Catena 156 (2017) 244–251

Contents lists available at ScienceDirect

Catena

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

Comparison of the thermal conductivity parameterizations for a freeze-thaw algorithm with a multi-layered soil in permafrost regions

Guojie Hu, Lin Zhao*, Xiaodong Wu, Ren Li, Tonghua Wu, Changwei Xie, Qiangqiang Pang, Defu Zou

Cryosphere Research Station on Qinghai-Xizang Plateau, Chinese Academy of Sciences, Lanzhou 730000, (China)
State Key Laboratoryof Cryospheric Sciences, Lanzhou 730000, (China)
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, (China)

ARTICLE INFO

Keywords:
Soil thermal conductivity
Freeze-thaw depth
Multi-layered soil
Permafrost
Tibet Plateau

ABSTRACT

Soil thermodynamic properties are critical for determining the soil freezing and thawing depths of active layers which is highly important for the hydrology and energy balances of permafrost regions. Here, three soil thermal conductivity parameterizations were evaluated against detailed field measurements at two field sites in the permafrost region of Qinghai-Xizang (Tibet) Plateau (QXP). The results revealed that the comprehensive parameterization based on different schemes for calculating soil thermal conductivity is relatively close to the measured values in unfrozen soil, and Johansen's parameterization is the best in the frozen soil. Then, we first combined three thermal conductivity parameterizations with a freeze-thaw algorithm to simulate freezing and thawing depths of multi-layered soil. The analysis showed that the average percentage difference between the observed and calculated soil thawing depth values for the Johansen's and comprehensive parameterization was 10.42% and 8.49% at Tanggula (TGL) and Xidatan (XDT), receptively. It indicated that the comprehensive parameterization with freeze-thaw algorithm simulated the soil thawing depth more similarly to the observed data for multi-layered soil. These findings can also be incorporated into other land surface, hydrological or ecosystem models to simulate the freeze-thaw cycles in permafrost regions.

1. Introduction

Permafrost, which is defined as ground in which temperatures remain at or below 0 °C for at least two consecutive years, is a key component of the cryosphere due to its influence on energy exchange, hydrological processes, natural hazards, carbon budgets, and the greater global climate system in general (Riseborough et al., 2008; Walvoord and Kurylyk, 2016; Woo, 1986). Previous studies have shown that permafrost can respond quickly to climate change, leading to dramatic changes in soil physical and chemical properties, water and heat dynamics, and nitrogen and carbon cycles (Hansson et al., 2004; IPCC, 2007). The changes in permafrost temperature are indicators of a warming climate, which would result in permafrost degradation (Li et al., 2008; Zhang et al., 2003). It is likely that thawing permafrost will result in significant societal and environmental impacts, some of which may have global consequences (Brown and Romanovsky, 2008). This topic has received increasing attention in recent years, with several studies focusing on understanding, assessing, and predicting changes in permafrost under various climate change scenarios (Lawrence and Slater, 2005; Sushama et al., 2006; Zhang et al., 2008b). However, there are large discrepancies in the prior predictions of permafrost fate which typically utilize freeze/thaw algorithm under similar climate change scenarios (Lawrence and Slater, 2005; Zhang et al., 2008b). More detailed research is required in order to better understand basic model assumptions and simulation processes, particularly thawing and freezing (Burn and Nelson, 2006; Delisle, 2007; Nicolsky et al., 2007).

Soil thermal conductivity is an important parameter in thawing and freezing algorithms that can impact the simulation of soil temperature and heat flux. Several soil thermal conductivity parameterization schemes, based on rigorous laboratory measurements, are widely used (De Vries, 1963; Farouki, 1981; Johansen, 1977; Kersten, 1949; McCumber and Pielke, 1981). Based on a large number of laboratory measurements, many parameterizations were developed (Farouki, 1981; Riseborough, 2004; Tarnawski and Wagner, 1993), Kersten's (1949) parameterizations have been shown to provide inaccurate predictions of soil thermal conductivity at lower water contents (Li et al., 2014). Some models require many input parameters (Bachmann et al., 2001; De Vries, 1963; Tarnawski and Wagner, 1993) and proper

* Corresponding author at: Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China.
E-mail addresses: huguojie123@126.com (G. Hu), linzhao@lzb.ac.cn (L. Zhao).

http://dx.doi.org/10.1016/j.catena.2017.04.011
Received 29 June 2016; Received in revised form 30 March 2017; Accepted 10 April 2017
0341-8162/

parameter selection is necessary to make accurate predictions (Horton and Wierenga, 1984; Ochsner et al., 2001). Soil thermal conductivity is a strong function of soil texture in the land surface model (Luo et al., 2009a). Among the various parameterization methods, Farouki (1981) and Johansen (1977) are most commonly used in land surface models (Farouki, 1981; Johansen, 1977; Luo et al., 2009a; Oleson et al., 2010). However, Farouki (1981) and Johansen's methods give larger simulation differences in permafrost regions depending on soil particle size distribution (Côté and Konrad, 2005; Farouki, 1981; Luo et al., 2009a, 2009b). Luo et al. (2009b) developed a comprehensive parameterization based on the soil thermal conductivity model developed by Farouki's (1981) which incorporated the soil thermal conductivity schemes of Johansen (1977) and Côté and Konrad (2005) and modified the thermal conductivity schemes of soil solids and dry soil using data collected from soil surveys and field sampling in the Central Tibetan Plateau to obtain improved simulation results. The applicability of these different parameterization methods are primarily attributed to local soil conditions and there is limited work on the soil thermal parameters in the active layer of permafrost regions within the Plateau (Gao et al., 2002; Li et al., 2005; Wang et al., 2005). Until recently, it was difficult to accurately describe freeze–thaw processes occurring within the active layer of permafrost regions. Therefore, there is the need for a comprehensive evaluation of the influence of soil thermal conductivity on simulations of freeze-thaw depth within land surface models in permafrost regions.

The most widely used analytical solution for freeze-thaw depth is Stefan's formulation (Stefan, 1891), which is most applicable in wet homogeneous ground conditions (Carlson, 1952; Jumikis, 1977; Lunardini, 1981; Riseborough et al., 2008). In previous studies utilizing this formulation, the soil profile is modelled as a homogeneous medium (Gough and Leung, 2002; Nelson et al., 1997; Pang et al., 2006; Romanovsky and Osterkamp, 1997; Shiklomanov and Nelson, 2003; Yang and Cheng, 2011; Zhang et al., 2005). Many efforts have been made to extend its applicability (Hayashi et al., 2007; Kersten, 1959; Woo et al., 2004) and to modify it for using in a multi-layered system (Jumikis, 1977; Lunardini, 1981). In this multi-layered algorithm, the freezing (or thawing) depth is calculated by evaluating the partial freezing/thawing index of the total surface thawing/freezing index that is necessary to thaw/freeze each soil layer. It has been frequently used to predict the active layer thickness in permafrost and the frost depth in seasonally frozen soils (Jumikis, 1977; Kurylyk, 2015; Woo et al., 2004). In this study, three different thermal conductivity parameterizations were first combined with this algorithm to simulate freezing and thawing depth. The specific objectives of the present study were to (i) compare the three soil thermal conductivity parameterizations for estimating soil thermal conductivity in different soil layers; and (ii) evaluate the accuracy and applicability of these parameterizations with freeze-thaw algorithms for predicting freeze/thaw depths in multi-layered soil in Qinghai-Xizang (Tibet) Plateau (QXP).

2. Study area and data

Study data were collected at the Tanggula and Xidatan sites in the permafrost regions of QXP (Fig. 1). The Tanggula site (TGL) was situated on a gentle slope in Tanggula Mountain (Table 1) and the average annual air temperature was −4.98 °C with a maximum air temperature of 9.32 °C and a minimum temperature of −22.17 °C (Fig. 2). The Xidatan site (XDT) was on the northern fringe of the plateau permafrost and the average annual air temperature was −4.35 °C with a maximum temperature of 10.53 °C and minimum temperature of −21.19 °C. The soil volumetric water content ranged from 6.18% to 26.43% at TGL and from 6.21% to 47.04% at XDT (Fig. 2).

The data measured in this paper, including soil temperature, ground temperature, and moisture content, were collected from experimental stations located in the TGL and XDT during the period from January 1, 2012 to December 31, 2012. The soil temperature and moisture content in the active layer were recorded every 0.5 h by a CR1000 data acquisition instrument (Campbell Scientific Inc.USA) at different depths (Xiao et al., 2013). The ground surface temperature (GST) was measured using an SI-111 precision infrared radiometer (Campbell Scientific Inc., USA) with an accuracy of ± 0.2 °C. The thermal conductivities were determined using KD2 Thermal Properties Analyzer (Decagon Devices, Inc.) at 5 cm depth.

3. Methods

3.1. Soil sampling and analysis

On 20 April 2011, 100 ml ring samplers were used to collect soil samples for measurement of the saturation moisture content. Three field replicates of each of the soils were collected and mixed together in the laboratory. The field wet bulk density (weight of soil per unit volume) was measured by the clod method and expressed as field moisture weight for each sample. Samples collected for moisture content determination were stored in soil sample aluminum boxes and carefully sealed to prevent changes in soil moisture. The soil moisture content was expressed gravimetrically as the ratio of the mass of water present to the oven-dry (60 °C, 24 h) weight of the soil sample. The collected soil samples were dried and tested for physical and chemical parameters. The soil samples were then sieved through a 2 mm sieve to homogenize them, where roots and rock fragments were removed for measuring soil texture. The gravel content (% by weight of rock material > 2 mm in size (i.e. not passing through a 2 mm sieve)) was calculated from oven-dried samples in the field laboratory (Wu et al., 2012).

3.2. Parameterization of soil thermal conductivity

(1) Farouki Parameterization scheme: Farouki's parameterization of soil thermal conductivity is one of the most frequently and widely used schemes (Farouki, 1981). Soil thermal conductivity λ ($\mathrm{W\,m^{-1}\,K^{-1}}$) is expressed as:

$$\lambda = \begin{cases} K_e\lambda_{sat} + (1 - K_e)\lambda_{dry}, & S_r > 1 \times 10^{-5} \\ \lambda_{dry}, & S_r \leq 1 \times 10^{-5} \end{cases} \tag{1}$$

where λ_{sat} is the saturated soil thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$), λ_{dry} is the dry soil thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$), K_e is the Kersten number, and S_r is the degree of saturation.

The saturated soil thermal conductivity, λ_{sat}, depends on the thermal conductivities of soil solids, liquid water, and ice:

$$\lambda_{sat} = \begin{cases} \lambda_s^{1-\theta_{sat}}\lambda_{liq}^{\theta_{sat}}, & T \geq T_f \\ \lambda_s^{1-\theta_{sat}}\lambda_{liq}^{\theta_{sat}}\lambda_{ice}^{\theta_{sat}-\theta_{liq}}, & T < T_f \end{cases} \tag{2}$$

where T_f is the freezing point, θ_{sat} is the soil saturated water content, θ_{liq} is the soil liquid water content, λ_{liq} and λ_{ice} are the thermal conductivities of water ($0.57\ \mathrm{W\,m^{-1}\,K^{-1}}$) and ice ($2.29\ \mathrm{W\,m^{-1}\,K^{-1}}$), respectively. The thermal conductivity of soil solids, λ_s, varies with the sand and clay content:

$$\lambda_s = \frac{8.80(\%\text{sand}) + 2.92(\%\text{clay})}{(\%\text{sand}) + (\%\text{clay})} \tag{3}$$

Dry soil thermal conductivity, λ_{dry}, is a function of dry soil density $\rho_d(\mathrm{kg/m^3})$:

$$\lambda_{dry} = \frac{0.135\rho_d + 64.7}{2700 - 0.947\rho_d} \tag{4}$$

Kersten's number, K_e, is only a function of the degree of saturation S_r and the phase of the water: