DEVELOPMENT OF THE SIMPLE MULTI-LAYER URBAN CANOPY MODELS

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Abstract

We propose four types of multi-layer urban canopy models; the Level4, Level3, Level2 and Level1 models, according to the levels of simplification for calculating the radiation and heat budget at the wall surface. Then, each canopy model is compared to the level4 model. In the comparison with the observations in Tokyo, the simulated temperatures from the four models are close to the observed ones, and the temperature differences among the four models are very small. However, additional model inter-comparison study based on idealized simulations indicates that the difference between the Level2,1 models and the Level4 model becomes larger when the sky view factor is smaller than 0.19 in summer or 0.40 in winter. On the other hand, the difference between the Level3 model and the Level4 model is very small under any sky view factor in both season. Therefore, the Level3 model can be used instead of the Level4 model in any conditions, while the Level2 and 1 models should be used under the limited conditions with a large SVF.

Keywords: Multi-layer urban canopy model, Simplification

1. INTRODUCTION

Numerical studies on the urban heat island phenomenon have been actively performed in order to investigate its formation mechanisms. Recently, several urban canopy models have been introduced (e.g. Masson 2000, Kusaka et al. 2001, Martilli et al. 2002, Kondo et al. 2005, Kanda et. al. 2005) in order to improve the representation of urban canopy characterristics in mesoscale models. Multi-layer urban canopy model (MUCM) is one of the models used to describe an urban thermal environment. This model has many merits on representing the features of the urban canopy layer, but its computational efficiency is higer than that of a single-layer urban canopy model (In particular, a three dimensional urban geometry is described in the model). When we incorporate the MUCM into a mesoscale meteorological model, the computational efficiency of MUCM should be small. It is necessary to examine how to simplify the MUCM to reduce the computational efficiency without declining its quality of performance. In this paper, we proposed some simplified multi-layer urban canopy models, in which the simplifications focus on the walls of the buildings. Additionally, we investigate the validity of the simplifications to perform the model inter-comparison.

2. MODEL DESCRIPTION

2.1 Atmospheric model

The Canopy model used in this study consists of one-dimensional diffusion equations for momentum, potential temperature, and specific humidity that is based on Kondo et al. (2005).

$$\frac{\partial u}{\partial t} = \frac{1}{m}\left(K_m m \frac{\partial u}{\partial z}\right) - cau\sqrt{u^2 + v^2} + f(v - v_g) \tag{1}$$

$$\frac{\partial v}{\partial t} = \frac{1}{m}\left(K_m m \frac{\partial v}{\partial z}\right) - cav\sqrt{u^2 + v^2} - f(u - u_g) \tag{2}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{m}\frac{\partial}{\partial z}\left(K_h m \frac{\partial \theta}{\partial z}\right) + \frac{Q_{AS}}{c_p \rho} \tag{3}$$

$$\frac{\partial q_v}{\partial t} = \frac{1}{m}\frac{\partial}{\partial z}\left(K_q m \frac{\partial q_v}{\partial z}\right) + \frac{Q_{AL}}{l \rho} \tag{4}$$

In the atmosphere, turbulent diffusion coefficients are computed using the Mellor-Yamada Level2. Here, m is the volume porosity. K_m, K_h, and K_q are the turbulent diffusion coefficient for momentum, heat, and specific humidity, respectively. Q_{AS} is the anthropogenic sensible heat, and Q_{AL} is the anthropogenic latent heat.

2.1 Urban models

Figure 1 shows a schematic diagram of our parameterization models, which consists of a three dimensional, infinitely-extended regular array of buildings with a square horizontal cross-section. The height of buildings are uniform. The Level4 model (Figure 1a) solves the heat budget equation for each layer and for each wall orientation. This model is similar to the models by Kondo(2005). The Level3 model (Figure 1b) considers each layer but does not take into account orientation. The Level2 and Level1 models (Figure 1c and Figure 1d,

respectively) do not divide the wall into many vertical layers when the heat budget at the wall surface is solved. The Level2 model considers orientation but the Level1 model does not consider this factor. Table 1 shows a number of facets in which the heat budget eqation is solved. The Level4 model needs to be solved to 4n+2 heat budget eqations (n represents the number of layers), but the Level1 model only requires 3 heat budget equations to be solved.
First, we explain the Level4 model. This model estimates the surface temperatures of the road, roof, and each level of the building's wall in four separate directions from the surface energy barance, as well as the individual fluxes from the various surfaces.

$$R_N = H + lE + G \tag{5}$$

The sensible heat flux from each surface is calculated from Jürges's formula when the surface skin temperature is higher than the air temperature. When the surface skin temperature is lower than the air temperature, the surface-layer formulae (Louis, 1979) are used to compute the sensible heat flux. The ground heat flux G and interior temperature at depth z to each surface are calculated by the one dimensional thermal conduction equation.
For the calculation of short wave radiation S_{net} on each surface, we consider direct solar radiation, diffuse solar radiation and reflected solar radiation. The reflection in the canyon is considered only once within the model.

$$S_{net}^g = (1-\alpha_g)[\{R_g I_{dg} + F_{g\to s}(S_p - I_p)\} + \sum_k \sum_j F_{g\to w_k} \alpha_w \{R_{w_j} I_{dw_j} + F_{w_k \to s}(S_p - I_p)\}] \tag{6}$$

$$\begin{aligned} S_{net\,j,k}^w = (1-\alpha_w)[\{(R_{w_{j,k}} I_{dw_{j,k}} + F_{w_k\to s}(S_p - I_p)\} + \alpha_g F_{w_k\to g}\{R_g I_{dr} + F_{g\to s}(S_p - I_p)\} \\ + \alpha_w \sum_{k'} \sum_{j'} F_{w_{j,k}\to w_{j',k'}} \{R_{w_{j',k'}} I_{dw_{j',k'}} + F_{w_{k'}\to s}(S_p - I_p)\}] \end{aligned} \tag{7}$$

$$S_{net}^r = (1-\alpha_r)\{I_{dr} + (S_p - I_p)\} \tag{8}$$

where the subscripts g, w, r, and s denote ground(road), wall, roof, and sky, respectively. I_d, I_p, and S_p are the direct solar radiation on each surface, direct solar radiation on the horizontal plane, and global solar radiation on the horizontal plane, respectively. α is albedo , F is view factor, R is sunshire rate.
The longwave radiation flux on each surface is,

$$\begin{aligned} L_{net}^g = \varepsilon_g \left[F_{g\to s} L_a + \sum_k \sum_j F_{g\to w_{j,k}} \left\{ \varepsilon_w \sigma T_{w_{j,k}}^4 + (1-\varepsilon_w)\left(F_{w_{j,k}\to s} L_a + F_{w_{j,k}\to g} \varepsilon_g \sigma T_g^4 + f(T_{w_{j',k'}}) \right) \right\} - \sigma T_g^{\,4} \right] \\ ,\quad f(T_{w_{j',k'}}) = \sum_{k'} \sum_{j'} F_{w_{j,k}\to w_{j',k'}} \varepsilon_w \sigma T_{w_{j',k'}}^4 \end{aligned} \tag{9}$$

$$\begin{aligned} L_{net_{j,k}}^w = \varepsilon_w \Bigg[F_{w_{j,k}\to s} L_a + F_{w_{j,k}\to g} \varepsilon_g \sigma T_g^4 + \sum_{k'} \sum_{j'} F_{w_{j,k}\to w_{j',k'}} \Big\{ \varepsilon_w \sigma T_{w_{j',k'}}^4 + (1-\varepsilon_w)\Big(F_{w_{j',k'}\to g} \varepsilon_g \sigma T_g^4 + F_{w_{j',k'}\to s} L_a \\ + f(T_{w_{j'',k''}}) \Big) \Big\} + (1-\varepsilon_g) F_{w_{j,k}\to g} \sum_{k'} \sum_{j'} F_{g\to w_{j',k'}} \varepsilon_w \sigma T_{w_{j',k'}}^4 - \sigma T_{w_{j,k}}^4 \Bigg] \quad , \quad f(T_{w_{j'',k''}}) = \sum_{k''} \sum_{j''} F_{w_{j',k'}\to w_{j',k'}} \varepsilon_w \sigma T_{w_{j'',k''}}^4 \end{aligned} \tag{10}$$

$$L_{net}^r = \varepsilon_r \left[L_a - \sigma T_r^{\,4} \right] \tag{11}$$

where L_a is the longwave radiation from the atmosphere, ε is emissivity, and T is the surface skin temperature.
In Level3 model, input radiations of the wall are calculated by

$$A_{w_k}^{level3} = 0.25 \sum_{j=1}^{4} A_{w_{j,k}} \tag{12}$$

where A is the input radiation. This indicates the averaged value of the four wall orientations.
In Level2 model,

$$A_{w_j}^{level2} = \sum_{k=1}^{n} w_k A_{w_{j,k}} \qquad w_k = dz_k / \sum_{k=1}^{n} dz_k \tag{13}$$

and in Level1 model,

$$A_{w_j}^{level1} = 0.25 \sum_{j=1}^{4} \sum_{k=1}^{n} w_k A_{w_{j,k}} \qquad w_k = dz_k / \sum_{k=1}^{n} dz_k \,. \tag{14}$$

For in the Level2 and 1 model, the input radiations mentioned above are given to the heat budget equation, and then the surface skin temperature is predicted. The values for wind velocity, air temperature, and specific humidity are averaged within the canopy. Next, the predicted surface skin temperature is given to all layers, and the surface fluxes (Sensible heat flux and Latent heat flux) are calculated at each layer using surface skin temperature and each layer's wind speed, temperature or specific humidity.

$$H_k = \alpha_k (T_w - T_{a_k}) \tag{15}$$

Table 1. A number of facets in which the heat budget equation is solved, CPU time, and MUCM memory usage. The CPU time and memory usage is the relative value compared with the Level4 model. Here, n indicates the number of vertical layers of the wall.

Model	Number	CPU time (n=7)	Memory (n=7)
Level4	4n+2	1	1
Level3	n+2	0.33	0.43
Level2	6	0.3	0.35
Level1	3	0.22	0.28

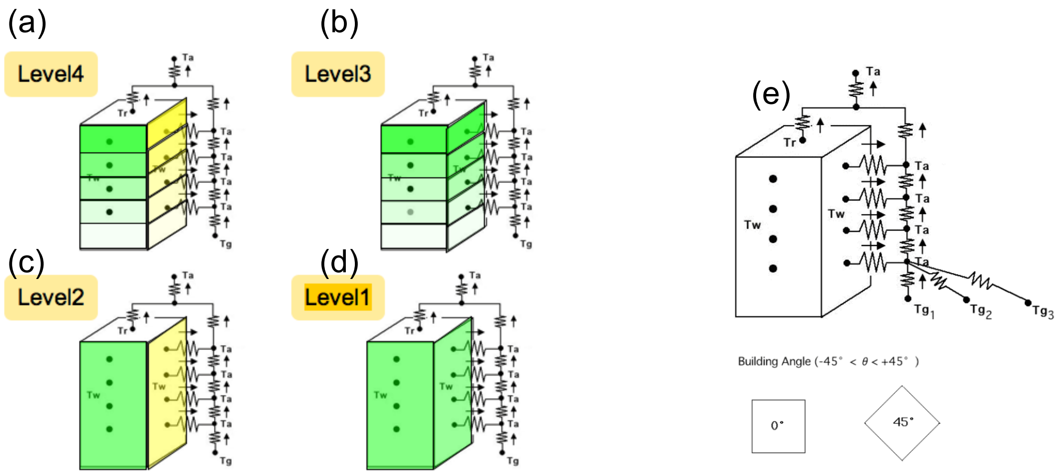

Fig. 1. (a)-(d) Energy fluxes and temperatures for the four models. (e) Options of the proposed canopy models. In these models, three types of ground conditions can be considered, and it is possible to change the angle of the buildings.

3. SIMULATED RESULTS

3.1 Tests of the proposed models against observations

The validation of each model is compared with the observations in Kanda (office area), Tokyo. This observational data was used by Kondo et al. (2005) and Ohashi et al. (2007) for testing their multi-layer urban canopy model. The observation was carried out during 29-30 July 2002. The initial and boundary conditions are almost the same as Ohashi et al. (2007). Figure 2 shows the simulated daytime surface air temperature at 1m, which is compared with the observations (symbols). The results simulated from the models are almost in agreement with the observations. The maximum difference of the surface air temperature between the Level1 and Leve4 is 0.039℃, and the maximum difference between Level3 and Level4 is 0.0049℃.

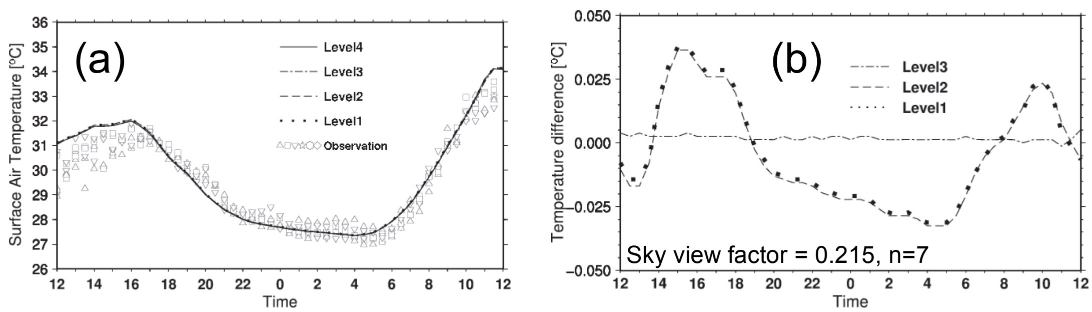

Fig. 2. (a) Diurnal variations of the surface air temperature at 1m height. The solid line indicates simulated results from the Level4, the chain line the Level3, the dashed line the Level2, the dotted line the Level1 model, and the symbols are observations. (b) Difference in temperature from the Level4 model (Level1,2,3 – Level4).

3.2 Inter comparison of four models

Our multi-layer urban canopy models, Level1-3 are each compared with the Level4 model. We set the same physical constants, surface parameters, urban geometry and atmospheric conditions for a typical clear summer day and a winter day. The calculation was executed for 6 days, and the results of the last day was used for the

inter-comparison. We investigated the difference of each model for the different sky view factor. Figure 3 shows the maximum difference of surface air temperature compared with Level4 model. In the summer case, the results of the Level3 model is almost the same as that of Level4 (Fig 3a). The maximum difference is about 0.003℃ (SVF=0.13). On the other hand, the difference of the result between the Level2,1 models and Level4 model becomes larger as the sky view factor becomes smaller. When the sky view factor is lower than 0.19, the difference increases rapidly. Next, we report the results under the winter conditions. Figure 3b indicates that the differences of surface air temperature between the Level4 model and the Level2,1 models are almost two or three times larger than that of the summer case. When the sky view factor is lower than about 0.4, the difference rapidly increases. In the Level3 model, the difference is lower than 0.1℃.
From these, we can conclude that the difference in the simulated surface air temperature mainly depend on whether the wall's heat budget equation is solved for each layer or not.

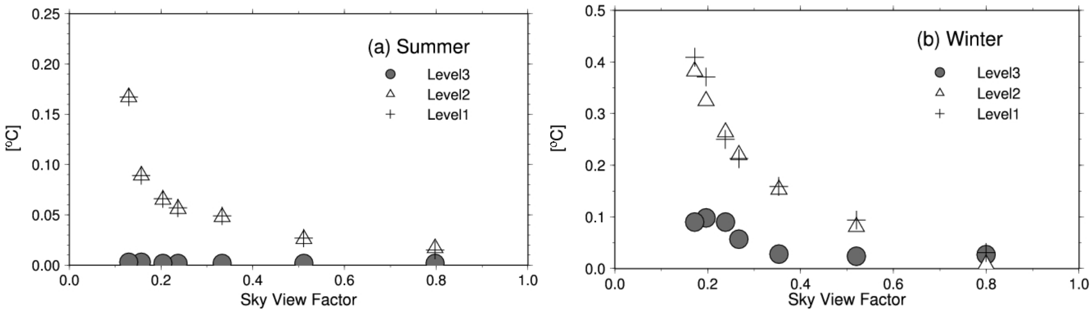

Fig. 3. The horizontal axis indicates sky view factor from a road, and the vertical axis is the absolute value of the difference in air temperature compared with the Level4 model. The closed circle indicates Level3, the triangle indicates Level2, the cruciform indicates Level1. (a) is summer case and (b) is winter case.

3 CONCLUSIONS

We proposed four simplified Multi-layer urban canopy models for use in atmospheric models, and then these were compared to the observations in Tokyo. The simulated surface air temperature agreed closely to the observed ones. Moreover, we performed a model inter-comparison. The results are summarized as follows:

1) The performance of the Level3 is nearly equal to the Level4 model. Whereas, the Level1,2 models produce lower performance. This indicates that the difference in the simulated surface air temperature mainly depends on whether the wall's heat budget equation is solved for each layer or not.
2) In the summer case, the difference in surface air temperature between the Level3 model and the Level4 model is very small. This tendency hardly depends on the sky view factor. On the other hand the difference between the Level2,1 models and the Level4 model is large when the sky view factor is smaller than 0.19.
3) The results from the winter case are similar to that of the summer case in the simulation temperature. However, the difference between the models is relatively larger in winter than in summer.

From these results, the Level3 model can be used instead of the Level4 model. The Level2 and the Level1 model can also be used if the sky view factor is smaller than 0.19 in summer or around 0.4 or more in winter.

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