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Development of an urban canopy model for the evaluation of urban thermal climate with snow cover in severe cold regions

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A B S T R A C T

Snow plays an important role in determining heat and moisture exchanges between the underlying surface and atmosphere in winter. However, the effect of snow cover is not considered or assumed to be negligible in existing urban canopy energy balance models. In this paper, a one-dimensional snow model that accounts for heat transfer within snow cover is developed, and the model is implemented into an urban canopy energy balance model to simulate energy and moisture exchanges in cold urban areas with stable snow cover. The numerical methods of the snow model and the urban canopy model are demonstrated first, and the urban canopy model is subsequently used to simulate the thermal climate of a residential area dynamically in Yichun, China during winter. The results indicate that the existence of snow cover decreases the outdoor air temperature by 0.15 °C on average and 1.16 °C at maximum. In addition, the outdoor mean SET* increases 0.43 °C with the removal of snow cover, indicating that the thermal comfort of people outside decreases due to the presence of snow cover.

1. Introduction

With rapid economic growth, there is a growing number of population shifts from rural to urban areas. In the past several decades, the urbanization process has undergone a notable development in China, with the level of urbanization increasing from 17.9% in 1978 to 51.27% in 2011, representing an average annual growth rate of 1.02% [1]. Many studies have shown that the process of urbanization has negative impacts on energy consumption, local thermal conditions, and air quality in urban areas [2–6]. The incidence of and concern about Urban Heat Island (UHI) and haze phenomena have increased in recent years. To create a better urban microclimate, it is necessary to analyze how urban morphology and underlying surface schemes influence the urban microclimate.

Many studies have been conducted to investigate the urban thermal climate; for example, the formation of UHI has been reported in different climatic regions worldwide, e.g., Padua [7], Columbus [8], Delhi [9], Beijing [10], London [11], Moscow [12]. These studies show that the urban thermal climate is strongly influenced by local meteorological conditions, land cover pattern and resident activities. In contrast to the situation in summer, during the winter in cold regions, solar radiation decreases dramatically, and the albedo of the ground changes due to the snow covering the urban underlying surface. In addition, the UHI mitigation strategies that are beneficial in summer may have a detrimental effect in winter. For example, cool roof technologies have been proved as effective strategies to mitigate UHI and optimize indoor thermal performance in summer, while the increasing of roof's albedo also brings slight winter penalties [13–18]. Besides, McPherson stated that high-branching shade trees can promote both shade and wind in summer, while in winter, the shading effect reduces solar radiation access to walls; thus, evergreen trees are not suitable for green roofs in cold climates [19]. Therefore, urban thermal climate and climatic-responsive strategies in winter are quite different from those in summer. To date, studies on the urban thermal climate of severe cold regions in winter are still scarce. Although there has been some research on UHI [9,12,20], thermal comfort [21–23] and energy conservation [24,25] in winter, these studies have mainly based on field experiment data. Due to the limitations of field measurement, experimental conditions, such as meteorological data and land patterns, are uncontrollable during the measurement period, and detailed information is difficult to obtain. In addition,

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the majority of study objects of these studies are single or several buildings rather than an urban area.

In winter, snow plays an important role in determining heat and moisture exchanges between the land surface and the atmosphere. Walsh et al. [26] found that snow cover accounts for approximately 10%–20% of the variation in monthly temperature throughout the United States. Mote's [27] work demonstrated that snow cover can result in daily temperature decreases throughout central North America. Compared to low-latitude cities, the urban thermal climate of cities in severe cold regions have different properties in winter due to the presence of stable snow cover and unique characteristics of climatic features, urban morphology and underlying surface schemes. Existing studies of snow in urban areas are mainly focused on two aspects: 1) predicting the development of wind-driven snowdrift and partial snow distribution around buildings using computational fluid dynamics (CFD) methods [28–32]; 2) examining the surface energy budget during the snow-cover period by continuous measurements using the eddy covariance technique, which are mostly conducted in Montreal, Canada [33–35]. In addition, using the Montreal Urban Snow Experiment 2005 database, Lemonsu et al. [36,37] examined the ability of the Town Energy Balance (TEB, [38]) canopy model's performance under snowy conditions. With the exception of the TEB model, the effect of snow cover on urban thermal climates is rarely taken into account in urban canopy models. Grimmond et al. [39,40] evaluated and compared the methods and performance of a broad range of urban energy balance models, and the effect of snow cover is not considered or assumed as negligible in these models, indicating that these urban energy balance models are not suitable for the study of urban thermal climate in severe cold regions with snow cover.

In this paper, a one-dimensional snow model that accounts for heat transfer within snow cover is developed, and the model is implemented into an urban canopy energy balance model (called UDC) to simulate energy and moisture exchanges in cold urban areas with stable snow cover. Field measurements were collected to validate the snow model. In addition, the thermal climate of a residential area in Yichun, China, was dynamically simulated and evaluated using the revised UDC model. The objective here is to investigate the impact of snow cover on the local thermal climate. The results show that the existence of snow cover leads to a depression of the outdoor air temperature. Furthermore, the thermal comfort for people outside has deteriorated due to the presence of snow cover.

2. Model development and validation of heat exchange in snow

Heat exchange in snow is simulated using a one-dimensional snow model that is based on energy balance. The snow model is designed to calculate the temperature within the snow cover and the energy exchange between the snow cover, soil and atmosphere. The framework of the model is briefly introduced below. Field measurements were carried out to validate the accuracy of the snow model, which are explained in more detail in Section 4.

2.1. The constitution of snow cover

Wei et al. [41] reported that there are two types of snow cover in China: dry-cold snow cover and humid-warm snow cover. In northeast China, under continental climatic conditions, the winter is long, dry and severely cold. The snow cover in northeast China shows characteristics of dry-cold snow cover: low water content, small density, large temperature gradient, etc. In this study, the snow cover is considered dry-cold and stable with no snow melt during the study period, meaning that the snow is mostly composed of ice and air and that the volumetric water content can be regarded as 0. Thus, the snow volume V_s (m^3/m^2) is composed of two parts: ice volume V_i (m^3/m^2) and air volume V_a (m^3/m^2):

$$V_s = V_i + V_a \tag{1}$$

The volumetric fraction of ice, θ_i, and the volumetric fraction of air, θ_a, can be calculated as

$$\theta_i = \frac{V_i}{V_s}, \theta_a = \frac{V_a}{V_s} \tag{2}$$

By definition, the volumetric fraction is between 0 and 1, and the following relationship should be rigidly enforced

$$\theta_i + \theta_a = 1 \tag{3}$$

Compared to the ice density ρ_i (kg/m^3), the air density can be neglected. Therefore, the density of snow cover, ρ_s (kg/m^3), can be expressed by

$$\rho_s = \rho_i \theta_i \tag{4}$$

2.2. Numerical method of the snow model

The heat exchanges between the snow cover, soil and atmosphere, including radiation, heat transfer and sublimation, are considered. A schematic diagram of heat transfer within the snow cover and soil in the snow model is shown in Fig. 1.

Snow cover is divided into several layers along the vertical direction. The temperature of the snow layer is represented by the intermediate snow temperature of each layer, while the density of every layer is uniform. The heat balance equations of the snow model are calculated as follows:

Top layer:

$$\frac{\partial}{\partial t}\{c_{v,s,l}\Delta Z_s T_{s,l}\} = C_{s,l+1} + R_{ns,l} + R_{nl} + H_s - lE_s \tag{5}$$

Inner layers:

$$\frac{\partial}{\partial t}\{c_{vs,l}\Delta Z_s T_{s,l}\} = -C_{s,l-1} + C_{s,l+1} + R_{ns,l} \tag{6}$$

Bottom layer:

$$\frac{\partial}{\partial t}\{c_{vs,l}\Delta Z_s T_{s,l}\} = -C_{s,l-1} + C_{sx} + R_{ns,l} \tag{7}$$

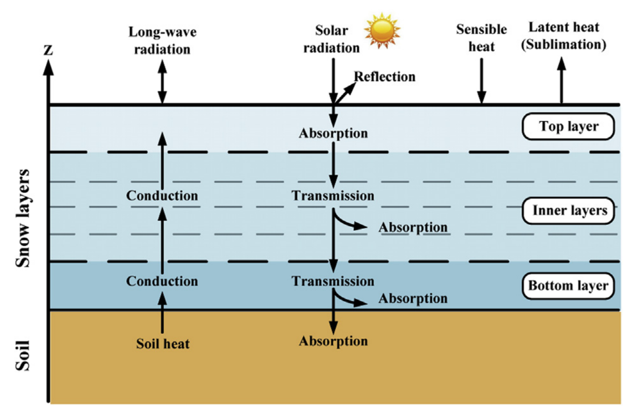

Fig. 1. Schematic diagram of heat transfer in the snow model.