J1.5

SIMPLE URBAN ENERGY BALANCE MODEL FOR MESO-SCALE SIMULATION (SUMM)

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1. INTRODUCTION

Urban surface geometry has a large, but complex, influence on urban meteorology. Unfortunately, explicit consideration of buildings into weather simulations using computational fluid dynamic methods is quite time-consuming and thus is still unrealistic for practical applications. An alternative approach has been to develop simple urban energy balance models for use in mesoscale simulations (Arnfield, 1982; Masson, 2000; Kusaka et al., 2001; Martilli et al., 2002; Sailor and Fan, 2002). These models generally assume two-dimensional (2-D) infinite street canyons mainly because it allows one to treat radiation with analytic theory. To overcome the restriction of a 2-D radiation scheme, we have recently developed a simple theoretical radiation scheme applicable for three-dimensional (3-D) rectangular obstacles arrays (Kanda et al., 2005).

In this paper, we propose a new simple urban energy balance model for mesoscale simulations (SUMM). The SUMM consists of a 3-D theoretical radiation scheme (Kanda et al., 2005) and the conventional heat transfer expression that uses a network of resistances (Masson, 2000; Kusaka et al., 2001). The present model allows one to readily calculate the energy balance and surface temperature at each face of the urban canopy (i.e., roof, floor, and four vertical walls) without time-consuming iterations.

2. THEORETICAL SCHEME

The detail of SUMM is described in Kanda et al. (2005a and 2005b). Therefore, the concept of the model is briefly reviewed here. The urban canopy geometry employed in this study is illustrated in Figure 1. In this model, streets and buildings are represented by an infinitely extended regular or staggered array of buildings with square horizontal cross-section and uniform surface properties. As long as uniform building arrays are used, the surface geometry can be characterized by only two geometrical parameters: plane area index and frontal area index.

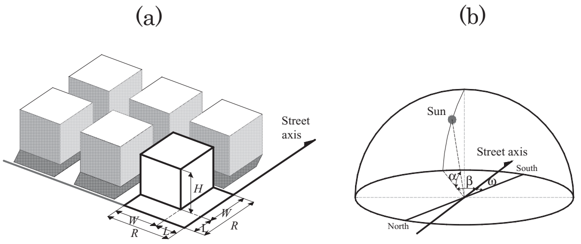

Figure 1 Urban canopy geometry employed in this study. (a) Building dimensions. (b) Orientation of the streets with respect to the sun and north-south.

It is assumed that all faces are Lambertian and thus the reflected radiations are isotropic. Mirror reflection of direct shortwave radiation does not occur. Under the above assumptions, multi-reflective exchange of shortwave is straightforward once the view factors and sunlit-shadow distributions are known. Without using time-consuming iterations or statistical approaches, we calculated the view factors of the faces, the complicated sunlit-shadow distributions, and the resulting canopy albedo for any time and location.

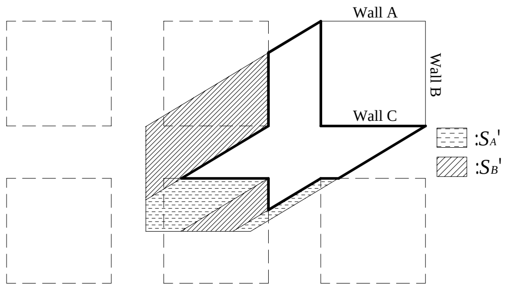

Figure 2 Example of shadow distribution on the floor. The solar energy on an unit horizontal area can be geometrically distributed to six constituent surfaces (walls, roof and floor).

Due to the nature of non-directional incident longwave radiation, the algorithm for solving the longwave radiation budget is essentially the same as that for the diffuse shortwave radiation except the treatment of the emission from the wall is directly related to the wall temperature.

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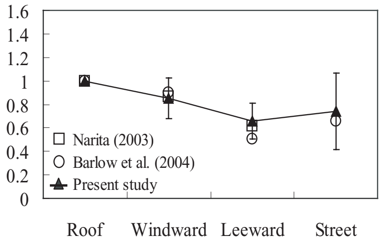
To treat the sensible and latent heat flux, we use the conventional heat transfer expression involving a network of resistances (Masson, 2000; Kusaka et al., 2001). The problem is how to parameterize the local bulk transfer coefficients. The common way is to adopt a wall function such as the Monin-Obukhov Similarity (MOS) relationship. However, the MOS is only valid for the 'integrated' heat transfer from the canopy-layer to the surface-layer, and the application to the 'local' heat transfer within the canyon is physically incorrect. For this reason, the estimation of bulk transfer coefficient has been a general problem in simple energy balance models (Barlow and Belcher, 2002; Narita, 2003; Barlow et al., 2004; Hagishima et al., 2005). The relative values of Bulk Transfer Coefficient (BTC) of six constituent surfaces are referred to a BTC-database for various building geometries. The BTC database was based on scale model experiments (Narita et al., 2005) and Large Eddy Simulation outputs (J8.3 in this volume).

(a) 2-D street canyon



(b) 3-D street canyon

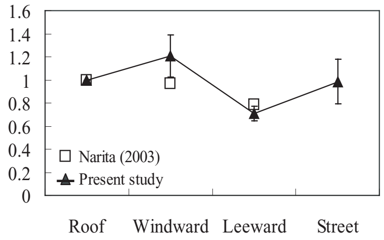


Figure 3 Local bulk transfer coefficients normalized by the value for the roof, from BTC-database.

The Indoor temperature is predicted on the basis of energy balance involving architectural aspect such as glazing, natural ventilation, and energy consumption (see JP2.1 in this volume).

3. MODEL VALIDATION

To test the numerical model, we did outdoor experiments using a 1/50 reduced-scale hardware model. The site was located in Matsusaka, Mie prefecture, Japan. Flat terrain and bare soil or short grasses extended at least 10 km in all directions. The model surface geometry consisted of cubic concrete blocks with the length of 0.15 m on a side, regularly distributed on flat concrete plates with a total area of 12m x 9 m. The plane aspect ratio of the model was 0.25. The long axis is roughly parallel to NW, the dominant wind direction at the site. To capture a sufficiently developed Internal boundary-layer (IBL), all sensors were installed 10 m downstream from the fetch. We judged from the observed vertical temperature profiles using thermocouples that the depth of IBL ranged from 2.6 to 4.0 times of the building height at the distance of sensors. Upward and downward shortwave and longwave radiation were measured separately using a radiation-balance meter (Eiko MR-40) 0.7 m above the ground. A compact sonic anemometer (Kaijo-WA590) with 0.05 m sensor length was installed 0.40 m above the ground. This was not used for the sensible heat estimation but only for the mean velocity measurements. To accurately close the energy balance, the conductive heat fluxes at each surface should be measured. This is because the energy balance residual of the net radiation minus the turbulent fluxes cannot be used instead of the conductive flux measurements due to the energy imbalance problem with the eddy covariance method (e.g. Kanda et al., 2004). The measurement of heat storage term was made possible by using very thin heat plates (Captec HF-300, 0.4 mm thick) and carefully coating them with the same material that the obstacles are made of. The sensible heat flux of individual surfaces was estimated from the energy balance residual of net radiation minus heat storage. The surface temperatures were measured at multiple points using 0.2 mm thermocouples. All measured data were stored once per second and averaged for 10 min using a datalogger (Campbell Scientific CR-23X). All the data selected for the present analysis were under sufficiently dry conditions to ignore the latent heat flux contribution.

Figure 4 A photo of reduced scale model for the validation of SUMM

We have started more comprehensive outdoor scale model experiments for urban climates using two different scale models: one is smaller model consisted of 0.15 m cubes and the other is larger one with 1.5m cube arrays (see J9.2 in this volume).

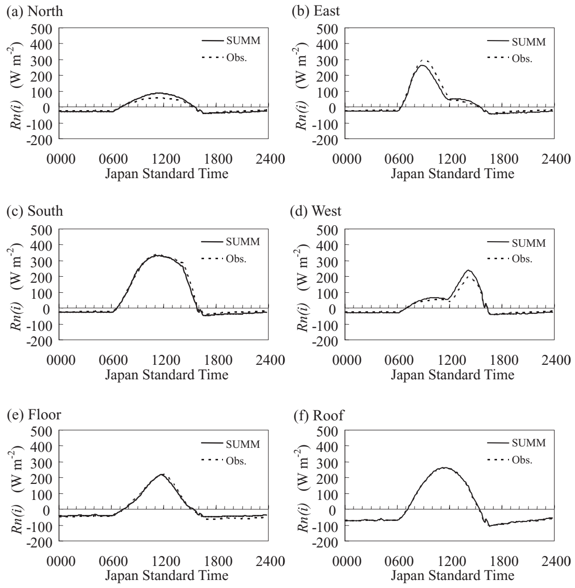


Figure 5 Comparison of measured and predicted net radiation at each constituent surface

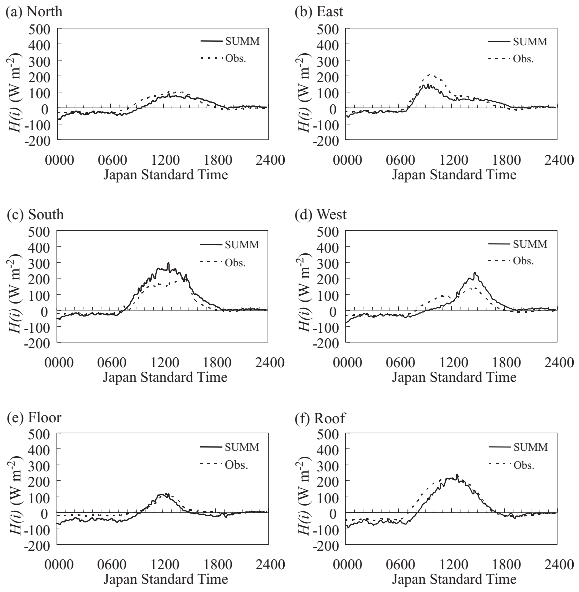


Figure 6 Comparison of measured and predicted sensible heat flux at each constituent surface

The simulated energy balance components and surface temperature of six constituent surfaces are compared with the observed counterparts. The simulated energy balance components generally follow the observed diurnal trends, although they have locally some quantitative disagreement.

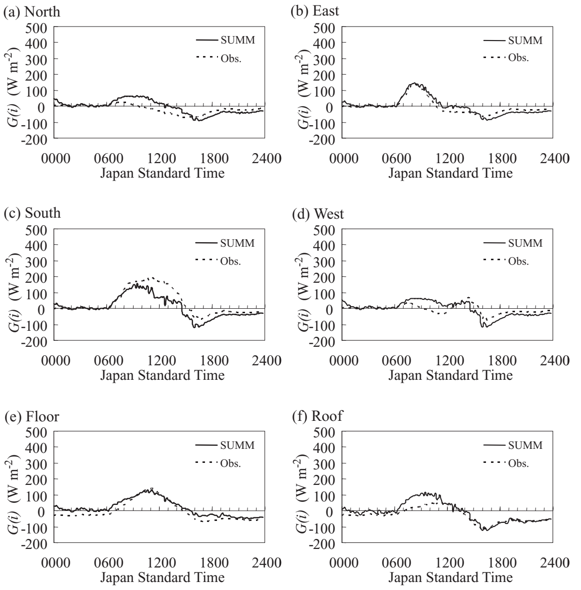


Figure 7 Comparison of measured and predicted conductive heat fluxes at each constituent surface

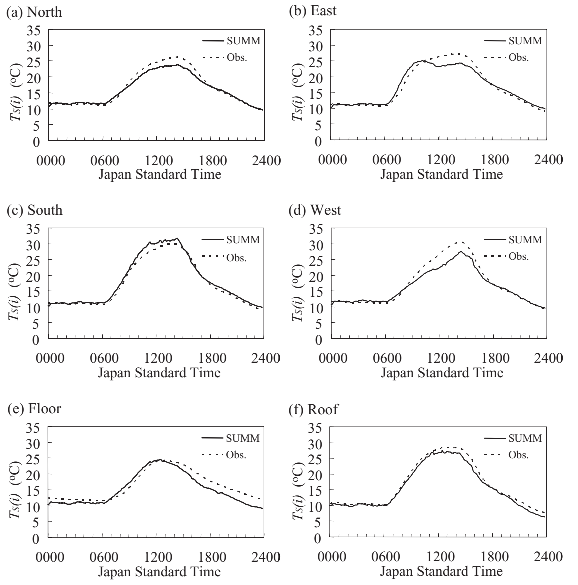


Figure 8 Comparison of measured and predicted surface temperature at each constituent surface

Particularly, the simulated net radiations (Rn) agreed fairly well with the observed values (Figure 5). The observed Rn could include some errors since they were not directly measured but were estimated from a high-accurate radiation model with the observed incoming radiations and surface temperatures. Voogt and Oke (1990) measured longwave fluxes at different points in a single canyon and reported that the accuracy of the radiation model of Arnfield (1982) was fairly good about ± 1 %. Kanda et al. (2005) reported that the high-accurate model can predict the observed shortwave fluxes within ±10 % accuracy. Thus the observed values could have at most ±10 % error.

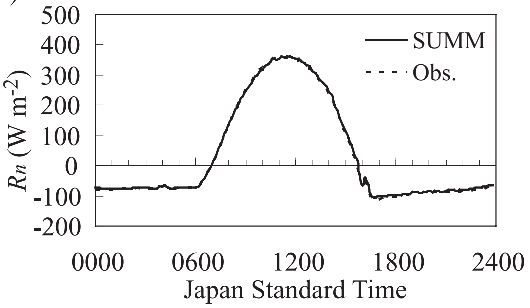
The simulated sensible heat fluxes (H) underestimate the observed values especially in the morning (Figure 6). One possible reason for this is that the current local bulk transfer coefficients were derived from neutrally stratified conditions and thus they do not consider the influence of local atmospheric stability. Generally in the morning, surface temperature increases more rapidly and the resulting local atmospheric instability becomes larger. Another possible reason on the observation side is the lower conductive heat fluxes (G) observed in the morning. The lower values of G give higher values of H, since the observed sensible heat fluxes were calculated as the residual of Rn-G .

Contrarily to the sensible heat fluxes, the simulated conductive heat fluxes overestimate the observed values (Figure 7). The heat plates have officially ±5 % random error, which can not account for the bias. The thickness of coating over the heat plate was less than 2 mm, and the heat capacity of the layer was enough negligible. One possible reason of causing the error is three dimensionality of heat conduction in such small scale concrete cubes. For example, the conductive heat at the roof top will be transferred not only to the vertical direction but also to the adjacent walls. Such three dimensionality of heat conduction within the concrete materials might decrease the measured at the surface especially in the morning when the temperature inside the cube is still low. The SUMM assumes only vertical heat conduction and no heat exchange between the different constituent surfaces.

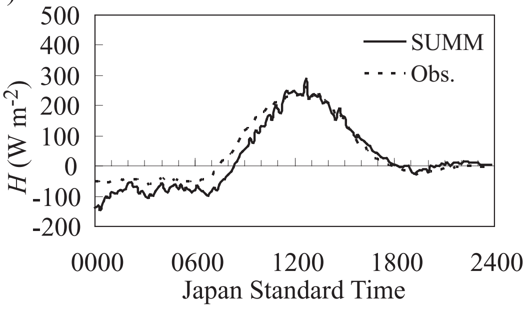
The simulated surface temperatures slightly underestimate the observed values (Figure 8. However, the maximum error of surface temperature is within 3 K, and the diurnal trend is well simulated.

Although the simulated energy balances and surface temperatures of individual surfaces show some systematic deviations from measured values, the simulated energy balance components of the surface-layer (Rn, H and G) agree fairly well with measurements (Figure 9). Probably, the negative and positive biases of heat fluxes of different surfaces have some cancellation when the process is integrated over the canopy-layer. This is expected in the present numerical scheme since the 'surface-layer' bulk transfer coefficient is first prescribed from the conventional formulation of roughness parameters and then it is distributed onto individual surfaces. Such top-down parameterizations guarantee the compatibility of the previous knowledge of surface-layer parameterizations, although the influence of local stability has not been taken into account. In contrast, bottom-up parameterizations, in which local bulk transfer coefficients are first determined from the local meteorological condition in the vicinity of surfaces and then they are integrated over the canopy-layer, are an alterative approach and more straightforward than the top-down approach (Masson, 2000; Kusaka et al., 2001). In using the bottom-up approach, however, the absolute values of local bulk transfer coefficients are more crucial, and thus they should be carefully calibrated on site. The review of Hagishima et al (2005) pointed out that the local bulk transfer coefficients vary considerably from site to site and are currently difficult to be arranged to a simple formulation whereas their relative values among individual surfaces are robust irrespective of measurement site and method, as shown in Figure 3.

(a) *Rn*



(b) *H*



(c) *G*

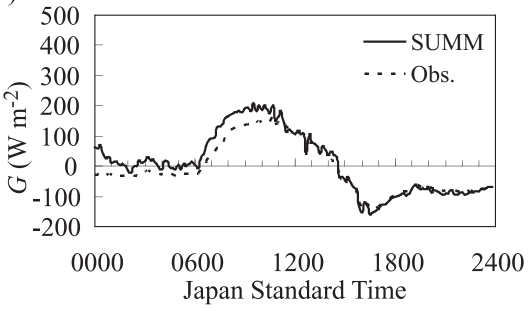


Figure 10 Energy balance components of the surface-layer throughout the day. Bold lines are simulation results and dotted lines are measurements. Components are (a) net radiation, (b) sensible heat flux, and (c) conductive heat flux.

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