Cold Regions Science and Technology 55 (2009) 130–140

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Development and validation of the frozen soil parameterization scheme in Common Land Model

Siqiong Luo [a,b,*], Shihua Lü [a], Yu Zhang [a]

[a] Laboratory for Climate Environment and Disasters of Western China, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, 730000, China
[b] Graduate School of the Chinese Academy of Sciences, Beijing, 100049, China

ARTICLE INFO

Article history:
Received 20 February 2008
Accepted 31 July 2008

Keywords:
Frozen soil parameterization
CoLM
Tibetan Plateau
Soil liquid water content
Soil temperature

ABSTRACT

In this paper, a frozen soil parameterization scheme is developed based on the Common Land Model. We modify a frozen soil parameterization scheme using soil matric potential to define maximum liquid water content when soil temperature is below the freezing point; the simulation performance is validated using the data from Maqu station on the Tibetan Plateau from 2005 to 2006. The simulated results indicate that the modified frozen soil parameterization scheme allows the liquid water to exist when the soil temperature is below the freezing point, and the simulated soil liquid water content is significantly improved. The simulated soil temperature is also improved because of the successful simulation of the soil liquid water content. The distribution of energy from the modified model is closer to the observed data. Also, the simulated latent heat flux from the modified model increases and the simulated soil heat flux descends compared with the original model.

1. Introduction

Frozen soil processes exert significant influence on the energy and water cycles in cold regions. It has a tremendous impact on the heat balance of the land surface due to fusion heat released/consumed by the freezing/thawing process. Frozen soil processes delay the winter cooling of the land surface, and thawed soil processes delay the summer warming of the land surface (Poutou et al., 2004). It also influences rainfall-runoff partitioning, the timing of spring runoff, and the amount of soil moisture that subsequently is available for evapotranspiration in spring and summer (Koren et al., 1999). Soil hydrology and thermal properties also change greatly with freezing/thawing process.

The Tibetan Plateau contains a lot of the permafrost and the seasonal frozen soil. Considering its unique geographical location with high latitude, the frozen soil on the Tibetan Plateau appears very different from that in the high latitude regions. The permafrost of the plateau is relatively warm and thin compared with the high latitude permafrost in both North America and Russia, and thus more sensitive to climate changes and surface conditions (Cheng, 1998). The well-known Chinese Qinghai–Tibet Railway passes across more than 632-km permafrost regions on the Tibetan Plateau. The ground temperature and the freezing/thawing process of soil in these regions have been discussed and are of concern (Wu and Liu, 2004; Wang et al., 2007; Zhang et al., 2006). The plateau receives much more solar radiation than that in the high latitude due to a larger solar elevation angle in the middle latitude, so the frozen period of the seasonal frozen soil on the Tibetan Plateau is shorter than that in the high latitude. The seasonal frozen soil on the Tibetan Plateau has a strong response to climate change, and its freezing/thawing process also affects the East Asia climate (Wang et al., 2003). The effect of seasonal frozen soil of the Tibetan Plateau on climate change is a meaningful research.

In recent years, the importance of soil freezing/thawing processes on regional and global circulation has been paid more and more attention, and the importance of frozen soil parameterization schemes in land surface model and climate model has been adequately understood (Pitman et al., 1999; Luo et al., 2003; Zhang et al., 2007). Neglecting frozen ground processes will lead to a significant underestimation/overestimation of soil temperature during soil freezing/thawing periods and underestimates total soil moisture content after extensive periods of soil freezing (Koren et al., 1999). Some frozen soil parameterization schemes have been developed in land surface model (Koren et al., 1999; Zhang and Lü, 2002; Li and Koike, 2003; Niu and Yang, 2006). It is important for estimating liquid water content in frozen soil. The liquid water content in frozen soil is calculated by simultaneous equations that soil matric potential relating to soil temperature (Fuchs et al., 1978) and soil matric potential relating to soil liquid water content (Brooks and Corey, 1966; Clapp and Hornberger, 1978) in many land surface models (Flerchinger and Saxton, 1989; Koren et al., 1999; Cherkaue and Lettenmaier, 2003; Zhang and Lü, 2002; Niu and Yang, 2006). Many researches have been focusing on the simulation of soil freezing/thawing processes in the high latitude region in PIPLS 2 and 3 phases (Henderson-Sellers et al., 1995; Luo et al., 2003; Bowling et al., 2003; Nijssen et al., 2003). But

* Corresponding author. Laboratory for Climate Environment and Disasters of Western China, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, 730000, China.
E-mail address: lsq@lzb.ac.cn (S. Luo).

0165-232X/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.coldregions.2008.07.009

Table 1
Observation items of Maqu station

Items	Height or depth (m)
Wind speed and direction	1.4, 3.2, 4.4, 8.4, 18.4
Air temperature and humidity	1.3, 3.1, 4.3, 8.3, 18.3
Pressure	Surface
Sensible heat flux	Surface
Latent heat flux	Surface
Radiation (DSR,DLR,USR,ULR)	1.50
Soil heat flux	0.05, 0.15, 0.35, 0.75
Soil temperature	0.05, 0.10, 0.25, 0.55, 0.95, 1.60
Soil moisture	0.05, 0.10, 0.25, 0.55, 0.95, 1.60

few researches on the simulation of frozen soil have been carried out on the Tibetan Plateau due to the lack of high quality continuous forcing and validation data in this region.

The Common Land Model (CoLM) is developed by Dai et al. (2003) and Dai (2005), which is the state of the art land surface model in the world. Luo et al. (2008) find that the frozen soil parameterization schemes in CoLM are not well by making an offline experiment with nearly 2-year data of Bujiao (BJ) site during the Coordinated Enhanced Observing Period Asia–Australia Monson Project on the Tibetan Plateau (CAMP/Tibet). The model underestimates the liquid water content in frozen soil.

In this paper, we try to improve a frozen soil parameterization scheme in CoLM by using soil matric potential to define maximum liquid water content when soil temperature is below the freezing point, and validate this scheme by using the data of Maqu station on the Tibetan Plateau from 2005 to 2006.

2. Development of the frozen soil parameterization scheme

2.1. Original frozen soil parameterization scheme in CoLM

In CoLM, soil water is predicted from a ten-layer model (as with soil temperature), in which the vertical soil moisture transport is governed by infiltration, runoff, gradient diffusion, gravity, and soil water extraction through roots for canopy transpiration (Dai et al., 2003). The conservation of liquid water for one-dimensional vertical water flow in the soil is stated as

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[k\left(\frac{\partial\psi}{\partial z}\right)-1\right]+S, \tag{1}$$

where θ ($m^3\ m^{-3}$) is the volumetric water content, k (mm s^{-1}) is the hydraulic conductivity, ψ (mm) is the soil matric potential, t (s) is the time and z (mm) is the height above some datum in the soil column, S (s^{-1}) is a soil moisture source/sink term.

The hydraulic conductivity k is a function of the water content:

$$k=k_{sat}\left(\frac{\theta_{liq}}{\theta_{sat}}\right)^{2b+3}, \tag{2}$$

where k_{sat} is the saturated hydraulic conductivity (mm s^{-1}) and depends on the sand content, b is the Clapp–Hornberger parameter, θ_{liq} ($m^3\ m^{-3}$) is the partial volume of liquid water content and θ_{sat} ($m^3\ m^{-3}$) is the saturated volumetric water content. For unfrozen soils ($T>T_{frz}$),

$$\psi=\psi_{sat}\left(\frac{\theta_{liq}}{\theta_{sat}}\right)^{-b}, \tag{3}$$

where the saturated soil matric potential ψ_{sat} (mm) varies with the sand content. For frozen or partially soils ($T\le T_{frz}$), the matric potential is only related to temperature (Fuchs et al., 1978):

$$\psi=10^3\frac{L_f(T-T_{frz})}{gT}, \tag{4}$$

where g is the gravitational acceleration (9.80616 m s^{-2}), T_{frz} is the freezing point (273.16 K), L_f is the latent heat of fusion (0.3336×10^6 J kg^{-1}).

The soil heat transfer invokes the following heat diffusion equation:

$$c\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\rho_{ice}L_f\frac{\partial\theta_{ice}}{\partial t}. \tag{5}$$

In the above equation, c (J kg^{-1} K^{-1}) and λ (W m^{-1} K^{-1}) are the volumetric heat capacity and the thermal conductivity, respectively, t (s) and z (m) are the time and height above some datum in the soil column, respectively, T (K) is the temperature, ρ_{ice} is the density of ice (917 kg m^{-3}), and θ_{ice} ($m^3\ m^{-3}$) is the partial volume of ice content.

The volumetric heat capacity c is from de Vries (1963):

$$c=c_s(1-\theta_{sat})+\theta_{liq}c_{liq}+\theta_{ice}c_{ice}, \tag{6}$$

where the volumetric heat capacity of the soil solids c_s (J $kg^{-1}K^{-1}$) varies with the sand and clay content, c_{liq} and c_{ice} are the specific heat capacities of liquid water and ice, respectively (4.188×10^3 J kg^{-1} K^{-1} and 2.11727×10^3 J kg^{-1} K^{-1}). The soil thermal conductivity λ is from Farouki (1981):

$$\lambda=K_e\lambda_{sat}+(1-K_e)\lambda_{dry}, \tag{7}$$

where K_e is Kersten number, λ_{dry} (W m^{-1} K^{-1}) is the thermal conductivity of dry soil and depends on soil bulk density. The saturated thermal conductivity λ_{sat} (W m^{-1} K^{-1}) is:

$$\lambda_{sat}=\left\{\begin{matrix}\lambda_s^{1-\theta_{sat}}\lambda_{liq}^{\theta_{sat}} & T\ge T_{frz}\\ \lambda_s^{1-\theta_{sat}}\lambda_{liq}^{\theta_{liq}}\lambda_{ice}^{\theta_{sat}-\theta_{liq}} & T\le T_{frz}\end{matrix}\right\}, \tag{8}$$

where the thermal conductivity of soil solids λ_s also varies with the sand and clay content, λ_{liq} is the thermal conductivity of liquid water (0.6 W m^{-1} K^{-1}) , and λ_{ice} is the thermal conductivity of ice (2.29 W m^{-1} K^{-1}).

To solve the heat diffusion equation, if the temperature is calculated without the phase change term then heat diffusion equation is readjusted for phase transition (Dai et al., 2003). This readjustment involves three steps: 1) the temperatures are reset to the freezing point for layers undergoing phase change when the layer temperature is greater than the freezing point and the ice mass is not equal to zero (i.e., melting), or when the layer temperature is less than the freezing point and the liquid water mass is not equal to zero (i.e., freezing); 2) the rate of phase change is assessed from the energy

Table 2
Initial soil temperature, soil water content and soil texture at Maqu station

Layer	Depth	Thickness	The depths at the layer interfaces	Initial soil temperature	Initial soil moisture	Soil texture	
						Sand (%)	Clay (%)
	z (m)	Δz (m)	z_h (m)	T (k)	θ ($m^3\ m^{-3}$)		
1	0.0175	0.0175	0.0071	273.65	0.2114	19.25	13.19
2	0.0451	0.0276	0.0280	274.13	0.2114	19.25	13.19
3	0.0906	0.0455	0.0623	274.61	0.2114	28.96	6.29
4	0.1656	0.0750	0.1189	275.15	0.2691	21.05	9.40
5	0.2891	0.1235	0.2122	275.81	0.2739	18.35	14.41
6	0.4930	0.2039	0.3661	276.63	0.2881	20.63	15.96
7	0.8289	0.3359	0.6198	277.66	0.3024	34.52	13.64
8	1.3828	0.5539	1.0380	278.96	0.1549	68.35	5.28
9	2.2961	0.9133	1.7276	280.61	0.2139	87.11	2.48
10	3.4331	1.1370	2.8647	282.72	0.2500	92.01	1.71