Simulating Soil Freezing and Thawing of Temperate Desert Ecosystem on the Qinghai-Tibet Plateau

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Abstract

Understanding the soil freezing and thawing processes of temperate desert ecosystem on the Qinghai-Tibet Plateau, especially considering that soil freezing and thawing is very sensitive to climate changes. Little changes of soil freezing or thawing may lead to changes in water and heat transition in soils and thus affect the structure and function of ecosystems. SHAW, as a physically based, Land-surface model, provides a useful tool for understanding and analyzing soil freezing and thawing processes. In this paper, using the measured data of temperate desert ecosystem in Dachaidan assessed the model performance in simulating soil freezing and thawing processes. Comparison of the simulated results by SHAW to the measured data showed that in the initial stage of freezing the simulated frozen depth was thinner than the measured; in the thawing period the simulated thawing rate was higher than the measured due to the overestimated soil temperature below 10 cm; however, for the most cold stage (the stable frozen stage), the simulated matched quite well with the measured. For the maximum frozen depth the simulation only overestimated by as much as 4%. On the whole, the SHAW model performed satisfactorily. This provides a good base for further application of LSMs to the temperate desert ecosystem on the Qinghai-Tibet Plateau.

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Key words: Qinghai-Tibet Plateau; SHAW model; Soil freezing and thawing

1. Introduction

Concerns about climate change have grown in importance in recent years, with increased public awareness. Predictions of future climate are based largely on general circulation models (GCMs), which nonetheless can be in considerable error due to incomplete physical knowledge. One of the key areas of uncertainty in GCMs is in their ability to represent the atmosphere-land surface interface [1]. A lot of research and field work has been done in the field of land surface process. Since the first Land surface Model (LSM) was incorporated into GCMs by Manabe in 1969 [2], great progress has been made, especially after the 1980s [3]). In China, the first land surface processes
scientifical experiment (HEIFE) was executed in 1987. From 1997 to 1999, four experiments, GAME Tibet, GAME HUBEX, TIPEX, and IMGRASS were carried out, which greatly promoted land surface process research [4].

So far, many LSMs have been developed, of which about 30 models involved in Project for Inter-comparison of Land-surface Parameterization Schemes (PILPS) [5], among which the most representative models are SiB [6], BATS [7], VIC [8] CLM [9]. Frozen soil plays an important role in the hydrology of cold regions but has been largely ignored in most hydrological models and land surface schemes until recently. Soil freezing and thawing affects both thermal and moisture fluxes of soil-water system. As soil freezes, ice in the soil increases its soil thermal conductivity, reduces its volumetric heat capacity, and requires a large influx of thermal energy for transformation to the liquid phase; meanwhile, ice blocks the soil pores, greatly diminishing the infiltration rates of the soil and leading to altering soil water dynamics and runoff. Lack of soil freezing and thawing processes description in land surface models will result in great uncertainty of soil moisture simulation [10], increasing diurnal variation of soil temperature and effects of soil cooling in wintertime [11]. When soil freezing is explicitly included in a model, it improves the simulation of soil temperature and its variability at seasonal and annual scales [12]. With the gradually revelation of the mechanism of freezing and thawing process, some land surface process models have considered freezing and thawing process, but most of which treat this simply, e.g. SSiB [6], a complicated land surface process model, comprises three soil layers, but it only focuses on water and heat transfer and features of phase change process in frozen soil in a simple manner, given freezing and thawing process merely occurs at 0°C. When the temperature of the third soil layer is lower than 0°C, the model will take the total precipitation as runoff. BATS [7] assumes the process more complicatedly that freezing and thawing process occur in few degrees up or down (-4 to 0°C) and adjust soil thermal diffusivity, but the simulated results is far from the reality. Because of the over-simple parameters of large-scale land surface process models, we selected SHAW (Simultaneous Heat and Water) model, which is the most representative one regarding to snow-melting effect and soil freezing and thawing process in detail [13,14]. The processes of soil freezing and thawing of SHAW model has been tested in croplands in northwest plain of America and Canada [15,16] and has been applied in alpine steppe on the Tibetan Plateau [17]. This paper tests the applicability of SHAW and analyzes soil freezing and thawing processes in high-altitude temperate desert.

2. The SHAW model

2.1. The simple introduction

The SHAW model was originally established in 1989 [13] and a vegetation canopy was added in 1991 [14]. It simulates a vertical, one-dimensional system composed of a vegetation canopy, snow cover (if present), residue and soil profile. The model integrates the detailed physics of interrelated mass and energy transfer through the multilayer system and includes the process of soil freezing and thawing. SHAW is quite successful in estimating soil temperature and soil freezing and thawing [18].SHAW model completely and systematically reflects the characteristics of frozen soil, and changes of water and heat flows in the system are determined by weather conditions, surface soil condition, and soil water and heat conditions of lower boundary. The necessary input weather conditions are routine weather variables above the canopy, including air temperature, wind velocity, air humidity, total radiation and precipitation. Moreover, soil water content and soil temperature of the surface and lower boundary layers at the simulation beginning date are needed The output items mainly contain surface energy flux, water flux, and frost and snow depth.

2.2. Modeling the processes of soil freezing and thawing

The basic computation procedures of the processes of soil freezing and thawing are consisted of energy and water flux equations and parameterization method for frozen soil.

The energy flux in the soil is given by:

\[
C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[ k \frac{\partial T}{\partial z} \right] - \rho_i c_i \frac{\partial q_i}{\partial z} - L_v \left( \frac{\partial q_v}{\partial z} + \frac{\partial \rho_v}{\partial t} \right) + \rho_f L_f \frac{\partial \theta_f}{\partial t}
\]

(1)
Where \( C_s \) is volumetric heat capacity \((J \ m^{-3} \ K^{-1})\); \( T \) is soil temperature \((K)\); \( \rho_i \) and \( \rho_q \) are ice and water density \((kg \ m^{-3})\); \( \Theta_i \) is volumetric ice content \((m^3 \ m^{-3})\); \( L_f \) and \( L_v \) are latent heat of fusion and evaporation \((J \ kg^{-1})\); \( k_s \) is soil thermal conductivity \((W \ m^{-1} \ K^{-1})\); \( c_i \) is specific heat capacity of water \((J \ kg^{-1} \ K^{-1})\); \( q_i \) and \( q_v \) liquid water and vapor flux \((kg \ m^{-2} \ s^{-1})\); \( \rho_v \) is vapor density within the soil \((kg \ m^{-3})\).

Volumetric heat capacity of soil, \( C_s \), is the sum of the volumetric heat capacities of the soil constituents:

\[
C_s = \sum \rho_j c_j \Theta_j
\]

Where \( \rho_j \), \( c_j \), and \( \Theta_j \) are the density, specific heat capacity and volumetric fraction of \( j^{th} \) soil constituent.

Thermal conductivity of the soil is calculated using the theory presented by De Vries [19]. A fairly moist soil is conceptualized as a continuous medium of liquid water with granules of soil, crystals of ice, and pockets of air dispersed throughout. The thermal conductivity of such an idealized model is expressed as

\[
k_s = \sum m_j k_j \Theta_j / \sum m_j \Theta_j
\]

Where \( m_j \), \( k_j \), and \( \Theta_j \) are the weighting factor, thermal conductivity, and volumetric fraction of the \( j^{th} \) soil constituent, i.e. sand, silt, clay, organic matter, water, ice and air.

The soil water flux equation for freezing and thawing soil is written as

\[
\frac{\partial \Theta_l}{\partial t} + \frac{\rho_i}{\rho_q} \frac{\partial \Theta_l}{\partial t} = \frac{\partial}{\partial z} \left[ K \left( \frac{\partial \psi}{\partial z} + 1 \right) \right] + \frac{1}{\rho_i} \frac{\partial q_v}{\partial z} + U
\]

where \( \Theta_l \) is volumetric liquid content \((m^3 \ m^{-3})\); \( K \) is unsaturated hydraulic conductivity of soil \((m \ s^{-1})\); \( \psi \) is soil matric potential \((m)\); \( U \) is a source/sink term for water flux \((m^3 \ m^{-3} \ s^{-1})\). Water flow in frozen soil is assumed analogous to that in unsaturated soil [20, 21]. Therefore, the relationships for matric potential and hydraulic conductivity of unsaturated soils are used to describe the water transport in frozen soils.

The unsaturated hydraulic conductivity of soil is computed from

\[
K = K_s \left( \frac{\Theta_s}{\Theta_i} \right)^{(2b+3)} = K_s \left( \frac{\psi}{\psi_v} \right)^{-(2+3/b)}
\]

Where \( \Theta_s \) is saturated water content \((m^3 \ m^{-3})\); \( b \) is a pore size distribution parameter, \( \psi_v \) is air entry potential \((m)\).

The unfrozen water content in frozen soil is determined by Fuchs function [22]. When ice is present, total water potential is equal to the matric potential and is related to temperature.

\[
\phi = \pi + \psi = \frac{L_f}{g} \left( \frac{T}{T_K} \right) = \frac{L_f \cdot T}{g(T + 273.16)}
\]

where \( \phi \) is total water potential \((m)\); \( \pi \) is osmotic potential \((m)\); \( \psi \) is soil matric potential \((m)\); \( T \) is soil temperature \((^\circ C)\); \( T_K \) is soil absolute temperature \((K)\). Osmotic potential in the soil is computed from

\[
\pi = -cRT \psi_v / g
\]

Where \( c \) is solute concentration \((eq \ kg^{-1})\); \( R \) is universal gas constant; is soil absolute temperature \((K)\).
Soil matric potential is calculated from

$$\psi = \psi_c \left( \frac{\theta_i}{\theta_s} \right)^{-b}$$  \hspace{1cm} (8)

If osmotic potential and matric potential in the soil in the equation (6) are replaced by equation (7) and (8), the unfrozen water will be computed out.

$$\theta_i = \theta_s \left[ \frac{\frac{L_f \cdot T}{T_k} + c R T_k}{\psi_c \cdot g} \right]^{-\frac{1}{b}}$$  \hspace{1cm} (9)

If osmotic potential is ignored the unfrozen water will be computed from

$$\theta_i = \theta_s \left[ \frac{L_f T}{\psi_c \cdot g \cdot T_k} \right]^{\frac{1}{b}}$$  \hspace{1cm} (10)

Then the ice content in soil is determined by

$$\theta_i = \theta - \theta_i$$  \hspace{1cm} (11)
3. Site Description

Qinghai-Tibet Plateau is in the southwest of China (Fig 1). The area of Qinghai-Tibet Plateau is about 2.5 million km², desert ecosystem mainly distributes over north and east of the Plateau. Qaidam basin is the typical temperate desert; lay in the north of the Plateau. This study was conducted at Dachaidan, located in the north of the basin, with an elevation of 3000~3500 m, at 37° 40’~38° 00’ N latitude, 95° 00’~95° 30’ E longitude.

Climate at the site is mainly controlled by high altitude current of west wind and Mongolia high pressure, also suffer warm high pressure of Qinghai-Tibet plateau, so, characterized by dry desert climate [23]. The average annual precipitation is 82 mm (measured from 1957 to 2005). Mean annual air temperature is 1.6°C, with the mean monthly maximum of 14.9°C occurring in July, and the mean monthly minimum of -13.7°C occurring in January.

Soil at the site is classified as lithoid desert soil; the organic matter content is low. The soil layer is thin, about 40~80 cm.

Dominant specie at the site is camel’s-hair pigweed (Ceratoides lateens) and grass (Sympegma regelii). The plant coverage is about 30%, approximately 30 cm in height.

Fig 1. The location of the study site
4. Data measurements

4.1. Weather and soil temperature measurements

The standard weather station of China meteorology bureau located at an elevation of 3173.2 m, at 37° 51'N latitude, 95° 22'E longitude in Dachaidan, to measure total radiation, net radiation, air temperature, wind velocity, rainfall, humidity, soil heat flux and soil temperature. This provided good dataset for driving the SHAW model.

4.2. Soil parameters and soil water content measurements

An observation plot was set near the weather station. Bulk density, soil particle-size composition (sand, silt, clay) and organic matter were measured by profile. And soil water content was measured at 10 cm, 30 cm, 40 cm, 60 cm, and 80 cm in July, 2005 and June, 2006.

5. Model calibration and validation

Based on the measured data of 2004 model parameters were adjusted to better present the site. The adjusted parameter included: saturated hydraulic conductivity, pore size distribution parameter and air entry potential for soil. And the temperature at which plant is assumed to start actively transpiring, critical leaf potential, and the stomatal resistance exponent for plant. Fig 2 shows the simulated and measured 14 O’clock soil temperatures of every day for 2004. Except the surface soil (0 cm), simulated temperatures for the other soil layers overpredicted by as much as 2.0-3.7°C during most time of the year. Simulated and measured soil temperatures were compared using the model efficiency, ME, which is the fraction of variation in measured values explained by the model [24] and is computed as:

\[
ME = 1 - \frac{\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{N} (Y_i - \bar{Y})^2}
\]  \hspace{1cm} (12)

Where N is the total number of observations, Yi is the observed value at a given time step, \(\hat{Y}_i\) is the simulated value at a given time step, and \(\bar{Y}\) is the mean of the observed values.

The ME for simulated daily soil temperatures for 0 cm, 10 cm, 20 cm, 40 cm, 80 cm, 160 cm are 0.47, 0.93, 0.94, 0.85, 0.87, and 0.78 respectively. This indicated that the simulated temperature for surface soil was not so well as for the deeper soil layers.

Model validation was accomplished by applying the model to an additional year of data (2005), using parameters calibrated by the 2004 year of data. The ME for simulated daily soil temperatures of 2005 for the six layers above mentioned ranged from 0.83 to 0.90, and there was no distinct difference for the surface soil. This means that there is no system error for the model used in the site. So, SHAW is applicable in the high altitude temperate desert ecosystem.
6. Model results

Soil freezing and thawing from Oct., 2004 to Sep., 2005 in Dachaidan was simulated by SHAW model. Freezing and thawing proceeded both from the soil surface downward. The soil began freezing downward from the surface in late October, and began to thaw in mid-February after reaching the maximum frozen depth, then in the mid-March the thawing process finished. Thus the freezing and thawing cycle was less than 5 months from late October to mid-March.

The simulated and measured freezing depths were showed in Fig 3. The simulations underpredicted the frozen depth from Nov. to Dec., 2004 and overpredicted the thawing rate from the end of Feb. to early Mar., 2005. Comparison of simulated and measured soil temperatures during the same periods indicates that simulated temperatures below 10 cm overestimated. This suggests that the overestimated temperatures blow 10 cm was the main reason for the underpredicted the frozen depth and overpredicted the thawing rate. However, for the most cold stage (the stable frozen stage), the simulated matched quite well with the measured. The simulated general trend for the whole freezing period was consistent with the measured. Both the simulated and measured freezing curves reached the maximum value at mid-February. The measured maximum frozen depth was 98 cm, and the simulated value was 102 cm; the simulation only overpredicted by as much as 4%.
7. Conclusions

As a physical model, SHAW can simulate soil freezing and thawing processes in temperate desert ecosystem on the Qinghai-Tibet Plateau by calibrating the parameters. This provides a good base for further application. By analysis of simulated soil freezing and thawing processes using the SHAW model after calibrated and validated, some conclusions are attained: (1) SHAW is applicable in the high altitude temperate desert ecosystem. (2) Freezing and thawing proceeded both from the soil surface downward. The freezing and thawing cycle was less than 5 months from late October to mid-March. And in mid-February soil reaches the maximum frozen depth. (3) Comparison of the simulated freezing depth by SHAW to the measured data showed that in the initial freezing stage the simulated frozen depth was thinner than the measured; in the thawing period the simulated thawing rate was higher than the measured due to the overestimated soil temperature below 10 cm; however, for the most cold stage (the stable frozen stage), the simulated matched quite well with the measured. For the maximum frozen depth the simulation only overestimated by as much as 4%. On the whole, the SHAW model performed satisfactorily. This provides a good base for further application of LSMs to the temperate desert ecosystem on the Qinghai-Tibet Plateau.

Acknowledgments

This research was supported by the National Basic Research Program of China (Grant no.2005CB422005), the National Basic S&T Project of China (Grant no.2006FY110200) and China Postdoctoral Science Foundation (Grant no.20090460506).
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