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Comparison of different soil temperature algorithms in permafrost regions of Qinghai-Xizang (Tibet) Plateau of China

Guojie Hu, Lin Zhao *, Xiaodong Wu, Ren Li, Tonghua Wu, Changwei Xie, Yongping Qiao, Guodong Cheng

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

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ABSTRACT

Soil thermal diffusivity is a crucial physical parameter that affects soil temperature. By applying sinusoidal boundary conditions, an analytical solution using separated variables for the heat conduction-convection equation was developed. The thermal diffusivity and liquid water flux density were calculated with data collected at field observation sites in permafrost regions of Qinghai-Xizang (Tibet) Plateau (QXP). By taking the soil layer at the depth of 5 cm as the upper boundary, the soil temperature at a depth of 10 cm was modeled by the thermal conduction-convection method, amplitude method and phase method. The statistical analysis of the standard error of the estimate (SEE), the normalized standard error (NSEE) and the root mean square error (RMSE) demonstrated that the thermal conduction-convection method provided the most accurate prediction of soil temperature, with average SEE, NSEE, and RMSE of 0.72 °C, 9.26% and 0.72 °C, respectively. The thermal conduction-convection method provides a useful tool for calculating soil thermal parameters, simulating soil temperature and land surface processes parameterization for permafrost changes modelling under global warming.

1. Introduction

Activities on the land surface can affect weather and climate through energy and water vapor exchange processes between the land and atmosphere. Several studies have been published regarding land surface processes (Ding and Zeng, 2006; Liu et al., 1995; Sun et al., 1998; Sun and Xue, 2001). Climate simulation results are particularly sensitive to the daily and seasonal variation in surface energy distributions. However, calculated values of total energy often differ from measured values and do not agree with behaviors predicted by the energy conservation law. The soil surface temperature directly affects the latent and sensible heat changes and thus impacts the distribution of soil temperatures and moisture content, which are key variables in an investigation of soil thermal properties (Jiang et al., 2015; Jiang et al., 2012). Soil temperature is the important parameter of land-atmosphere interaction, which directly influence on soil heat flux and energy balances (Niu et al., 1997). But there are errors when simulating soil temperature by some land surface schemes and general numerical models (Gao et al., 2004; Kahan et al., 2006). An accurate description of the heat transfer processes in soil is therefore needed to consider the effects of vertical migration of soil moisture on soil temperature and develop more in-depth analyses of heat transfer processes in soil (Shao et al., 1998; Wang et al., 2012).

Soil surface temperature can affect the exchange of energy and substances between the land and atmosphere (Liu et al., 2006). The three key soil thermal-physical parameters required to simulate soil temperature are soil thermal conductivity, volumetric heat capacity, and thermal diffusivity. The thermal conductivity can be calculated using values of volumetric heat capacity and thermal diffusivity. Generally, thermal diffusivity is used to describe the transient process of heat conduction based on temperature boundary conditions (Zhang et al., 2011). Soil thermal diffusivity can be determined using several different methods, most of which are based on the hypothesis that soil can be considered a semi-infinite medium. The one-dimensional heat conduction equation can then be solved by assuming a periodic boundary (Bhumralkar, 1975; Dai et al., 2009). These previous methods can be classified as amplitude, phase, arctangent, logarithmic, numerical, or harmonic methods (Horton et al., 1983). Gao et al. (2003, 2008) showed that change in soil temperature was not only related to the soil thermal conductivity, but also to soil thermal convection caused by liquid vertical movement (Verhoef, 2004). These results allowed for the development of conduction and convection thermal equations (Gao et al., 2003), which can be solved analytically by applying the harmonic method (Wang et al., 2008). This method differs from traditional methods since the effects of heat conduction and convection on soil temperature changes are considered.

The Qinghai-Xizang Plateau (QXP) plays an important role in the Asian monsoon system and is also an important component of the global energy and water cycle (Yue, 2006). The QXP is highly sensitive to

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* Corresponding author.
E-mail address: linzhao@lzb.ac.cn (L. Zhao).

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climate change and considered a climate promoter area for China (Liu and Chen, 2000; Tang et al., 1979). The complex terrain, irregular snow-coverage in winter months, large areas of permafrost, and other climate factors create particularly complex land-atmosphere interactions in QXP. There are approximately 140×10^4 km^2 of permafrost in the QXP, covering 54.3% of the entire plateau (Cheng and Zhao, 2000), necessitating an understanding of the water and heat processes in this region.

Although several different soil heat and water transfer equations have been proposed, most solutions use numerical techniques (Jaynes, 1990; Nassar and Horton, 1992a). A few analytical solutions are also available (Gao et al., 2003; Gao et al., 2008; Shao et al., 1998). In QXP, there have been limited efforts to characterize the thermal conduction-convection processes in non-permafrost regions through analytical methods (Gao et al., 2003; Yue, 2006). To our knowledge, even less is known about the soil thermal parameters in the permafrost regions on the plateau (Li et al., 2005; Wang et al., 2005). There is a need for more information regarding the effect of soil water vertical movement on the soil thermal properties in this area. In the current study, a variable separation approach was used to solve the thermal conduction-convection equation in order to simulate soil temperature. Soil temperature was then analyzed to determine how soil water vertical movement influenced the soil thermal characterizes in the QXP. The objectives of the present study were to (i) propose a method to solve thermal conduction-convection equation; (ii) compare the simulation results for soil thermal diffusivity, water flux density, and soil temperatures obtained using different methods and determine the applicability of these methods in the permafrost regions of QXP.

2. Field experiments

Data for the current study are collected at the Tanggula, QT05 and QT06 sites in permafrost regions of QXP (Fig. 1). These three sites have different underlying surface and soil characteristics. The Tanggula site is situated on a gentle slope on Tanggula Mountain (Table 1). The vegetation consists of an alpine meadow distributes in clusters with plant a height of less than 10 cm. The soil temperature and moisture is collected in 30 min intervals in the active layer by CR1000 data acquisition instrument (Campbell Scientific Inc.) at different depths at TGL and 1 h intervals at QT05 and QT06. The ground surface of QT05 is relatively flat and the soil in the site contained 7.9% silt and a high proportion of sand. The site QT06 has contained a vegetation cover of alpine grasslands, and soil consisting of the 10.6% silt with a high proportion of sand. Both QT05 and QT06 sampled using a borehole and the data is recorded hourly.

In this study, the average temperature (T_1, T_2) of soil layers at 5 cm and 10 cm depth was taken as the mean daily soil temperature. The amplitude (A_1, A_2) was equal to half of the difference between the maximum temperature and the minimum temperature. The initial phase(φ_1, φ_2) was taken as the mean value on the day of time into $\omega t - \varphi = \pm\pi/2$ when soil temperature was highest and lowest. The data used in this study were collected from September 1st, 2012 to September 5th, 2012 during an intensive observation and sunshine period in permafrost regions of QXP.

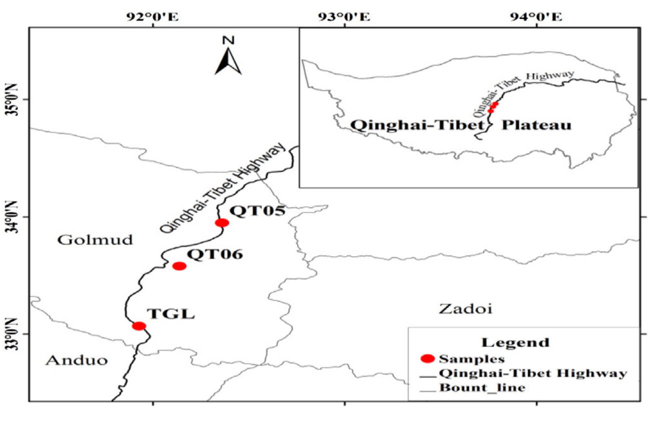

Fig. 1. Location of the Tanggula, QT05 and QT06 site on the Tibet Plateau in China.

Table 1
The Geographical position of observatories.

Site	Longitude/latitude	Elevation(m)	Vegetation type
TGL	33.07°N/91.93° E	5100	Alpine meadow
QT05	33.95° N/92.40° E	4652	Alpine desert steppe
QT06	33.58° N/92.24° E	4650	Alpine grasslands

3. Methods

3.1. Thermal conduction equation for soil temperature

In a one-dimensional isotropic medium, the fundamental solution of the classic heat diffusion equation can be described as:

$$\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \tag{1}$$

where k is the thermal diffusivity (m$^2\cdot$s) and $k = \lambda/Cg$, λ is the thermal conductivity (W$\cdot$m$^{-1}\cdot$°C^{-1}), Cg is the volumetric heat capacity of the soil (J$\cdot$m$^{-3}\cdot$°C^{-1}).

The boundary condition at a depth z_1 was taken as:

$$T\big|_{z=z_1} = \overline{T}_1 + A_1\sin(\omega t - \varphi_1), \quad t \geq 0 \tag{2}$$

where $\overline{T}_1$ is the mean soil temperature (°C) at a depth z_1, A_1 is the amplitude (m), φ_1 is the initial phase (rad) and ω is the angular velocity of the Earth's rotation (rad/s).

According to Eqs. (1) and (2), the soil temperature (T) at a depth z_2 can be calculated as:

$$T_{z=z_2} = \overline{T}_2 + A_1\exp[-(z_2 - z_1)\alpha]\cdot\sin[\omega t - \varphi_1 - (z_2 - z_1)\alpha] \tag{3}$$

where $\alpha = \sqrt{\omega/2k}$, A_2 and φ_2 are defined as the amplitude and phase at a depth z_2, respectively, and the following can then be calculated:

$$A_2 = A_1\exp[-(z_2 - z_1)\alpha] \tag{4}$$

$$\varphi_2 = \varphi_1 + (z_2 - z_1)\alpha \tag{5}$$

3.2. Thermal conduction-convection equation for soil temperature

Gao et al. (2003, 2008) presented the following conduction–convection equation for one-dimensional, unsteady soil heat transfer in the presence of steady water flow:

$$\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} + W\frac{\partial T}{\partial z} \tag{6}$$

where T(°C) is temperature, t(s) is time, and $W = \partial k/\partial z - C_w/C_g w\eta$, $\partial k/\partial z$ is the vertical gradient of soil thermal diffusivity, $C_w/C_g w\eta$ is the water flux density term, w (m/s) is the liquid flow rate (positive downward), η is the volumetric water content of the soil, and C_w (J$\cdot$°C$^{-1}\cdot$m^{-3}) is the heat capacity of water. It should be noted that the parameter W not only considers the effect of thermal convection by soil water vertical movement, but also the gradient of soil thermal diffusivity.