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Numerical study on urban wind environment and thermal climate of cities in cold region with snow cover

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1. Introduction

Over the past several decades of rapid economic growth, the urbanization process has a rapid development in China, with the level of urbanization rising from 17.9% in 1978 to 51.27% in 2011, an average annual growth rate of 1.02%. However, many studies have shown that the process of urbanization has negative impacts on energy consumption, thermal environmental conditions, and air quality in urban areas [1-4]. Therefore, in order to create a better microclimate, it is necessary to analyze the factors that affect urban microclimate.

Considerable studies have been conducted to investigate the urban wind environment and thermal climate, especially urban heat island effect in summer [5-7], but there is still a lack of study on urban thermal climate of cold areas in winter with stable snow covered on land surfaces. Compared to cities in other regions, urban microclimate of cities in cold region have different properties due to the unique characteristics of climatic features, building configuration and underlying surface composition.

The main purpose of this study is to investigate the impact of snow cover and building configuration on local wind environment and thermal climate. A one-dimensional snow model was modelled based on energy balance to calculate the heat transfer within the snow cover. In addition, the snow model was added into an urban canopy energy balance model to simulate energy and moisture exchanges in cold urban areas with stable snow cover. Factors including the snow cover, floor area ratio of building and building height are considered and dynamic simulations were conducted to analyze the wind environment and thermal climate of a residential area in Yichun, China. The results not only show the influence of the snow cover and building configuration on local microclimate, but also provide a guide on planning and management of cities.

2. Model development and validation of snow model

Based on energy balance, a one-dimensional snow cover heat transfer calculation model was established to calculate the temperature within the snow cover. In order to simplify the calculation, the model was divided into single-layer snow model (SLSM) and multi-layer snow model (MLSM). In this study, the snow cover is considered dry and stable with no snow melt during the study period. The framework of the model is briefly introduced below. Field measurements were conducted to validate the accuracy of the snow model.

2.1 Single layer energy budget model (SLSM)

Based on Fujimoto's work [8], the vertical heat transfer in the snow layer can be ignored when the thickness of snow $Z_s \leq 0.02$ m. Thus the snow cover is considered as a single layer in order to simply the calculation. The heat exchanges between the snow cover, soil and atmosphere, including radiation, heat transfer and sublimation, are taken into account. Heat balance of single snow layer is given by

$$\frac{\partial}{\partial t}\left\{(\rho c_p)_s Z_s T_s\right\} = C_{sx} + R_{ns} + R_{nl} + S_a - L_e \tag{1}$$

where $(\rho c_p)_s$ is the snow volume heat capacity (J/(m3•K)); T_s is the temperature of snow (K); R_{ns} is the net solar radiation heat flux (W/m^2); R_{nl} is the net long wave radiation heat flux (W/m^2); S_a is the sensible heat flux (W/m^2); L_e is the latent heat of sublimation (W/m^2).

2.2 Multi-layer energy budget model (MLSM)

Experimental results show that when the thickness of snow $Z_s > 0.02$ m, internal heat transfer between snow layers must be considered. Thus, under this case, snow cover is divided into several layers along vertical direction. The temperature of snow layer is represented by intermediate snow temperature of each layer, while the density in every layer is uniform. Heat balance equations of MLSM are calculated as follows:

Top layer:

$$\frac{\partial}{\partial t}\left\{(\rho c_p)_s \Delta Z_s T_{s,i}\right\} = C_{s,i+1} + R_{ns,i} + R_{nl} + S_a - L_e \quad (2)$$

Inner layer:

$$\frac{\partial}{\partial t}\left\{(\rho c_p)_s \Delta Z_s T_{s,i}\right\} = -C_{s,i-1} + C_{s,i+1} + R_{ns,i} \quad (3)$$

Bottom layer:

$$\frac{\partial}{\partial t}\left\{(\rho c_p)_s \Delta Z_s T_{s,i}\right\} = -C_{s,i-1} + C_{sx} + R_{ns,i} \quad (4)$$

where ΔZ_s is the thickness of each layer (m); $T_{s,i}$ is the temperature of each layer (K); $C_{s,i-1}$, $C_{s,i+1}$ is the heat flux caused by the upper and lower layers temperature difference (W/m^2), respectively, , $R_{ns,i}$ is the solar radiation absorbed by each layer (W/m^2).

2.3 Model validation

Field measurements were carried out in a certain campus in Harbin (45°45'N, 126°40'E) to validate the accuracy of snow models. A series of measurements were performed in natural ground with 2cm snow cover for SLSM and 18.5cm snow cover for MLSM. A comparison between the measured and simulated snow temperature are shown in Fig. 1. It can be seen that the calculated results are generally in good agreement with the experimental data. Although there exists some discrepancies, but the deviation is acceptable. Further information about the snow models and field measurements can be found in Zhang [9].

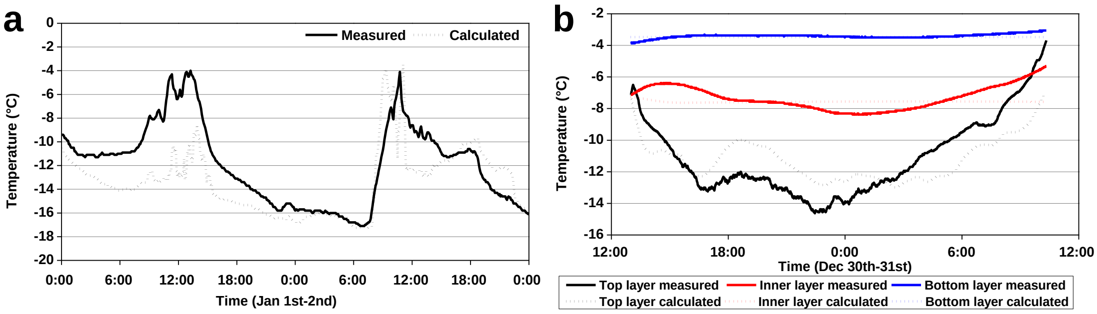

Fig. 1. Comparison of calculated and measured results for snow temperature: (a) SLSM; (b) MLSM.

3. Urban canopy energy balance model

The urban canopy energy balance model was developed to dynamically study urban thermal climate and local heat island intensity's change. The model includes the following sub-models: urban layout sub-model, local climate sub-model, building heat and moisture load sub-model, urban underlying surface heat and mass transfer sub-model, solar radiation sub-model and thermal comfort sub-model. These sub-models are coupled dynamically. The framework of this model and sub-models related to this study are briefly presented below. The one-dimensional snow model that is developed in this study is implemented into the urban canopy model as a sub-model. The framework diagram of the revised UDC model is presented in Fig. 2.More detailed information of this model can be found in Zhu [10].

4. Numerical set-up

In this study, wind environment and thermal climate of a residential area located in Yichun (45.77°N, 126.77°E) was investigated by the revised urban canopy energy balance model. All of the buildings in the residential area are slab-type with the same specification. In this study, these buildings were simplified to identical cuboids with a bottom area of 676 m2. The height of each layer was set to 3m. Except for building coverage, the underlying surface is made up of asphalt pavement and soil, whose area is 1:1.5. The hourly data of a typical meteorological month of Yichun in winter was used as input data.

The impact of snow cover and building configuration on local wind environment and thermal climate was investigated in this study. The factors considered in this study include: (1) whether snow cover exists, (2) floor area ratio of building, (3) building height. Besides, the study area without buildings was also calculated as a reference case. The values of each factor chosen in 17 cases are summarized in Table 1.

5. Results and discussion

5.1 Snow cover

In order to study the impact of snow cover on local thermal climate, simulations of were carried out for the residential area with or without snow covered on underlying surfaces.

Fig. 3 shows the comparison of outdoor temperature at 1.2m high between Case 1-1 and 1-2. It can be found that, when snow cover exists, the average outdoor air temperature at 1.2 m is -16.34ºC, while the average outdoor

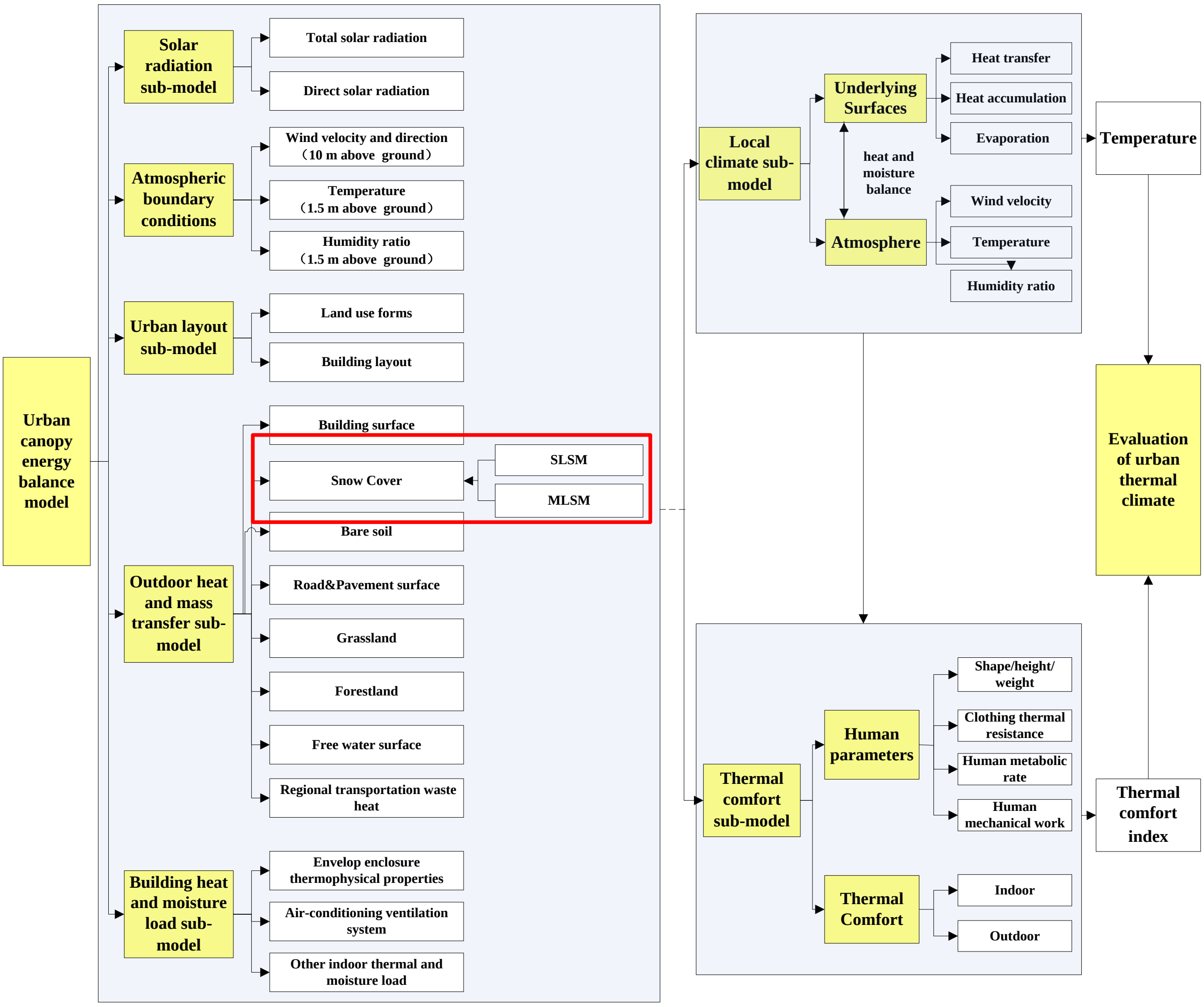

Fig.2. Framework Diagram of the urban canopy energy balance model.

Table 1. Description of cases for simulation.

	Building types	Snow cover	Floor area ratio of building	Building height (m)/ Number of floors
Ref. Case	-	Yes	-	-
Case 1-1	Multi-story	Yes	1.345	18/6
Case 1-2	Multi-story	No	1.345	18/6
Case 2-1	Multi-story	Yes	0.808	18/6
Case 2-2	Multi-story	Yes	0.943	18/6
Case 2-3	Multi-story	Yes	1.116	18/6
Case 2-4	Multi-story	Yes	1.345	18/6
Case 2-5	Multi-story	Yes	1.658	18/6
Case 3-1	High-rise	Yes	2.047	33/11
Case 3-2	High-rise	Yes	3.163	33/11
Case 3-3	High-rise	Yes	4.093	33/11
Case 3-4	High-rise	Yes	5.023	33/11
Case 3-5	High-rise	Yes	5.953	33/11
Case 4-1	High-rise	Yes	4	33/11
Case 4-2	High-rise	Yes	4	51/17
Case 4-3	High-rise	Yes	4	66/22
Case 4-4	High-rise	Yes	4	81/27

air temperature is -16.19ºC with no snow cover. The snow cover decreased the 1.2 m air temperature by 0.15 ºC on average and 1.16ºC at the maximum. It can be considered that the increased outgoing shortwave radiation due to the higher albedo of the snow-covered surface mainly accounted for the temperature decrease.

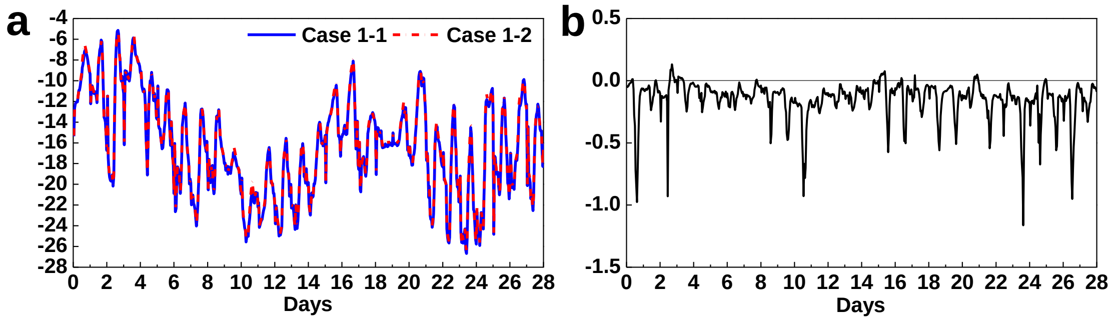

Fig. 3. Comparison of outdoor temperature (ºC): (a) outdoor temperature at 1.2m high of Case 1-1 and 1-2; (b) temperature difference at 1.2m high between Case 1-1 and 1-2.

5.2 Floor area ratio of building

Fig. 4 shows the variation of average wind velocity ratio and average temperature rise with different floor area ratio of building, including multi-story building with 6-story and high-rise building with 11-story are considered. The average wind velocity ratio $R_{u,i}$ is defined by

$$R_{u,i} = U_i / U \quad (5)$$

where U_i is wind velocity at pedestrian height level calculated in different case; U_R is the wind velocity at pedestrian height level calculated in the reference case.

It can be seen that, due to the blocking of buildings, the entire outdoor wind velocity calculated in Case 2 and 3 is less than the wind velocity in the reference case. In addition, the wind velocity has a significant attenuation with the increase of the floor area ratio of building: the average wind velocity ratio decreases from 0.8 to 0.47 as the floor area ratio of building of multi-story buildings increases from 0.8 to 1.65, while the average wind velocity ratio decreases from 0.45 to 0.22 as the floor area ratio of building of high-rise buildings increases from 2.0 to 6.0. When the floor area ratio of building is low, the variation of floor area ratio of building has a strong impact on wind velocity and the attenuation rate of average wind speed ratio is approximate to linear. However, when the floor area ratio of building is large, the influence of floor area ratio of building's variation on wind velocity decreases significantly.

The average temperature rise $R_{t,i}$ is defined by

$$R_{t,i} = T_i - T \quad (6)$$

where T_i is temperature at pedestrian height level calculated in different case; T_R is the temperature at pedestrian height level calculated in the reference case.

As shown in Fig. 4b, the outdoor temperature increases as the floor area ratio of building increases: the temperature rise increases from -0.27 ºC to 0.56 ºC as the floor area ratio of building of multi-story buildings increases from 0.8 to 1.65, while the temperature rise increases from -0.43 °C to 1.72 °C as the floor area ratio of building of high-rise buildings increases from 2.0 to 6.0. This is due to that, with the increase of floor area ratio of building, more buildings will produce more anthropogenic heat. Besides, wind velocity has a significant attenuation with the increase of the floor area ratio of building as discussed before, thus the anthropogenic heat is more easily to accumulate within the residential area. On the other hand, solar radiation can be blocked by buildings. Due to the shading effect, less solar radiation can reach the ground level with building exists, which may explain why the outdoor temperature calculated in Case 2-1 and Case 3-1 is lower than the temperature in the reference case. However, with the increase of the floor area ratio, more anthropogenic heat is produced and released into the atmosphere, result in a significant increase of the outdoor temperature.

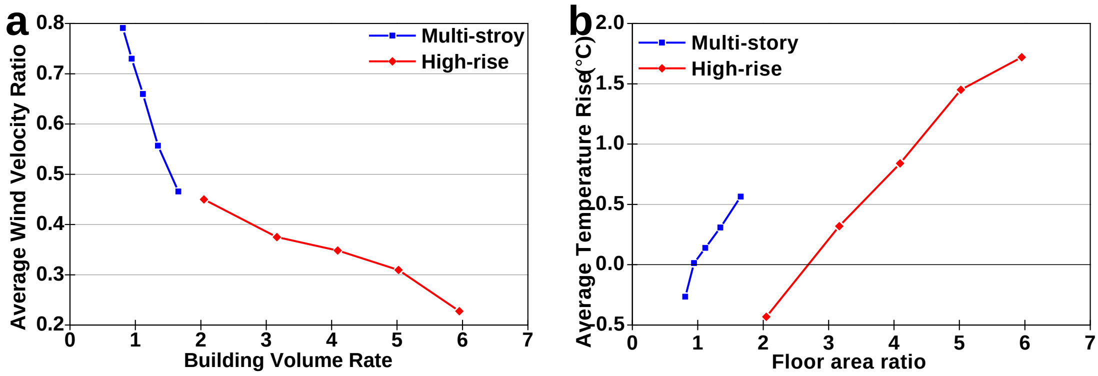

Fig. 4. Variation of (a) average wind velocity ratio and (b) average temperature rise with different floor area ratio.

5.3 Building Height

Fig. 5 shows the variation of average wind velocity ratio and average temperature rise with different building height. It can be seen that, due to the blocking of buildings, the outdoor wind velocity calculated in Case 4 is much less than the wind velocity in the reference case. With the increase of building height, the average wind velocity ratio decreases first, reaches the minimum of 0.3 when the building height is 50m, and then increases. The reason is considered as that the cross-sectional area of buildings decreases with the increases of building height when the floor area ratio of building is constant. Since the buildings are getting thinner, the blocking effect to wind is becoming weaker.

As shown in Fig. 5b, the outdoor temperature decreases obviously with the increase of building height and the entire temperature calculated in Case 4 is larger than the temperature in the reference case. Specifically, the temperature rise decreases from 1.72 ºC to 0.39 ºC as the building height increases from 33m to 81m, which suggests that in order to achieve a better outdoor environment in winter during the process of city planning, the height of the building must be strictly controlled.

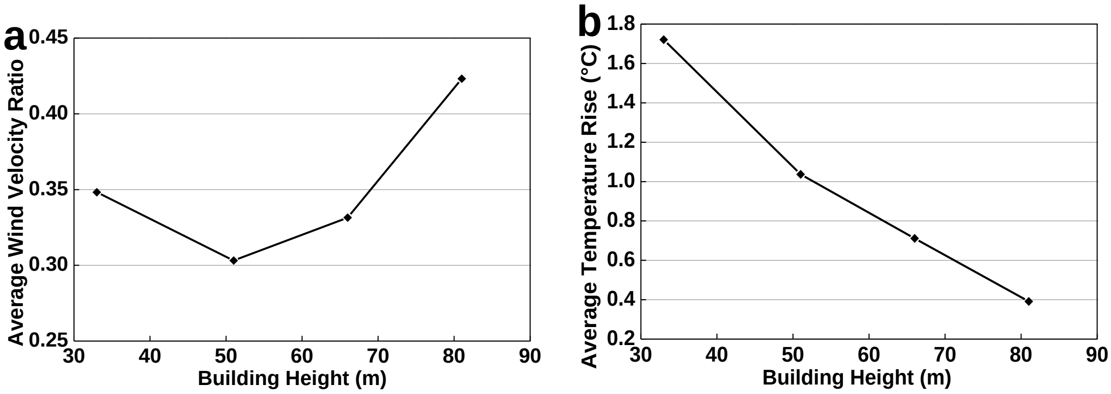

Fig. 5. Variation of (a) average wind velocity ratio and (b) average temperature rise with different building height.

6. Conclusions

A one-dimensional snow model that accounts for heat transfer within snow cover is developed and is implemented into the urban canopy energy balance model to study the effects of snow cover and building configuration on local outdoor wind environment and thermal climate. Several conclusions can be drawn as follows:

(1) The existence of snow cover leads to a depression of the outdoor air temperature.

(2) With the increase of floor area ratio of building, the outdoor wind velocity increases and the temperature decreases.

(3) With the increase of building height, the outdoor wind velocity decreases first and then increases, while the temperature decreases.

Therefore, in order to create a better microclimate, the optimal floor area ratio of building need to be chosen based on the specific planning scheme and the building height must be strictly controlled.

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