New Parametrization of Mixing Length in Urban Canopy Model
都市キャノピーモデルにおける混合距離の新しいパラメタリゼーション

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1. Introduction

Citizens have witnessed urban areas' prolonged economic boom and superfluous urbanization in the last century. At the same time, the consequent population shifts from rural areas to urban areas and the increased demand for concrete and asphalt contributes much to the urban heat island phenomenon. As a result, the air temperature of urban districts increases markedly in the inner city than in the suburban area and the increasing numbers of tropical days and tropical nights result in heatstroke and sleep disorders.

Various local activities against UHI have been increasingly promoted. To evaluate these UHI countermeasures, Ihara et al [1] developed CM-BEM, which is composed of two sub models — canopy model (CM) and building energy model (BEM). The model describes the feedback process inside an urban canopy and the effects of exhaust heat on the external environment.

The main objective of this study is to develop a new parametrization method to utilize overall characteristics describing the homogenous features for a particular canopy. Together with strict mathematical deduction, we can describe the drag effect and accelerating effect derived from the pressure-gradient force as critically as we can. Also, LES-urban [2] describing the flux in Tokyo and Nagoya district will be referred to to improve simulation performance.

2. Method

The structures of simulation systems were shown in Figure 2.1. [3] The simulation system consists of three sub-models: the mesoscale meteorological model, the urban canopy model, and the building energy simulation model. The Weather Research and Forecasting (WRF) model, which is developed by the National Center for Atmospheric Research (NCAR), was a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. Apparently, it is an outstanding model to simulate mesoscale meteorology worldwide. However, given the fact that the mesh size of this model is too big compared to ordinary blocks in the center areas of cities, the multi-layer urban canopy model (CM) was adopted for the meteorological forecast on a city-block-scale. At last, the building energy model (BEM) was developed to explore the intrinsic relation between outdoor thermal conditions and air-conditioning energy consumption.

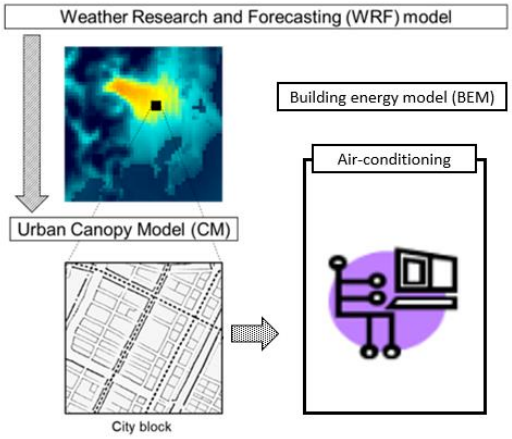

Figure 2.1 Composition of the simulation models

2.1 Normalized Wind Speed for One-Dimension Canopy

Based on Navier-Stokes equations the equation utilized to describe a well-developed canopy boundary is given as [7]

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = U\frac{dU}{dx} + \gamma\frac{\partial^2 u}{\partial z^2},$$

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial z}=0,$$

Where it is assumed that u is horizontal velocity, w is vertical velocity, x is horizontal length scale, z is vertical length scale, U is the velocity of coming flow, γ is kinematic viscosity respectively.

δ is assumed to be canopy thickness, then the elevation is normalized as,

$$\eta=\frac{z}{\delta},$$

There is no doubt that more model complexity results in a better fit. However, infinite model complexity leads to over-fitting. In that way, it is assumed that quartic polynomial is complex enough to describe wind speed profile. Here, I have normalized wind speed $f(\eta)$ as

$$\frac{u}{U}=f(\eta)=a\eta+b\eta^2+c\eta^3+d\eta^4,$$

Together with boundary condition given as

$$\eta=1,\frac{\partial u}{\partial z}=0,\frac{\partial^2 u}{\partial z^2}=0,f(\eta)=1,$$

$$\eta=0,f(\eta)=0,$$

The equation to normalize velocity in the urban canopy is solved as

$$a=2+\frac{\Lambda}{6},b=-\frac{\Lambda}{2},c=-2+\frac{\Lambda}{2},d=1-\frac{\Lambda}{6},$$

$$\frac{u}{U}=F(\eta)+\Lambda G(\eta),$$

$$F(\eta)=1-(1-\eta)^3(1+\eta),$$

$$G(\eta)=\frac{1}{6}\eta(1-\eta)^3,$$

Notably, Λ is called the shape factor. It primarily depends on the shape of canopy elements, which contributes mostly to pressure gradient force at a certain altitude.

Figure 2.2 and Figure 2.3 show normalized wind speed with shape factor Λ. The positive Λ means positive pressure gradient force and canopy elements generally have an accelerating effect, while negative Λ implies a general drag effect.

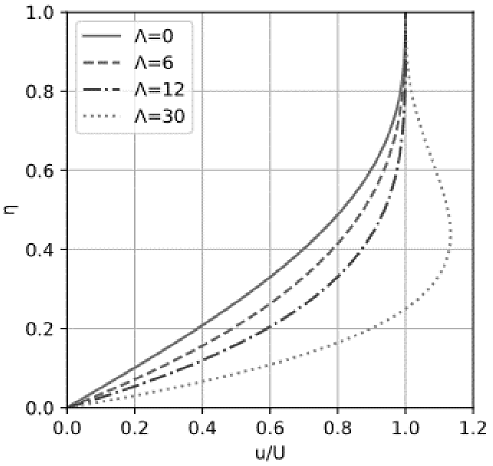

Figure 2.2 normalized wind speed profile with positive Λ

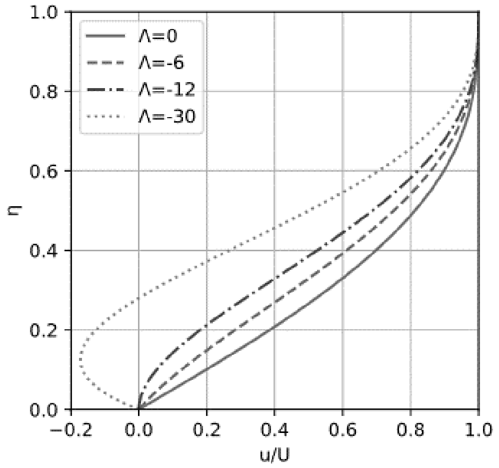

Figure 2.3 normalized wind speed profile with negative Λ

2.2 Mixing Length Approximation

From Blackadar (1962) [4], we can acquire the universally acknowledged equation to simulate mixing length beyond canopy as,

$$L=kz\left(1+\frac{kz}{L_B}\right)^{-1},$$

L is mixing length, k is Karman constant, z is elevation. Kondo et al (2015) [5] demonstrated that 100 m is a rather competitive candidate for L_B. As H_{uw} is utilized as the canopy boundary height, we can calculate mixing length at boundary height L_m as,

$$L_m=kH_{uw}\left(1+\frac{kH_{uw}}{L_B}\right)^{-1},$$

Kondo et al (1976) [6] started from a simpler basic equation in which a horizontally homogeneous and stationary field is assumed (permeability is ignored). Thus, we can have

$$\frac{d}{d\eta}\left(l_{m+}^{2}\left(\frac{d\left(F(\eta)+\Lambda G(\eta)\right)}{d\eta}\right)^{2}\right)=S_{(\Lambda,\eta\ )}\left(F(\eta)+\Lambda G(\eta)\right)^{2},$$

Where l_{m+} is mixing length L normalized by L_m. $S_{(\Lambda,\eta\ )}$ depending on the shape factor and normalized elevation is to simulate vertical building density distribution

The equation to describe l_{m+} should always make sense. Together with boundary conditions as

$$\eta = 0; l_{m+} = 0,$$
$$\eta = 1; l_{m+} = 1,$$

Finally, we can have

$$l_{m+} = \Big(\frac{1}{5\Lambda^2 + 426\Lambda + 26424}[140(\Lambda^2 - 12\Lambda + 36)\ \ \eta^6 + 945(-\Lambda^2 + 10\Lambda - 24)\ \ \eta^5 + 540\ (5\Lambda^2 - 36\Lambda + 48)\ \eta^4 + 840(-5\Lambda^2 + 15\Lambda + 36)\eta^3 + 756(5\Lambda^2 + 16\Lambda - 96)\eta^2 - 1890(\Lambda^2 + 12\Lambda)\eta + (420\Lambda^2 + 10080\Lambda + 60480)]\ \eta^3\ \Big)^{0.5},$$

2.3 Data Science Methodology

This study focuses on canopy elements' influence on the flux transfer process. In micro terms, the atmospheric particle rubs against non-slip surfaces. Consequently, kinetic energy is generated to promote the local momentum flux transferring process. Thus, canopy bulk geometric variables, (local average building height, local maximum building height, building height deviation) which describe the distribution of no-slip surface, are rather competitive variables to approximate canopy height H_{uw} and shape factor Λ. [2]

There is no denying that Linear Regression is a competitive method for modeling the relationship between one or more independent variables. However, Multilayer Perceptrons increases modeling complexity and that can be a great addition to data fitting. ReLU layers are involved to activate linear neurons. Drop-out layers are employed to inject noise into each layer of the network and enforce smoothness.

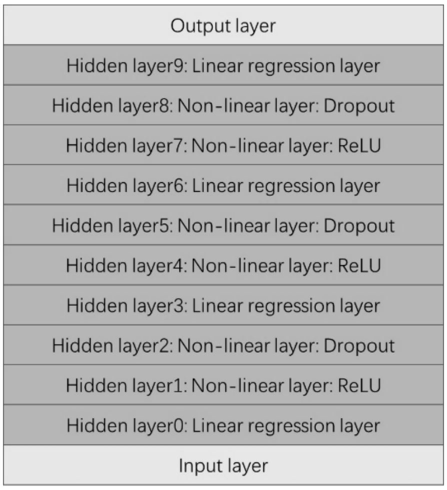

Figure 2.4 the components of MLP utilized

3. Result

3.1 Canopy Height and Shape Factor Validation

Thanks to LES-urban [2], we can have the negative peak of vertical momentum flux H_{uw} and shape factor Λ. To reveal the intrinsic relationship between these two parameters and basic canopy geometries (average building height, maximum building height, and building height deviation), MLP method is adopted to make the prediction. To evaluate the prediction performance of MLP, the traditional linear regression method is also adopted to make a comparison.

At the aspect of shape factor, there are 85 sets of LES-urban used as training dataset, and 37 sets of LES-urban are used for validation. Compared to the traditional linear regression method, with log RMSE 0.693551, MLP improved predicting performance and the log RMSE becomes 0.655406. For canopy height, the traditional linear regression method is with log RMSE 0.742313, MLP improved predicting performance and the log RMSE becomes 0.562255.

3.2 Mixing Length Profile Validation

3.2.1 Simulation condition

Having 3 wind speed profile sounding spots, Tokyo tower, included, the typical office block

500 m×500 m is chosen as a research region. The simulation period was from July 29th, 2002 to August 12th, 2002, during which period there was no rainfall.

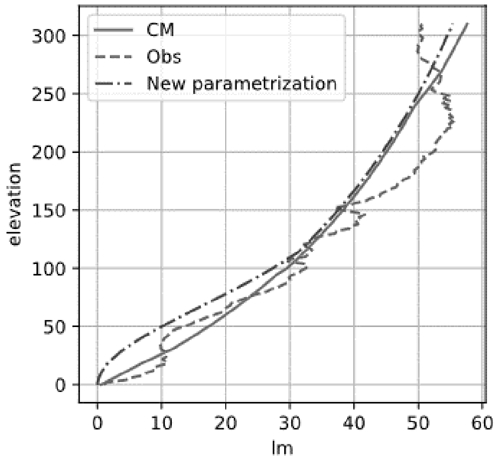

Figure 3.1 Profile of Mixing length in Tokyo tower district

The mixing length profile in the Tokyo tower district is obtained from CM-BEM simulation, new parametrization, and LES-urban. Their similarity proved both the old method and the new parametrization are capable of performing well for commercial districts.

3.2.2 Wind Speed Validation

The velocity from WRF is generally much bigger than the velocity observed at all altitudes. As WRF provides CM-BEM with periodical boundary conditions, we can assume that can result in over-valuation of flux in the early simulation process.

However, we can see that compared to conventional parametrization, the average velocity simulated by new parametrization is very close to the velocity observed, although WRF is not that accurate. New parametrization reduced RMSE by 0.01, 0.18, and 1.7 with the height 25m, 107m, and 250m from the ground respectively. This result is not surprising: after a series of vertical momentum flux transfer processes, the velocity bias is weakened due to the robustness of CM-BEM.

4. Conclusion

H_{uw} implies beyond which altitude the general solution for atmospheric layers with low building density should be employed. In the lower areas, shape factor Λ, derived from basic canopy geometric features, is capable of describing the influence of canopy elements. The utilize of these two parameters results in good mixing length simulation performance.

MLP is utilized to approximate H_{uw} and Λ. Compared with the traditional linear regression method, the prediction bias is reduced.

Although WRF is not able to guarantee accurate periodical boundary conditions, the bias between velocity simulated and velocity observed diminished gradually. That proved the robustness of the new parametrization together with CM-BEM.

Reference

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