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The functions of soil water and heat transfer to the environment and associated response mechanisms under different snow cover conditions

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ABSTRACT

This study investigates the response mechanisms between soil water-heat transfer and environmental factors during freeze-thaw periods and establishes soil water-heat transfer functions in a cold region. Based on field-measured values of soil temperature and liquid-phase water content collected at an automatic weather station in the black soil area of the Songnen plain, the influence of the cumulative negative temperature on the soil freezing depth was analyzed under different snow cover conditions. A gray correlation analysis method was used to screen the environmental factors and determine those with the most influence on changes in soil water-heat transfer processes. Then, soil water-heat transfer functions were established between the selected environmental factors and soil temperature, the liquid-phase soil water content. The results showed that during the freezing and thawing period, snow cover hindered the effects of the cumulative temperature on the thickness of the frozen soil layer. Additionally, the time of occurrence of the maximum freezing depth under natural snow (NS), compacted snow (CS) and thickened snow (TS) treatments was delayed 7, 12 and 20 days, respectively, compared with that under bare land (BL). The correlation between atmospheric temperature, total radiation and soil temperature was relatively high, and this effect decreased with the increasing of snow cover. The main driving factors of variations in the liquid-phase water content were ambient humidity and saturated vapor pressure, and the effects of these factors decreased with increasing soil depth and snow cover thickness, similarly. In the active frozen layer, the correlation coefficients of the soil water-heat transfer functions were relatively high, and the function model can be tested by the significance ($P < 0.05$) test. However, the R^2 values of functions below the active layer were relatively low, and the soil water-heat transfer in the area below the active layer was less affected by the environment. This study reveals the characteristics of energy transfer and mass transfer in a composite system of atmospheric factors and frozen soil under snow cover conditions. It provides a reference for accurate forecasting and the efficient utilization of soil water and heat resources in cold and arid regions.

1. Introduction

The northern part of China is mainly characterized by seasonally frozen soil. This region accounts for approximately 54% of the land area in China, and the majority of the region is composed of arid and semi-arid areas that experience serious water resource shortages (Cheng, 1991). The dynamic processes and mechanisms of water and heat transport in the surface portions of seasonally frozen soils play important roles in land surface processes (Yang et al., 2007; Qiu et al., 2007; Zhao et al., 2010). Many studies have focused on the soil-cover-atmosphere system as a combination and performed simulations of coupled atmospheric and surface water-heat processes (Kang et al., 2008; Comola et al., 2015). The variations in soil moisture and heat reflect soil drought, waterlogging and soil energy storage. These processes involve important energy transfer and transformation in nature (Wang, 2015; Guglielmin et al., 2008a, 2008b). Additionally, the vegetation cover of frozen soil influences the temperature variations and liquid water content (Chen et al., 2013). In the process of soil freezing and thawing, a strong coupling has been observed between the atmospheric environment and the water and heat in the soil. Notably, atmospheric changes led to changes in the water and heat states of the soil, structural reorganization and solute transport in the soil (Liu et al., 2015).

Previous studies of the effects of regional climate on freeze-thaw cycles on soils have confirmed that differences in environmental factors (temperature, precipitation, water vapor pressure, atmospheric radiation, etc.) will affect the water and heat contents of the active layer of the soil both temporally and spatially, thus affecting the stability of terrestrial ecosystems. With the continuous development of global warming, significant changes are likely to occur in the active layer.

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These changes may affect surface runoff, soil moisture content, surface evapotranspiration, plant growth cycles, soil and subsurface stability, etc. (Anisimov et al., 1997). The relationship between the hydrothermal activity and vegetation in permafrost is a significant indicator of climate change. Notably, permafrost and hydrothermal changes affect the development of vegetation, and the vegetation also affect the water and heat transfer in frozen soils (Guglielmin et al., 2008a, 2008b). In the context of global climate change, the freezing process of soil in seasonally frozen soils showed a tendency of degeneration, and the freezing depth in the soil decreased by 34 cm over 60 years (Frauenfeld et al., 2004). Additionally, climate warming has an important effect on the evolution of permafrost, soil heat transfer and freeze-thaw processes. Driven by environmental changes, areas of frozen soil gradually migrated northward (Halsey et al., 1995). Soil freezing is strongly influenced by air temperature and snow insulation in winter, and the active layer depth decreases as the mean air temperature increases. Based on the results of a linear regression model, Henry (2008) found changes in the atmospheric environment due to climate change had a major impact on the dynamics of the soil freezing process. Additionally, the environmental temperature and precipitation affect soil temperature during the freeze and thaw cycle, and temperature warming reduces the thickness of snow cover, which decreases average soil temperature in winter (Brooks et al., 1998). Sharratt (1993) and Isard and Schaetzl (1998) noted that due to climate warming, the global snow-covered area will decrease, which will make the soil more prone to environmental temperature fluctuations. Additionally, climate warming and atmospheric drying will likely increase the frequency of the freeze and thaw cycles in the soil.

Based on the analysis of the relationship between soil water-heat variation and environmental factors, some scholars established the model of soil water-heat migration under the influence of meteorological factors, and realized the water-heat dynamic simulation and prediction of freeze-thaw soils. Bonnaventure et al. (2012) identified the environmental factors associated with soil freezing characteristics; established local models using digital elevation model (DEM) data, solar radiation data and other climatic data; and modeled the distribution probability of alpine permafrost. Less snow in winter will reduce snowmelt in spring, and the corresponding soil moisture will decrease. Thus, the dry soil conditions will cause the surface layer to respond to changes in the ambient temperature more rapidly, i.e., less latent heat will be consumed in the spring of the following year in the soil, resulting in a higher soil surface temperature. Flerchinger et al. (1996) used the SHAW (Simultaneous heat and water) model to simulate the freezing depths, snow layer characteristics and soil temperatures of pastures under different climatic conditions in the United States, and the error between the simulated and measured values was low. Additionally, the sensitivity of the model output to the input parameters was analyzed. Based on atmospheric temperature, ground temperature, rainfall and frost depth data collected at 50 meteorological stations on the Qinghai-Tibetan Plateau over the past 30 years, Zhao et al. (2000) analyzed the changes in air temperature and seasonally frozen soil. They found that the surface temperature during the cold season was the main factor that controlled changes in seasonally frozen soil. Based on maximum freezing depth and soil thawing data collected at 17 sites in Tibet from 1961 to 2010, the climatic propensity rate and the R/S method, Du et al. (2012) analyzed the annual variation in permafrost near 50A on the Qinghai-Tibet Plateau. The results showed that the maximum permafrost depth at most sites in Tibet significantly decreased. Fu et al. (2015) used the gray correlation analysis method to determine the environmental factors that contribute to the soil temperature and confirmed that snow cover hinders the transmission of energy between the atmosphere and the soil. Chen and Sun (2004) considered snow cover, the atmospheric system, soil water and heat transfer, and physical changes in the boundary layer to establish a process model that reflected the energy exchange and transport mechanisms between the soil and the atmosphere. Tang et al. (2012a, 2012b) used long-term observation data from the Environmental Information System (ENVIS) and found that the main controlling factors of soil moisture during the seasonal freezing and thawing process were temperature and relative air humidity. Additionally, the main controlling factors of soil temperature were ambient temperature, saturated vapor pressure and upward net radiation.

In addition, vegetation cover has an important influence on soil freezing and thawing and dynamic changes in soil water and heat. Notably, land cover not only inhibits the loss of soil heat, reduces water evaporation, and increases soil moisture but also improves soil fertility, soil nutrient, salt contents and balances. Flerchinger et al. (1996) tested the effects of different mulch and vegetation types on the soil temperature and water content and found that due to energy accumulation and water retention, surface cover hindered the energy exchange between soil and the environment and decreased the loss of heat at low temperatures. Iwata et al. (2010) noted that snow cover hinders the transmission of energy between the atmosphere and soil, slows the loss of soil heat, and cuts off atmospheric radiation, i.e., the soil energy supply. Additionally, the thickness of the snow layer influenced the growth and depth of the frozen front and controlled the flux of water below the frozen layer. Granberg et al. (1999) used meteorological, precipitation and temperature data as driving variables to simulate the redistribution of soil water and heat and showed that winter snow cover can reduce the freezing depth of the soil. Huang et al. (1993) measured and quantitatively analyzed soil moisture, temperature and salinity in permafrost and found that the regulation effect of film mulching on soil moisture and fertilizer was more obvious compared to those in plastic film mulching, tillage, and other treatments. Li et al. (2010) found that under the influences of vegetation transpiration, surface evapotranspiration and soil temperature gradient, water migrated to the top and bottom of the profile during the melting period. During freezing and thawing periods, soils were treated with different thicknesses of straw mulching, which provided heat preservation effects and altered the freezing condition of the soil (Xing et al., 2012). Additionally, as the thickness of the straw mulching increased, the surface water volatility decreased.

This study focuses on the black soil area of the Songnen Plain and analyzes the relationships between soil water-heat transfer and environmental factors during the freezing-thawing period. Additionally, the mechanisms of snow cover that hinder interactions between the atmosphere and soil systems were identified, and transfer functions between the atmosphere and soil were established under different snow treatments. This study not only provides basic data associated with water and heat transfer but also improves upon previous studies of hydrothermal migration. In addition, the research has practical significance for estimating the soil moisture content during the snowmelt period.

2. Materials and methods

2.1. Study area

The experimental area is located in Harbin City, Heilongjiang Province, in the Northeast Agricultural University comprehensive test field. The geographical location of the study area is 45°44′N, 126°43′E. The area is characterized by flat terrain with numerous rivers and large plain areas, as shown in Fig. 1. The average elevation of the region is 138 m. The region has a temperate continental monsoon climate characterized by high temperatures and precipitation in summer and limited rain in winter. The annual average temperature is 3.8 °C/d, and seasonal temperature variations are obvious, including cold winters and windy springs, which can lead to drought conditions and large temperature fluctuations. The highest annual temperature (38 °C) occurs in August, and summer precipitation accounts for > 65% of annual precipitation. The lowest annual temperature (−38.1 °C) occurs in January. The soil freezes in mid-November and begins to thaw gradually in