); D is the total soil depth (m).

Linking the frozen soil parameterization with SiB2

The frozen soil submodel is ran in SiB2 just after the surface temperature is updated with snow cover effect. The procedures of linking the new frozen soil parameterization with SiB2 are as follows:

(1) Determine the position of the frozen/thaw front and therefore subdivide the three soil layers of SiB2 into frozen and thawed sub-layers.

(2) Calculate the soil temperature of each layer.

(3) The liquid water content and its changing rate are calculated, and then the volume ice and liquid water contents in each layer are updated.

(4) Solve the water balance equation, the hydraulic conductivity is updated by considering the effect of soil freezing/thawing.

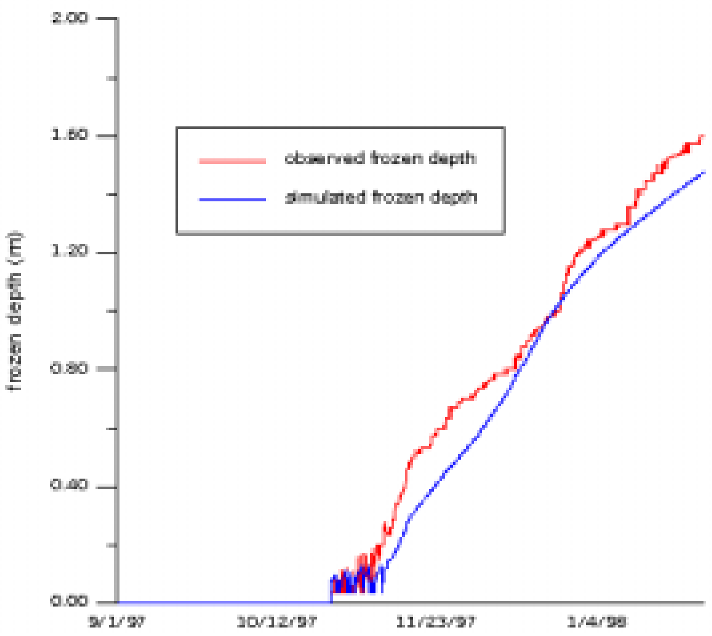

Fig. 1. Simulation result of frozen depth.

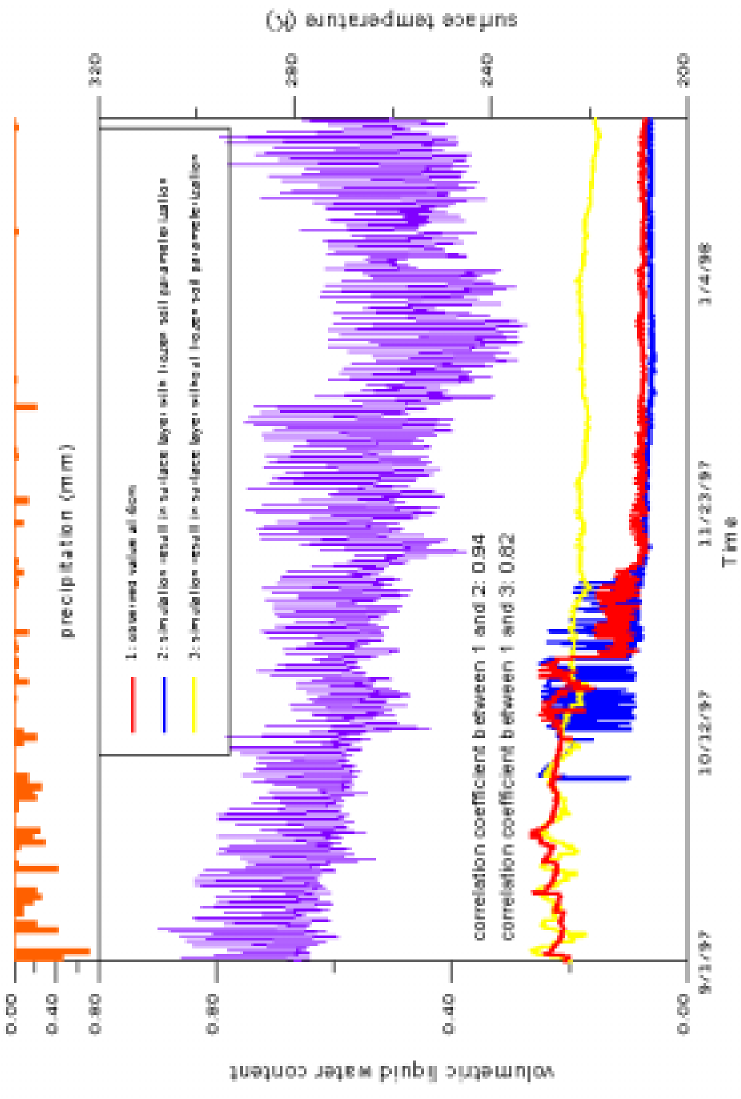

Fig. 2. (a) Simulation result of liquid soil moisture content in the surface soil layer.

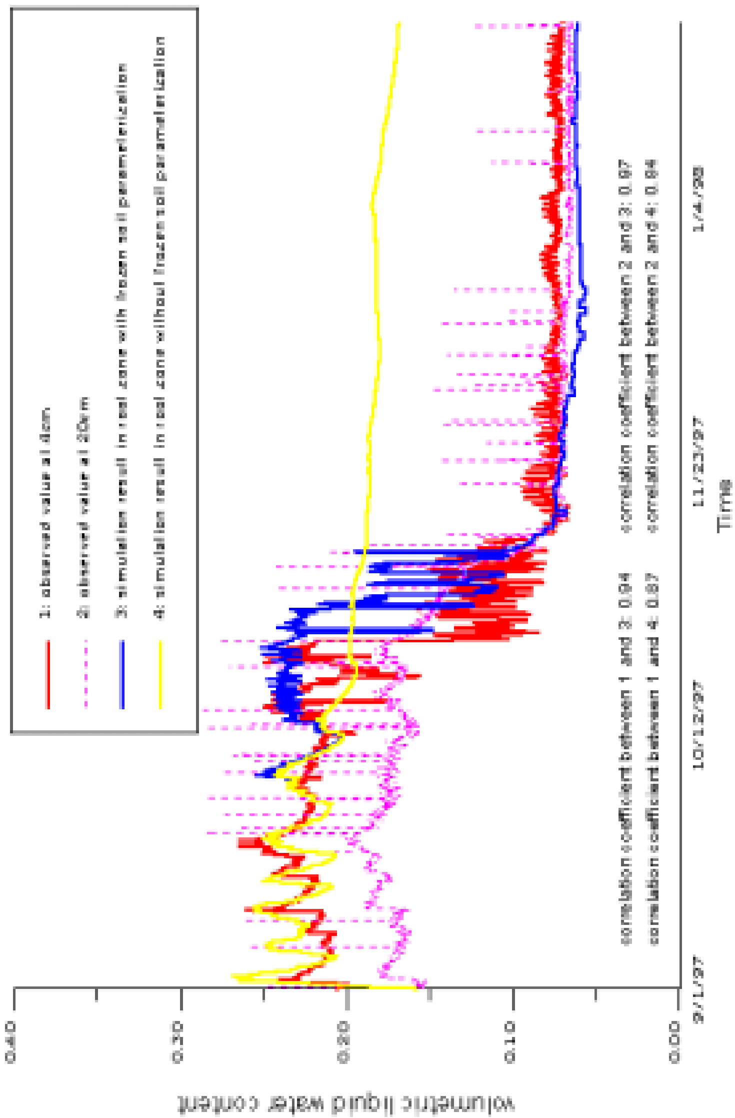

Fig. 2. (b) Simulation result of liquid soil moisture content in the root zone.

(5) Calculate the soil thermal properties (thermal conductivity and heat capacity) for the next time step from the updated ice and liquid water contents (averaged for each layer).

VALIDATION WITH GAME-TIBET OBSERVATIONS

Data

The Tibetan Plateau was chosen as one of the experiment regions of GAME. A plateau scale experiment and a meso-scale experiment were carried out by the POP (prephase observation period) field work in August–September 1997 and the IOP (intensive observation period) field work in May–September 1998. Because the Tibetan Plateau is a region with dominant area of frozen soil, the GAME-Tibet observations of soil moisture and temperature provide an important dataset for validating frozen soil parameterization. We select the MS3608 site near the Nagqu station for both calibration and validation. MS3608 is located at 31°13.6′ N, 91°47.0′ E, with a elevation of 4610 m. The landscape at this site is short grassland. The forcing data required to run SiB2 were obtained from an AWS and the precipitation measurement during the IOP. Validation data of soil moisture and temperature profiles were obtained from a set of SMTMS. The Frost/thaw depth was not measured directly in GAME-Tibet experiment. It was linearly interpolated from the temperature profile.

Calibration of SiB2

SiB2 parameter set is firstly calibrated in the summer season with the IOP data. The land cover type at MS3608 is the bare soil, which is the sixth class in Seller's definition of global land cover class (Sellers *et al*., 1996b). Most of the static parameters are derived from Sellers *et al*. (1996b) directly, while some of them are from GAME-Tibet experiment. The soil type at MS3608 is sub-sand. Parameters associated with soil type are from published literatures and from optimal calibration. The time-space varying vegetation parameters are estimated from the measurements of spectral reflectance of different vegetation type during the POP and the IOP. The aerodynamical parameters, especially the roughness is a big issue of GAME-Tibet experiment. The roughness is derived from different methods. The derived value is about 0.001 + 0.0003 m.

Validation results at site MS3608

(1) Frost depth

Observed (interpolated) and simulated values of frost depth are compared in Fig. 1. This model estimates the frost depth precisely, with a averaged error of 0.092 m.

(2) Soil moisture estimation

The new frozen soil parameterization improves the soil moisture estimation significantly. The liquid water content and phase transition time are predicted reasonably. Figures 2a and b are the simulation results of liquid soil moisture in the surface layer and root zone, respectively. Soil moisture observations are compared with model results with and without frozen soil parameterization.

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