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Academic Article

Fundamental Urban Morphology Analysis for Use in Urban Canopy Model

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ABSTRACT

For urban climate analysis, mesoscale meteorological models are widely utilized. The urban canopy models are used as sub-models of land surface models in mesoscale meteorological models to represent the effect of urban morphology in terms of kinetic effects and surface energy budgets. Normally, in an urban canopy model, buildings in an analysis mesh are assumed to be uniform. However, in reality, the buildings in any given area are not uniform; they can differ in terms of their heights, areas, and shapes. This raises the question whether the gaps between the morphologies of the presumably uniform modelled buildings and the real non-uniform buildings are significant or not. In this study, the urban morphology in Japanese cities is analyzed by the means of Geographical Information System (GIS). Some urban canopy models represent the variations in buildings' heights based on normal distribution. However, in this study, building distribution in terms of heights reflects power-law distribution on a macro scale in entire Japan, and on a micro scale with a resolution of about 1 square kilometer.

Key Words: Urban Morphology, Building Height, Geographical Information System, Urban Canopy Model

1. Introduction

In the field of urban climatology, numerical simulation tools, such as mesoscale meteorological models, are useful. To reflect the effects of buildings (e.g. decreasing wind velocity, production of turbulence, solar radiation shading and trapping, decreasing the sky view factor, etc.), urban canopy models are coupled with mesoscale models. For urban canopy models, building geometries are essential input data to parameterize the effects of the urban canopy layer consisting of building complexes. Grimmond et al. showed that building geometries affect the calculated energy budget at the surface in the urban canopy models[(1), (2)]. Accurate analysis by urban canopy models requires accurate input data. Therefore, both sophisticated analysis models and accurate building geometric data are necessary as input for accurate surface energy budget analysis in mesoscale models coupled with urban canopy models.

On the other hand, most of the urban canopy models are based on uniform building complexes, meaning that building geometries (building height, building width, and canyon width) in each analysis mesh are determined by average values. There is an urban canopy model that reflects building height distributions; the single layer urban canopy model in WRF[(3)] uses standard deviation to reflect building heights distribution. However, building heights may not exhibit a normal distribution.

The author's group developed an urban canopy model in previous studies[(4), (5), (6)]. To utilize that urban canopy model accurately, building geometric datasets have to be prepared. Furthermore, effects of non-uniformity that are neglected in uniform urban canopy models have to be investigated. In addition, the urban canopy model must be modified to include non-uniformity if necessary. The objective of this study is to clarify non-uniformity of urban morphology, especially for building height distributions, to revise the uniform urban canopy model to a non-uniform urban canopy model with actual urban morphology datasets as input.

2. Materials and Methods

The urban morphology data for Japan used in this study, was published by ESRI Japan in 2012. A total of 46,974,800 building shapes, heights, and locations are recorded in the dataset, and these data were analyzed using ArcGIS 10.2. Building height was determined by multiplying number of stories by a fixing height of 3.0 m. Thus, all double storied buildings were considered to be 6.0 m tall. Moreover, building heights were discrete values every 3.0 m.

Statistics were based on the "Basic Grid Square" (Third Area Partition) with a resolution of about 1 km^2 and a grid spacing in latitude and longitude of 30 seconds 45 seconds, respectively. "Basic Grid Square" is widely used for statistics on population, land-use, and urban planning, among others, by national and local governments in Japan. About 1 km^2 resolution is also suitable for input data to the urban canopy model coupled with the mesoscale model. Buildings are allocated to the Basic Grid Square based on these centroids. If any building overlaps more than one Basic Grid Square, it is allocated to the mesh that includes the centroid. A total of 46,974,800 buildings in the dataset were allocated to 124,160 meshes and analyzed.

3. Urban morphology analysis of building height

3.1 Buildings' heights distribution in whole of Japan

Fig.1 shows a histogram of building heights in Japan. Note that the vertical axis is logarithmic. Moreover, 9 buildings with heights over 171 m were not plotted because of discontinuous distribution in Fig1.

About 95.0% of building heights are 6.0 m, indicating that double story buildings are dominant. As a result, average building height of whole buildings in Japan is 6.289 m. The distribution of building heights does not show normal distribution. Moreover, a sudden drop between 45 m and 48 m is apparent. In Japan, earthquake-resistance safety measures require buildings over 45 m to be analyzed with a Time-History Response Analysis and certified by the Minister of the Ministry of Land, Infrastructure, Transport, and Tourism. Therefore, the quantity of buildings taller than 45 m is small.

To clarify the distribution characteristics, the building height histogram was redrawn on a double logarithmic plot (Fig.2). Nine buildings, which were neglected in Fig.1, are included in Fig. 2. The scatter plot data can be fit with straight line on the double logarithmic plot. Thus, the building height distribution in Japan follows a power-law distribution. The determination coefficient for the approximation equation estimated by the least square method is 0.938. This result describes Japanese building height distributions from a macroscopic point of view, but does not describe distribution characteristics from a microscopic point of view. Mesh statistics with a resolution of 1 km^2 are detailed in the next section.

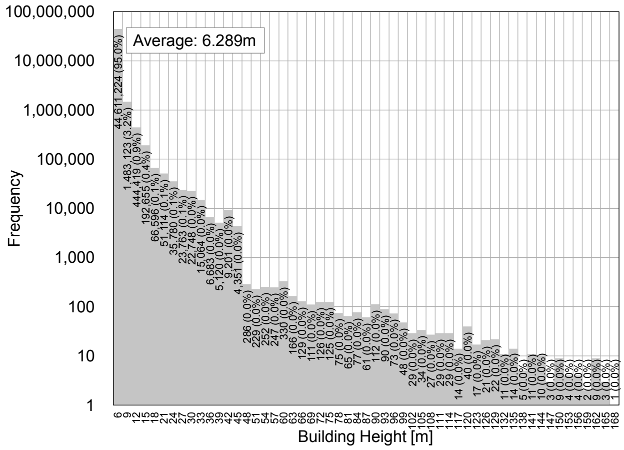


Fig.1 Histogram of building heights in Japan. The following 9 buildings are neglected in this histogram: two buildings with heights of 174 m, one building with a height of 177 m, two buildings with heights of 180 m, one building with a height of 210 m (Landmark Tower, Kanagawa), one building with a height of 234 m (Fukuoka Tower, Fukuoka), one building with a height of 333 m (Tokyo Tower, Tokyo), and one building with a height of 810 m (Tokyo Sky Tree, Tokyo).

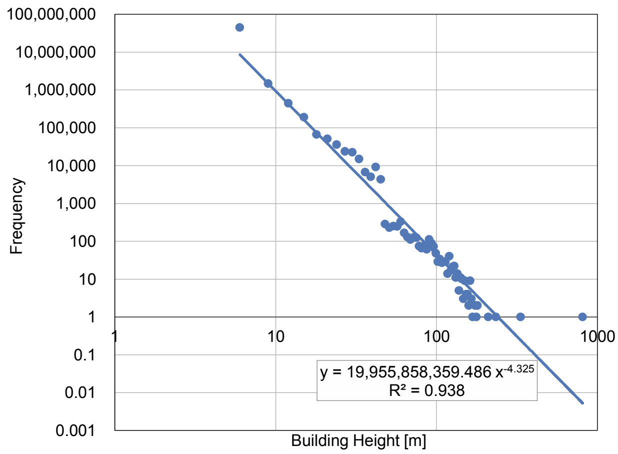


Fig.2 Double logarithmic scatter plot of building height distribution in Japan. The approximation equation was estimated by the least square method, and the R^2 value is the determination coefficient for this approximation equation.

3.2 Buildings' heights distribution in Basic Grid Squares

Approximation equations expressing the relationship between building heights and their frequency were estimated using the least square method for 124,160 meshes. However, if all buildings in any mesh are the same height, the approximation equation cannot be estimated. Therefore, 55,972 meshes with building height variation are plotted in Fig.3. Fig.3 shows the relationship between the number of buildings in each mesh and the determination coefficient (R^2) for the approximation equation calculated using the power law function. Fig.4 shows a histogram of determination coefficients (R^2) for 55,972 meshes.

The results indicate that a power law approximation is appropriate to estimate building height distribution. In 63.14% of meshes, determination coefficients were greater than 0.90, and 82.75% of meshes had determination coefficients greater than 0.80. There is an apparent trend of larger determination coefficients with a larger number of buildings. The urban canopy model is intended to be applied in the urbanized area. Therefore, three samples were chosen to investigate meshes with greater than 1,000 buildings (Fig.5): Marunouchi in Tokyo (highest average building height), Nishi-Shinjuku in Tokyo (largest standard deviation of buildings' heights), and Kokura in Fukuoka (largest number of buildings). In these three meshes, determination coefficients ranged from 0.806 to 0.880. Fig. 6 shows the scatter plot of average building height versus standard deviation for 14,347 meshes with a number of buildings greater than 1,000.

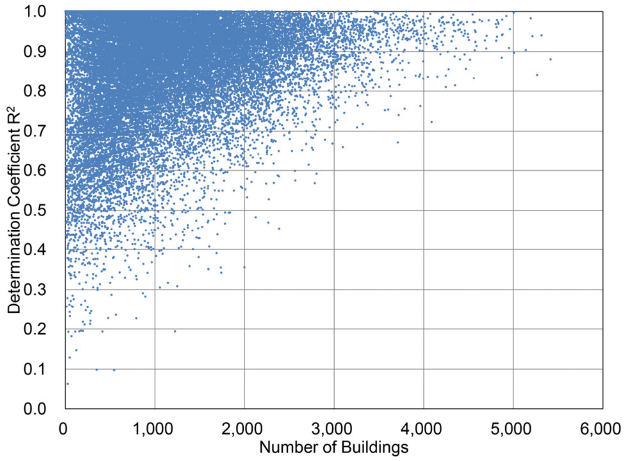


Fig.3 Scatter plot of the number of buildings and the determination coefficient R^2 for the power law approximation of 55,472 meshes.

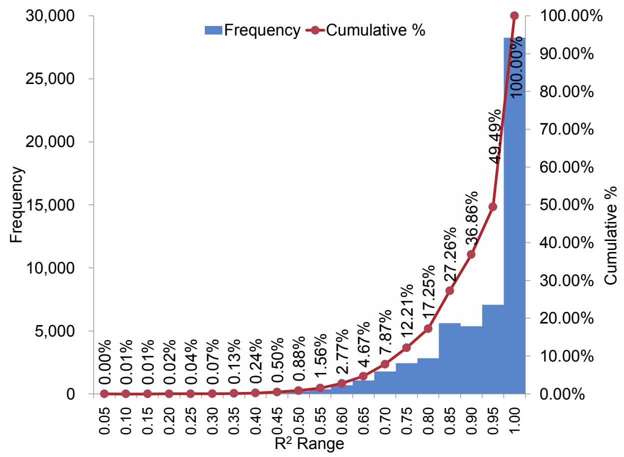
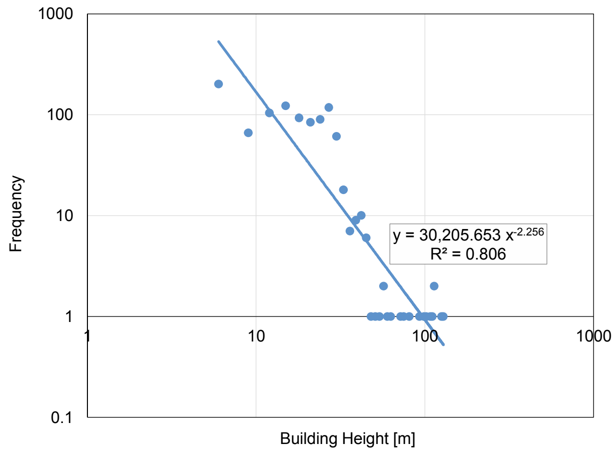
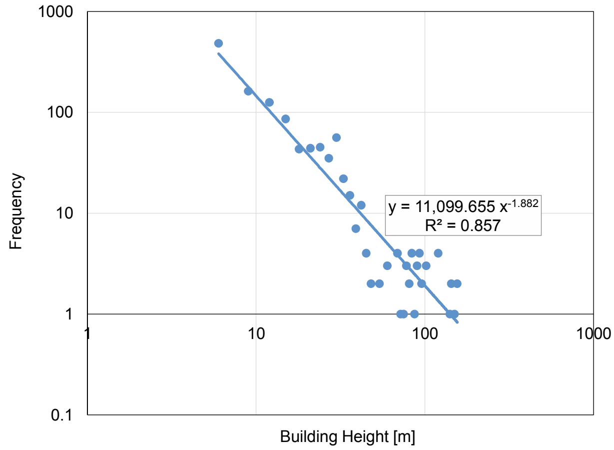


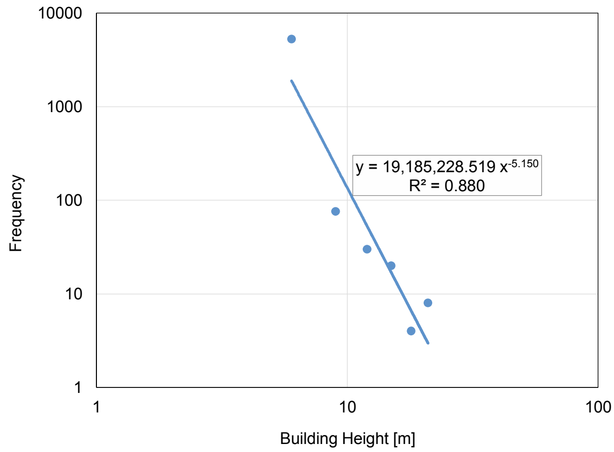
Fig.4 Histogram of the determination coefficient R^2 for the power law approximation of 55,972 meshes and their cumulative frequency.



a) Marunouchi, Tokyo



b) Nish-Shinjuku, Tokyo



c) Kokura, Fukuoka

Fig.5 Double logarithmic scatter plot of building height distribution in a) Marunouchi, b) Nishi-Shinjuku, and c) Kokura. The approximation equation was estimated by the least square method, and the R^2 value is the determination coefficient for this approximation equation.

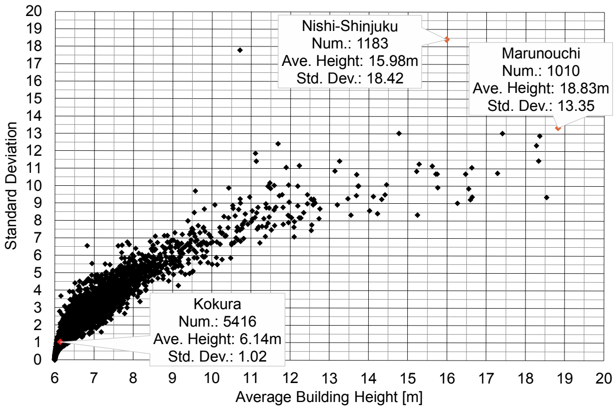


Fig.6 Average building height vs. standard deviation for 14,347 meshes with a number of buildings greater than 1,000.

4. Sky view factor estimation in non-uniform urban canopy

In the urban canopy model, long wave radiation and diffuse sky radiation intensity to urban canyons are strongly affected by estimation of the sky view factor. For the uniform geometric urban canopy model, a simplified estimation method for sky view factor was proposed[4], [5], [6]. The simplified estimation method for sky view factor uses average building height, average building width, and average canyon width, assuming that the building complex is uniform. Other effects of urban canopy in the urban canopy model, including drag forces and production of turbulence, are based on the assumption of uniformity. Therefore, this simplified method for sky view factor estimation matches the uniform urban canopy model. On the other hand, this method has not been tested for non-uniform geometric urban canopies. By targeting the three meshes described above, the sky view factors estimated by the simplified method for uniform canopy and the three-dimensional GIS analysis were compared.

4.1 Outline of simplified sky view factor calculation method in uniform urban canopy

A simplified model for the sky view factor was proposed as follows.

From the ground, only the view factors for building sidewalls and the sky were considered. Firstly, the view factor for the building sidewall was calculated. View factors from point A and point B were area-weight averaged to calculate the normalized view factor, F_{gw}, from the ground for the sidewall (Fig.7).

$$F_{gw} = \left(w^2 F_{agw} + 2wbF_{bgw}\right) / \left(w^2 + 2wb\right) \quad (1)$$

View factors from surface 1 (a small surface on the ground) to surface 2 (building sidewall) can be calculated analytically using Eq. (2)[7].

$$F_{n12} = \frac{1}{2\pi}\left[\tan^{-1}\frac{b}{h} - \frac{h}{\sqrt{a^2+h^2}}\tan^{-1}\frac{b}{\sqrt{a^2+h^2}}\right] \quad (2)$$

Here, a is the height of surface 2 [m], b is the width of surface 2 [m], and h is the distance between the centres of surface 1 and surface 2 [m]. Then, the sky view factor F_{gsky} can be calculated.

$$F_{gsky} = 1 - F_{gw} \quad (3)$$

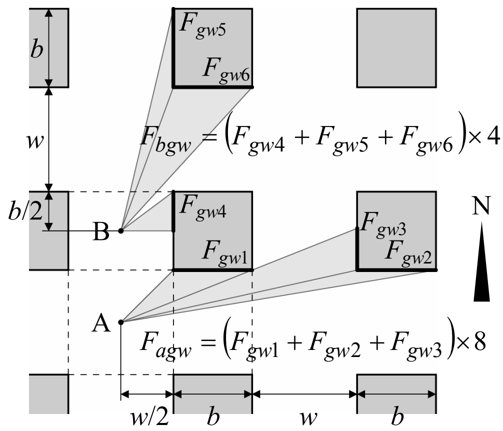


Fig.7 Schematic graph of the calculation for view factors from ground to building sidewalls.

4.2 Comparison of simplified method and GIS analysis for sky view factor calculation

To estimate the average sky view factor in an area with ArcGIS, observation points are set at random locations inside the area. The average sky view factor calculated for a large number of samples converges to specific value. However, a larger number of samples incur higher calculation costs. Therefore, the average sky view factor calculated using 1,000 and 10,000 sampling points in Marunouchi were first compared. Calculation times were about 35 hours for 1,000 samples and about 350 hours for 10,000 samples. Table 1 shows the average sky view factors calculated by the simplified method and GIS analysis. In Marunouchi, the results using 1,000 samples and 10,000 samples were almost the same. Therefore, 1,000 random sampling points were adopted hereafter. Comparing the simplified method and GIS analysis, the Kokura results show large error. Fig.8 shows the Kokura area and the random sampling points used to calculate sky view factors. In the uniform geometric urban canopy model, buildings are arranged at equal spaces. However, in real space, buildings are arranged in blocks, and open spaces are preserved between the blocks. This kind of contrast in building density is not reflected in the uniform geometric urban canopy model, which could be the reason for error in the average sky view factor estimation by the simplified method. Furthermore, as shown in the previous section, buildings height distribution tends to show power-law distribution. This characteristic has to be considered in the calculation of sky view factors for non-uniform urban areas using a power-law probability distribution function. Representation of the non-uniformity of urban morphology in the calculation of sky view factors remains a pressing issue.

Table 1 Average Sky View Factors Calculated by the Simplified Method and GIS Analysis.

Location	Marunouchi		Nishi-Shinjuku	Kokura
Average Building Height [m]	18.826		15.979	6.140
Average Building Width [m]	20.484		17.172	9.644
Average Canyon Width [m]	11.693		9.644	4.407
Simplified Method				
Average Sky View Factor by Simplified Method	0.370		0.465	0.394
GIS Analysis				
Number of Samples	1,000	10,000	1,000	1,000
Average Sky View Factor by GIS Analysis	0.403	0.410	0.418	0.615
Medium	0.419	0.427	0.411	0.617
Standard Deviation	0.158	0.154	0.165	0.182
Minimum	0.025	0.010	0.019	0.114
Maximum	0.727	0.730	0.733	0.930

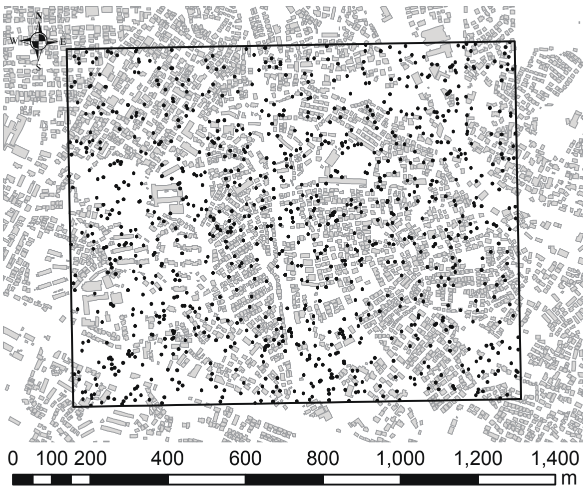


Fig.8 Map of the Kokura area. Grey polygons are buildings and black points are sampling points set in ArcGIS to calculate sky view factors.

5. Summary

In this study, urban morphology in Japanese cities was analyzed to create an input data set for the urban canopy model and to investigate the non-uniformity of urban canopies by means of GIS. The results show that the building height distribution in entire Japan follows a power-law distribution. At a local scale with a resolution of about 1 km^2, building height distribution also showed a power-law distribution. Furthermore, sky view factors calculated by GIS analysis and the simplified method for real urban areas were compared. The results of the simplified method displayed non-negligible errors because of the lack of consideration for contrasts in building density within meshes. These analytical results will be used to update the non-uniform urban canopy model in future work.

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