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Influences of climate variation on thawing–freezing processes in the northeast of Three-River Source Region China

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ABSTRACT

In cold region, precipitation, air temperature and snow cover significantly influenced soil water and heat transfer, and thus freezing–thawing processes of active soil layer. On the basic of physical processes of water and heat balances and their transfers in the snow covered soil, a water-heat coupling model for snow cover and its underlying soil layers was established in this paper. Numerical solution of the model was conducted by a full-implicit finite volume method. Observation data of snow cover depth, soil water content and active soil depth at two typical sites in the northeast of Three-River Source Region of China were selected for model calibration and validation. The results indicate that the model can capture soil freezing–thawing processes at the two sites. Simulated results reveal that variations of soil water content, soil temperature and soil freezing depth depend on climate conditions of air temperature, precipitation and snow cover as well. In comparison of the simulated results at two sites, we know that thick snow cover hinders temperature transfer from air to soil, resulting in prolonging the time lag between air and soil temperatures, decreasing variations of soil temperature and soil water content and reducing soil freezing depths of active soil.

1. Introduction

Climate change and its effect on human society have grown to be an important research in recent years. As one of the most sensitive regions to climate change, permafrost has been suffered from temperature rise, resulting in downward moving of active layer in the upper soil. Meanwhile, degradation of grassland and land desertification due to human activities significantly altered regional ecosystem and water cycling (Wang et al., 2007b), thus influenced permafrost.

Soil water movement and heat transfer during the processes of seasonal soil freezing and thawing significantly influence hydrological processes, water resources, agriculture and environment in cold region. On the other hand, snow cover takes a great influence on heat and water movements of the frozen soil (Wang, et al., 2011). Snowmelt infiltration affects temperature of the frozen soil and soil water content. The frozen soil impedes the snowmelt infiltration. Therefore, soil water movement, freezing process, and heat transfer are highly interrelated.

Physical processes of the soil thawing–freezing are closely related to water and heat movements. According to the experimental study by Mao et al. (2003), during the freezing period, as soil water from the deep layer moved upward to a freezing front at shallow layer, soil water was accumulated to the highest at the freezing front with the depth of 4 cm. Meanwhile, this upward moving reduced deep soil water to the lowest at the depth of 8 cm. Experiment results by Guo et al. (2002) showed water content at the shallow depth of 1 m could be increased to 36.2–37.9 mm during the freezing period. Iwata et al. (2011) found that the soil covered by a shallow snow usually produced a thin frozen zone (<0.14 m). This thin frozen soil was easily thawed and produced a substantial amount of snowmelt infiltration. However, a thick frozen layer (>0.4 m) impeded snowmelt infiltration.

The basic processes involved in soil freezing were studied in the late 1960s. Based on the field experiment, Dirksen (1964) and Hoekstra (1966) found that when the soil temperature was below a freezing point, water in the unfrozen zone moved toward the frozen zone and then was frozen. Harlan (1971, 1973) firstly developed a coupled model for analyzing water and heat movements in a hypothetical soil, but he did not verify this model with experimental data (Kung and Steenhuis, 1986). Jame and Norum (1980) validated Harlan's mathematical model using field experiment data on the basis of empirical function in Jame's model (Jame and Norum, 1980) to describe relationship between unfrozen soil water content and. temperature. Additionally, the Harlan's model and Jame's model were based on viscous flow of liquid water in porous media and the heat balance in soil. They cannot describe the divergence induced by ice lenses. To overcome limitations in description of water flux for a partly frozen soil in Harlan's model, Kung and Steenhuis (1986) derived a computer model to simulate water and heat movements in soil based on theory of irreversible thermodynamics. The model adopted the finite difference method to

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obtain a numerical solution. This model is more accurate in predicting heat and moisture movements without frost heaving and frost boiling (Wang et al., 2011).

Additionally, as an upper boundary condition of soil water, snow cover offers energy and water input into soil and plays an important role in description of the depth and permeability of freezing soil. According to net radiation, latent heat, sensible heat and heat transfers during precipitation and variations of heat storage in snow cover, Anderson (1976) developed a snow cover energy-mass balance model (SNOW-17) to analyze infiltration due to snowmelt and due to thickening and densification as the snow cover increased. Combining with SNOW-17, Fu et al. (2011) developed a snow covered soil water model for simulation of water content and temperature of a soil profile at a dry farming field in Heilongjiang province of northeast China.

Another development of the models in description of freezing and thawing processes in cold region is to incorporate available hydrological models with land surface processes. These models include SiB (Xue et al., 1991), BATS (Dickinson et al., 1993), SHAW (Flerchinger and Saxton, 1989a, 1989b; Flerchinger et al., 1998) and VIC (Liang et al., 1994). As an improved version of SiB model, SSIB focuses on water and heat transfers and liquid and solid phase variations of the frozen soil on the assumption that freezing and thawing processes merely occur at 0 °C (Xue et al., 1991). For BATS, the freezing and thawing processes occur in a few degree intervals (−4–0 °C) (Dickinson et al., 1993). Used for the Project for Inter-comparison of Land-surface Parameterization Schemes (PILPS), SHAW describes effects of soil freezing and thawing processes in one-dimensional model under different surface configurations (Flerchinger and Saxton, 1989a, 1989b; Flerchinger et al., 1998).

The seasonally frozen region in China occupies an area of 5.137×10^6 km^2, according for 50% of the total area of China. Cold regions, including seasonally frozen and permafrost regions, cover approximately 75% area of China (Xu and Deng, 1991). Soil water variation is closely related to changes in precipitation, evaporation and soil freezing (Yan et al., 2007; Yang et al., 2003). A large part of the northern China, especially the Three-River Source Region (hereafter TRSR), is fragile in ecosystem. Climate change and human activities have resulted in decrease of the grassland in some regions (Qian et al., 2010). Since hydrology played an important role in ecosystem of TRSR, changes in the interrelated water and heat transfers within snow and soil would affect ecosystem structure and function.

From the eastern to the western of TRSR, annual mean soil temperature increased gradually. This increase was especially significant in summer (Wu et al., 2009). Affected by air temperature rise, soil temperatures at most observation stations increased significantly. Meanwhile, soil water storage was reduced about 3 mm in the depth of 0–50 cm below ground surface during 1989–2005 (Yan et al., 2007). Large variations of soil water storage between the freezing and the thawing periods were found.

In this study, one-dimensional numerical model coupling water-heat processes of soil and snow cover was developed. This model is able to describe dynamic processes of water loss due to evaporation from soil layers or sublimation from snow cover. The model includes functions of heat and vapor fluxes from the atmosphere used as the upper boundary condition of the snow covered soil. The model is used to simulate influences of precipitation and air temperature variations on the freezing and thawing processes of active soil, which rely on snow cover depth, soil temperature, evaporation, water content and freezing depth of active soil at two sites in TRSR. In comparison of the simulated results at two sites with different snow cover thicknesses, isolation effect by snow cover on the soil freezing and thawing processes was revealed.

2. Site description and data

The Three-River Source Region (TRSR) is located in west of China (31.39°–36.12° N latitude, 89.45°–102.23° E longitude in Fig. 1) and it has an area of 3×10^{-5} km^2. Ground elevation ranges from 3500 to 4800 m. As the only permafrost region in the mid-latitude, TRSR is more sensitive to climatic warming than the arctic region (Wang et al., 2009; Zhang et al., 2003; Zhou et al., 2000). Climate in TRSR is mainly controlled by high altitude air current of west wind and Mongolia high pressure. The typical of plateau continental climate in TRSR includes strong radiation, long sunshine duration and seasonal variations just in warm and cold, and wet and dry alternations. About 75% of the total precipitation occurred from June to September in TRSR. Because of the frozen soil, water retention capacity by soil during rainfall and snow melting periods in TRSR is larger than that in non-frozen or temperate regions. The dynamic changes of the frozen soil greatly influence hydrological processes.

Two sites of Henan (34.73°N, 101.60° E) and Xinghai (35.58° N, 99.98°E), located in the east and the north east of TRSR, respectively, were selected for this study. The elevations of Henan and Xinghai are 3500 and 3323 m, respectively (Fig. 1). In the years of 2005 and 2006, mean annual precipitation was 378 mm and 472 mm and mean annual air temperature was 18.5 °C and 3.6 °C at Xinghai and Henan, respectively. The two year mean precipitation was larger than the mean annual precipitation from 1970 to 2000 (278 mm and 443 mm at Xinghai and Henan, respectively) and the two year mean temperature was much higher than the mean annual air temperature from 1970 to 2000 (8.6 °C and −0.6 °C at Xinghai and Henan, respectively). The average air temperature in winter from December 2005 to February 2006 was −8.3 and −9.1 °C at Xinghai and Henan, respectively, which was higher than that from 1970 to 2000 (−9.88 and −10.75 °C at Xinghai and Henan, respectively). Generally, the mean air temperature and land surface temperature at Henan station were lower than those at Xinghai station. The annual mean wind speed was 2.2 and 2.04 m/s, with a maximum of 7.3 and 6.7 m/s at Xinghai and Henan, respectively. The relative humidity was between 10% and 88% at both stations.

The soil depths in the two study sites are larger than 3.2 m (Wu et al., 2009; Zhang and Wu, 2012). According to the observation data at Xinghai station during 2005–2006, soil freezing started as the soil temperature was consecutively negative in winter. The freezing depth of active soil layer reached the largest of 1.3 m in March. The land surface temperature and air temperature reached the highest in the middle of July, about a half month later than the longest sunshine hours (13.4 h) in late June.

The observed atmospheric data for this study includes hourly precipitation, air temperature, relative humidity, wind velocity, sunshine hours and atmospheric pressure. Daily snow thickness and soil freezing depths are available. Soil temperatures at the land surface and at the depths of 5, 10, 15 and 20 cm below ground surface were monitored from January 2005 to December 2006. The soil water contents at the depths of 10, 20, 30, 40 and 50 cm were measured by time-domain reflectometry (TDR) in a time interval of 8 days. The soil water contents measured by TDR probes refer to volumetric liquid water content when soil is thawed and volumetric unfrozen water content when soil is frozen.

3. Methods

3.1. Snow cover model

3.1.1. Energy balance equations for snow cover

The snowpack exchanges energy with atmosphere and underlain soil. The net energy flux of the snowpack can be expressed as

$$Q_{net} = Q_r + Q_s + Q_p + Q_g + Q_l \tag{1}$$

where Q_{net} is net input energy for snowpack (J/m^2), Q_r is net radiation flux (W/m^2), Q_s is flux of sensible heat (W/m^2), Q_p is heat flux supplied by precipitation (W/m^2), Q_g is ground surface heat flux (W/m^2) and Q_l