ACCURACY VALIDATION OF URBAN CLIMATE ANALYSIS MODEL USING MM5 INCORPORATING A MULTI-LAYER URBAN CANOPY MODEL
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Abstract

The Urban Heat Island (UHI) phenomenon is becoming very serious in Japanese cities, and a three-dimensional meteorological mesoscale model is often used to determine the mechanism behind UHIs. However, the conventional model employs a roughness parameter in order to represent the effects of building complexes. In order to analyze the thermal environment at pedestrian level in an urban area, the authors proposed incorporation of the urban canopy model into MM5, as proffered by NCEP and Pennsylvania State University. In this study, the results of the newly proposed model are compared with field observations so as to validate its accuracy.

Key words: Urban Heat Island, Mesoscale Analysis, Urban Canopy Model

1. INTRODUCTION

The incidence of Urban Heat Islands is becoming very serious in Japanese cities, and a three-dimensional meteorological mesoscale model is often used to determine the mechanism behind UHIs. However, in such mesoscale analysis – which was originally developed in order to predict the climate above the surface boundary layer – a one-dimensional heat balance model is usually used to represent the ground boundary conditions. In this conventional model, a roughness parameter is employed in order to represent the effects of building complexes. As the vertical grid size adjacent to the ground surface must be made several times larger than the roughness length in the conventional model, physical phenomena within the surface layer cannot be estimated. Furthermore, the definition of surface temperature is rather vague in the conventional model because its relationship with ground, roof and wall surface temperatures is unclear. Therefore, it is necessary to include the effect of the urban canopy precisely in order to analyze the thermal environment at pedestrian level in an urban area. So as to resolve these problems, the authors proposed incorporation of the urban canopy model into MM5, as proffered by NCEP and Pennsylvania State University. In this study, the results of the newly proposed model are compared with field observations in Kugahara, Tokyo conducted by Moriwaki and Kanda (2004, 2006, 2008) to validate the accuracy.

2. OUTLINE OF ANALYSIS MODEL

2.1. Outline of mesoscale model

MM5, which is formally known as “The fifth-generation Penn State/NCAR Mesoscale Model”, is based on the original version described by Anthes and Warner (1987) that had been modified to broaden its application. In this study, the following schemes are applied – Planetary Boundary Layer scheme:Eta PBL scheme (Janjic, 1990); Radiation scheme: Cloud-radiation scheme (Dudhia, 1989); and the Surface scheme: Five-layer soil model (Dudhia, 1996); with the Eta PBL scheme being modified to incorporate the urban canopy model.

2.2. Outline of multi-layer urban canopy model

The following five factors relating to the building complex are incorporated into the MM5: (i) wind reduction by the building complex, (ii) production of turbulence by the building complex, (iii) solar radiation heat transfer inside and outside of the building complex, (iv) long-wave radiation heat transfer inside and outside of the building complex, and (v) sensible and latent heat transfer from the building surfaces. Four factors related to the plant canopy are also incorporated: (i) wind reduction by the plant canopy, (ii) production of turbulence by the plant canopy, (iii) solar radiation absorption by the plant canopy, and (iv) heat exchange inside the plant canopy. The method used to analyze radiation flux inside the urban canopy layer is based on Kawamoto (2006).

2.2.1. Modeling the Building Complex

The effects of the building complex are incorporated into the MM5 model as additional terms. A uniform city block, i.e. a series of buildings with the same height \((h)\), width \((b)\), and interval \((w)\) is assumed within each grid in the mesoscale analysis. These parameters are obtained using GIS data.

2.2.2 Effect of the Building and Plant Canopies on the Flow Field

The underlined terms are added to the following momentum equation for the drag of the building and plant canopies, with reference to the forest canopy model proposed by Yamada (1982).
\[
\frac{\partial \rho u}{\partial t} = -m^2 \left[ \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} \right] - \frac{mp}{\rho} \left[ \frac{\partial \rho u}{\partial x} - \frac{\partial \rho v}{\partial x} + u \nabla \cdot \mathbf{v} \right] + \rho f v - \rho \varepsilon \cos \theta + D_\varepsilon \frac{\eta C_{a u}}{\sqrt{u^2 + v^2 + w^2}}
\]

\[
\frac{\partial \rho v}{\partial t} = -m^2 \left[ \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} \right] - \frac{mp}{\rho} \left[ \frac{\partial \rho v}{\partial y} - \frac{\partial \rho u}{\partial y} + v \nabla \cdot \mathbf{v} \right] + \rho f u - \rho \varepsilon \sin \theta + D_\varepsilon \frac{\eta C_{a u}}{\sqrt{u^2 + v^2 + w^2}}
\]

Here, \( \eta \) is the ratio of the city block or planted area to the grid area, \( C_d \) is the drag coefficient, and \( a \) is the building or leaf area density. In the building canopy, the building area density \( a \) is assumed to be \( \frac{4b}{(w+b)^2} \).

The underlined terms are added to the following turbulent kinetic energy \( q^2/2 \) and turbulent length scale \( q \) equations respectively.

\[
\frac{d}{dt} \left( \frac{q^2}{2} \right) = \beta \left( \frac{q^1}{2} \right) - \lambda F_{\varepsilon} \left[ \frac{\partial \rho}{\partial z} - \frac{\partial \rho}{\partial z} \right] - \frac{q^3}{B_l} \left[ 1 + \frac{1}{\kappa \varepsilon} \right] + 2\eta C_{a u} \left( u^2 + v^2 + w^2 \right) \]  
\]

Here, \( S_q, S_l, F_1, F_2 \) and \( \beta \) are empirical constants, \( \varepsilon \) is the virtual potential temperature, and \( \kappa \) is the von Kármán constant.

### 2.3. Flux evaluation

In M-Y model level 2.5 (Mellor and Yamada, 1982), sensible and latent heat flux are represented as follow.

\[
\frac{H}{c_p \rho} = \frac{w q'}{\theta'} = -K_u \frac{\partial \Theta}{\partial z} = -l q S_h \frac{\partial \Theta}{\partial z}, \quad \frac{L E}{c_p L} = \frac{w q'}{\theta'} = -K_u \frac{\partial Q}{\partial z} = -l q S_h \frac{\partial Q}{\partial z}
\]

Here, \( c_p \) is the specific heat at constant pressure, \( \rho \) is the density of air, \( L \) is the latent heat of vaporization, \( K_u \) is the eddy diffusivity and \( S_h \) is the stability function based on the Richardson number. In M-Y model level 2.5, length scale \( l \) and turbulent kinetic energy \( q \) are solved explicitly.

### 3. ANALYSIS CONDITIONS AND SETTINGS

In this study, which aims to compare the original slab model and the modified model incorporating the Urban Canopy model, two cases are analyzed. For simplicity, the former case is abbreviated as “Case z_0” and the latter case is abbreviated as “Case UC”.

#### 3.1. Domains

Figure 1 illustrates the analysis domain, which covers 1,890 km (east-west) × 1,890 km (south-north) with a resolution of 27 km. The whole analysis domain (Domain 1) is two-way nested into two sub-domains; Domain 2 (756 × 675 km with a resolution of 9 km) and Domain 3 (369 × 297 km with a resolution of 3 km). Domain 4 is one-way nested from the coarse domain and analyzed as two cases; one is without the urban canopy model (Case z_0) and the other is incorporated with the urban canopy model (Case UC). The lowest grid height in Case UC is approximately 2.2 m while that in Case z_0 is approximately 14.5 m.

![Fig. 1 Analysis domains](image-url)
3.2. Analysis conditions

Analysis is conducted for the thermal environment on August 20th, 2005. The simulations begin from 9:00 a.m. (JST) on August 19th, and time integration is performed for 39 hours. The initial conditions are given by the JRA-25 dataset (Onogi et al., 2007). As lateral boundary conditions, relaxation lateral boundary conditions are applied to Domain 1 and nest lateral boundary conditions are applied to Domains 2, 3 and 4. As lower boundary conditions, surface temperature and sea surface temperature are applied from the JRA-25 dataset. As upper boundary conditions, radiative conditions are applied.

4. RESULTS

4.1. Radiation balance

Figure 2 shows the radiation balance of each analysis case and observation at a height of 25 m above ground level. Both analysis results overestimate the downward short-wave radiation flux slightly. On the other hand, analysis results of upward short-wave radiation flux differ in the two cases; Case UC shows good agreement with observation results, however, Case \( z_0 \) overestimates because the reflection of solar radiation in Case \( z_0 \) is considered on one flat surface and it is unable to represent trapping inside the urban canopy layer. Focusing on long-wave radiation, both analysis results underestimate upward flux. This means that the analyzed ground surface and building surface (in Case UC) temperatures are lower than observed. These results suggest that further detailed investigation is needed of the surface thermophysical parameters in the model.

4.2. Sensible heat and latent heat fluxes

Figure 3 shows net radiation, sensible heat and latent heat fluxes for each analysis case and observation. The height is 25 m above ground level (AGL) for net radiation and 29 m for sensible and latent heat fluxes. As previously mentioned, net radiation fluxes of analysis results include some calculation errors, and the analyzed sensible heat and latent heat fluxes are influenced by these errors. Though both analysis results overestimate the sensible and latent heat fluxes, the reason is attributed to the intensity of the net radiation.
4.3. Temperature profile within canopy layer

Figure 4 shows the air temperature profiles for each analysis case and observation under both stable and unstable conditions. Because thermometers and sonic anemometers, which measure air temperature, were used in the observation, both results are plotted respectively. Before dawn, the observation results show stable condition. However, both analyses show different tendencies. In the daytime, the profile gradients of the analyses appear almost the same as the observations. However, both analyses underestimate the air temperature. This difference is thought to be caused by the intensity of the net radiation. The difference between the two analysis cases is the vertical resolution. Because the urban canopy model is able to resolve the surface boundary layer, the results for Case UC represent the profiles near ground level. On the other hand, Case \( z_0 \), in which buildings are represented by means of a roughness parameter, is unable to resolve within the surface boundary layer.

5. CONCLUSION

In this study, the results of MM5 incorporating a multi-layer urban canopy model are compared with field observations in Kugahara, Tokyo to validate the accuracy. This comparison with the observation results suggests some clues for improving this new model; for instance, detailed investigation of surface thermophysical parameters, comparison of the ground surface and building surface temperatures with those observed, and so on.

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