B-53.3.1 Modeling of Thermal Energy Balance in Cities

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Abstract Destruction of the global environment is typically embodied in big urban complexes through removal of natural ecosystem and a large quantity of energy consumption. This research project aims to develop a numerical model system for the assessment of urban thermal environment related with the urban canopy structure and energy system. For this purpose, three kinds of sub-models have been developed, expressing thermal conditions of a building, the canopy layer in a section of city, and the mesoscale region surrounding the city, respectively.

Several series of observation have been carried out to catch meteorological properties around buildings in different city blocks. In particular, the observation at a business building in the downtown area of Tokyo was continued over one year, during which the data of electric and thermal energy supplied to the building were also obtained. These data have been analyzed to clarify the their characteristics and relationship, and used for the verification of the model system. The relationship between energy consumption and urban thermal environment has been simulated, and the result agreed well with the observed data. Therefore, the model system can be expected for application to the assessment of various countermeasures for urban heating.

Key Words Urban Climate Modeling, Urban Canopy, Urban Heat Budget, Energy Assessment

1. Introduction

In many countries of the world, the population has been concentrating into urban areas. At the same time, energy consumption per person is expanding, and the rapid increase of energy consumption in large cities deteriorates the urban environment. Furthermore, there is a positive feedback that the poor environment accelerates energy consumption. This system brings fear to influence the global environment. Improvement of urban system, including urban structure and energy system, is expected to raise the efficiency of energy use and cut of the above feedback. This project aims to develop a numerical model-system which represents the dynamic relations between the urban thermal environment and the urban structure, such as configuration and shape of buildings, air-conditioning apparatus, and energy use. Then the model can be offered as an assessment system for planning future cities.

2. Research Method

Modeling of thermal and energy structure in urban system is primarily based on meteorological formulas. Mesoscale modeling was an already established technique, which could be used for a sub-model (MM) to give the meteorological condition in the region of 100km scale around the urban area of interest. Some elements of calculation needed to be changed to more precise procedure.

The grid size of MM is at least 2km or such, so that it was necessary to develop a smaller scale sub-model (named as the urban canopy model, CM) to represent fine structures of urban canopy and its thermal conditions.

Furthermore, a sub-model (named as the building energy model, BEM) was indispensable to incorporate the relations between the supplied artificial energy and the meteorological factors inside and outside of buildings.

In parallel to developing this model system, acquisition of verification data was performed every year, because no systematic observation data was available in the past representing meteorological properties around a building related with consumed energy amount.

3. Acquisition of thermal environment data and its analysis

Three series of seasonal observation around buildings of different type, and a long term observation were performed. Measured properties include air temperature and relative humidity, surface temperature of the roof of buildings, and downward short- and long-wave radiation, etc.. The long term observation was continued for nearly 17months on the roof of a business building with 24 stories located in Ootemachi, the old downtown area of Tokyo. In parallel, the electric power supply and heat/cold water supplied from the district heating/cooling system monitored by the building were compiled.

1) Typical summer temperature profile

From the summer observation in the Shinjuku new center area of Tokyo, temperature data showing a typical diurnal variation were obtained (Fig. 1). The selected building is a combination of a tower of 29 stories and lower building of 8 stories. On the roof of lower building (L), the duration receiving direct solar radiation is confined to mid-afternoon, during which time the surface temperature does not largely exceed that of the soil ground in a green area in the vicinity. During the evening through the next morning, however, the building temperature decreases much more slowly than that of the ground surface. This exhibits large effect of the building surface material as heat reservoir. The building surface is warmer than the air, and presumably the air is heated by the building throughout the night. The air temperature decreases with height during the daytime, and that at the ground level is higher even in the green area than the building roof level, while the temperature in the green area falls to the ground surface temperature during the night.

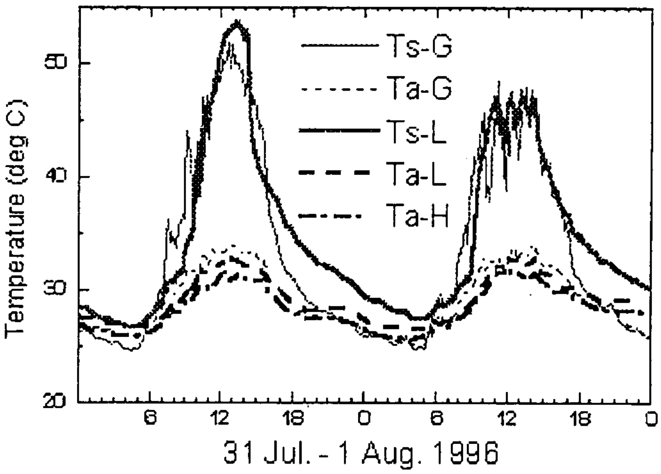


Fig. 1 Surface temperature Ts and air temperature Ta in the summer.
G: green area,
L: roof of low building,
H:roof of tall building.

2) Relation between outdoor condition and energy use

The meteorological data from the roof of the building of 24 stories in Ootemachi have been analyzed with the energy supply data. As the representative property of outdoor thermal environment, enthalpy ***E*** calculated as the following is used for the analysis.

$$E = Cpd \cdot T + r \ (L + Cpw \cdot T) ,$$

where Cpd and Cpw are the specific heat at constant pressure of dry air and water vapor, respectively, L the latent heat of evaporation, r the mixing ratio of water vapor, and T the air temperature in °C.

Daily average value during 08-19 JST is taken for every property. Fig. 2 indicates the cooling energy demand C of the days during June through September 1999 as a function of E. The days on which C<2500MJ/h are holidays. Excluding them, the correlation is very high as shown by R=0.948. The linear relation is given by C=622E-734, and the deviation from this, namely C-(622E-734), is related with the total electricity demand of the building as in Fig. 3. Although the correlation coefficient is not large, a rough tendency is found that the cooling energy demand increases as the electricity consumption increases.

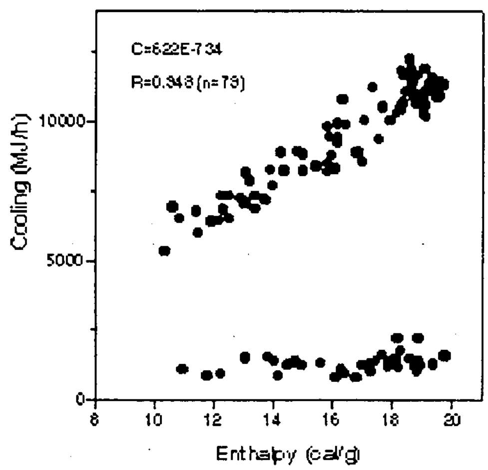


Fig. 2 E *vs.* C in the summer of 1999. See text for the detail.

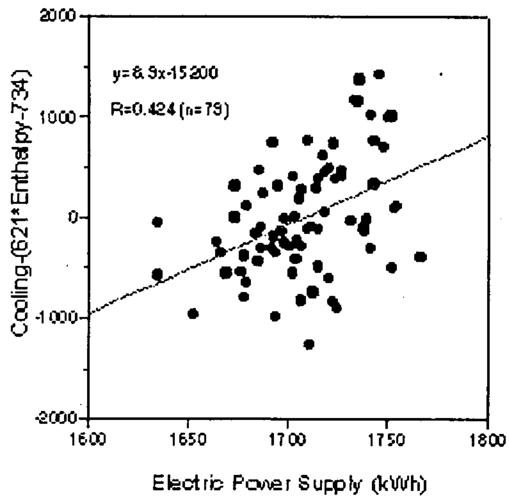


Fig. 3 Deviation from the regression line in Fig. 2 as a function of electricity demand.

4. Modeling of urban thermal environment

1) Improvement of the mesoscale model (MM)

Today, MMs are practically used by many research groups for various kind of work. For the purpose of the present research, however, our original MM [1)] had some deficiencies. One major point was lack of equations concerning water vapor, which was an important factor influencing the urban thermal environment. Therefore, the equations for evaporation, conversion of latent and sensible heat, transport of water vapor, etc. have been newly incorporated. Second point was inability to evaluate sub-grid scale inhomogeneity of surface characteristics. It has been improved by introducing multi-surface process.

The important role of the MM is to give the external meteorological condition to the urban canopy air represented by the canopy model (CM). The external condition varies with time, and the variation has to be taken into account when the model verification is performed using observed data. For this purpose, a four-dimensional data assimilation procedure has been incorporated.

2) Development of the canopy model (CM)

A new concept of one-dimensional urban canopy model has been formulated to represent detailed urban climate around buildings. The model region should be a section of city which consists of relatively homogeneous building shape and category. Size of one block is assumed $b \times b$, the street width w, and the height of buildings are allowed to have a distribution given by any function. The basic equations have a pattern as follows.

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

The second term on the right side represents the canopy resistance, and m is a function of b and w.

For evaluate sensible heat flux at the building surface, Jurges' formula is applied when the surface is warmer than the air, and Monin-Obukhov's formula for the opposite case. water vapor transport conductance for surface substances up to three kinds is introduced so as to evaluate surface evaporation and transport.

An example of verification results is shown in Fig. 4. The observed temperature is from

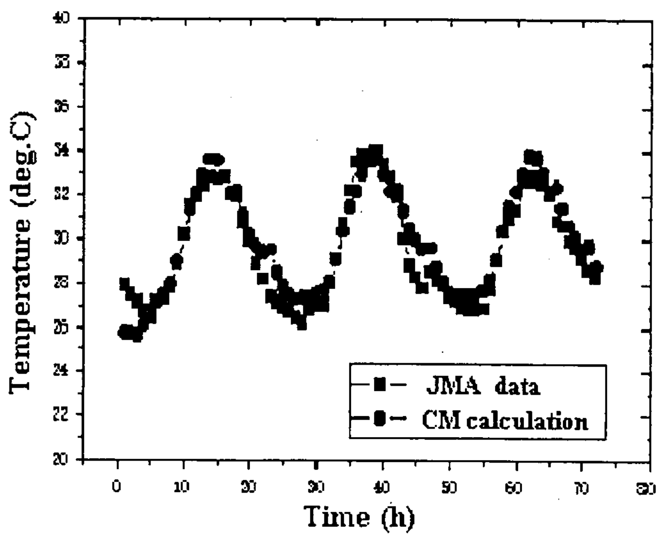


Fig. 4 Comparison of the calculated temperature variation with the measured data at the JMA observatory.

the Japan Meteorological Agency at Ootemachi, and the CM parameters were fitted to that section based on a GIS data. The temperature variation during the three days is well simulated.

3) Development of building energy model (BEM)

While the CM gives the surface temperature of buildings, neither indoor thermal condition nor influence of the buildings upon the outdoor climate through energy consumption are evaluated within it. It is necessary for the model to incorporate this feedback system. To calculate the conditions on the building side, the BEM has been developed.

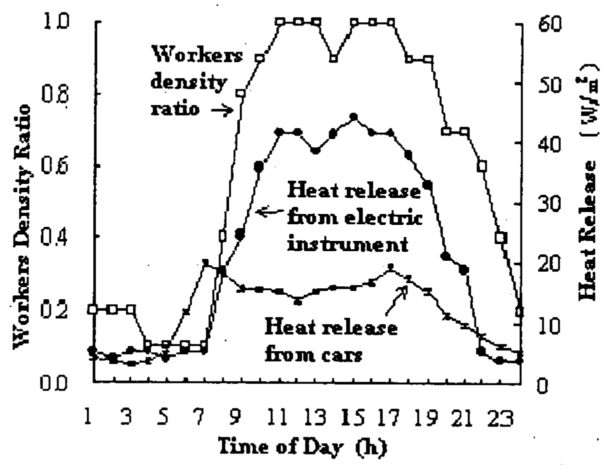
In the BEM, cooling load at buildings is treated separately as the sensible heat H_{in} and the latent heat E_{in}. H_{in} is the sum of penetration through walls, heating resulted from the radiation input through windows, indoor heat release, etc., and E_{in} consists of inflow due to ventilation and indoor evaporation. On the other hand, removal of the sensible and latent heat by air-conditioning apparatus, H_{out} and E_{out} respectively, are related with H_{in} and E_{in} depending on operation condition of the apparatus, which can be assumed somehow. Indoor air temperature and humidity are determined through the equations for these four variables.

4) Assessment of urban thermal environment

An assessment system of urban thermal environment is composed of the three sub-models MM, CM and BEM. The system has been applied to the Ootemachi area as an attempt of verification. The observation data mentioned in 3. 2) were available for the simulation.

The configuration of the block in the CM was based on a GIS data. Typical values were assumed for building and pavement body structures. Operation condition of air-conditioning were given in the BEM as that in a standard-type business building. Partial load of COP and its dependence on the outdoor air temperature was taken into account by referring to Asie et al.[3]. Some variable parameters were given as in Fig. 5.

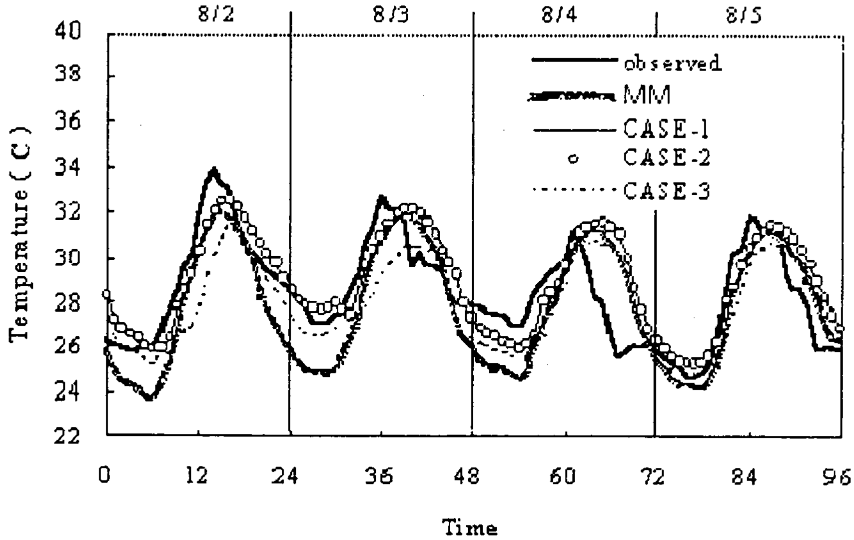
Fig. 5 Diurnal variations of parameters concerning the urban activities used in the test simulation.



A four days period in August 1998 was selected during which typical summer weather continued, and a simulation by the MM was performed. Under the meteorological conditions given by the MM, the coupled CM/BEM was operated for three cases, in which the exhaust heat from air-conditioning was put at the roof (Case 1), put at the 3m height (case 2), and removed to outside of the model region (Case 3), respectively.

The results are shown in Fig. 6. The result for the grid of the MM covering Ootemachi exhibits excessive cooling during the nights and overestimate for the amplitude. This

Fig. 6 Observed and calculated air temperature for the 100m height during 4 days in August at Ootemachi, Tokyo.



deficiency can be attributed to the neglect of two factors, heat capacity of building mass and trapping of long-wave radiation within the urban canopy. In contrast, the results of Cases 1-3 using the CM/BEM indicate better coincidence with the observed daily maximum and minimum temperatures. Cases 1 and 2 are quite similar to each other, and better than Case 3 in which the exhausted heat is neglected.

5. Conclusion

In order to cope with the deterioration of the global environment, improvement of integrated urban structure is recognized as crucial. This research project was proposed to establish a model system available for assessment of various options to reduce energy consumption and improve thermal environment in urban areas. Two submodels CM and BEM have been developed to formulate the relationship between outdoor climate and thermal structure of buildings, such as the thermal properties of building materials, indoor climate, and energy use for air-conditioning and others.

In parallel to the modeling, meteorological observation around buildings and data acquisition concerning energy demand in a buisiness building were performed to obtain verification data for the model.

The result of test simulations using the CM/BEM, coupled with an advanced mesoscale model MM, is satisfactory, and the model system is expected for application to the assessment of more efficient urban energy systems and countermeasures for urban heating.

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