EVALUATION OF SIMPLE URBAN ENERGY BALANCE FOR MESO-SCALE SIMULATION (SUMM) TO REAL URBAN FIELDS

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This paper reports on the evaluation of Simple Urban Energy Balance for Mesoscale Simulation (SUMM) to two cities (i.e. Kugahara, Japan; Basel, Switzerland) in winter, spring and summer. This new version of SUMM is incorporated with vegetation scheme to meet the existence of vegetation fraction in real city. SUMM simulated the urban energy balance and radiative temperature (T_r) generally well in Kugahara and Basel. However, SUMM slightly underestimated T_r in the nighttime and overestimated T_r in the daytime in Basel.

Key Words : *Urban Canopy Model, Energy Balance, Vegetation Scheme, Evaluation in Real City*

1. INTRODUCTION

Modeling urban surface geometry through urban canopy model (UCMs) is a nowadays scientific way to simulate energy exchange between surface and atmosphere. Several UCMs have already been developed[1),2),3),4),5)]. Simple Urban Energy Balance for Mesoscale Simulation (SUMM) has also been developed with unique feature: the three dimensionality of surface geometry. This feature is considered as an advanced model and the main advantage of SUMM among the reports on the developed UCM.

Validation as well as evaluation of UCM is very important, since UCM is usually developed by simple parameterization[6)]. However, to our knowledge, there is very limited number of validation study of UCM using observed data in real urban field[7), 8)].

SUMM was already evaluated using Small Scale model experiment in Matsusaka, Mie prefecture, Japan (34º34'N, 136º32'N)[5)] and also using Comprehensive Outdoor Scale Model Experiment (COSMO) located at campus of Nippon Institute of Technology Saitama prefecture, Japan (39º04'N, 139º07'E)[9)]. The geometry of small scale model as well as COSMO model are completely the same as SUMM model geometry. The evaluation fully conducted for one year period, representing good performance of SUMM to all season. This is an advantage of SUMM, which is already validated with physical model.

The next step of study is to implement SUMM into a real city environment mainly characterized by irregular geometry and heat emission of the buildings and some vegetation cover. In this study, SUMM which is incorporated with vegetation scheme, will be evaluated to two urban databases: Kugahara (Japan) and Basel (Switzerland, Central Europe). The diversity of the city, in terms of surface conditions, locations and time, sets challenges for SUMM to show its performance.

2. DESCRIPTION OF SUMM

The concept of the urban surface energy balance which was defined by Oke[10)] is written as:

$$Q^* + Q_F = dQ_S + Q_H + Q_E + \Delta Q_A \qquad (1)$$

with Q^* is net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the turbulent sensible heat flux, Q_E is the turbulent latent heat flux, ΔQ_S is

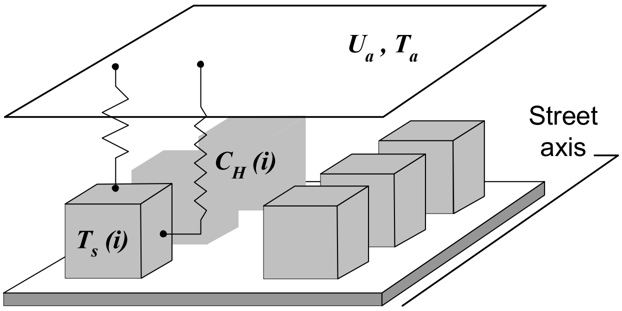

Fig.1 Scheme Geometry of SUMM

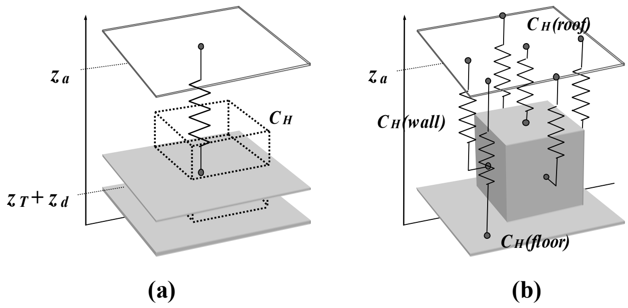

Fig.2 Parameterization of Bulk Transfer Coefficient

the storage heat flux, and ΔQ_A is the net advective heat flux, respectively. In this paper the existence of ΔQ_A and Q_F are not considered, because those are expected to be very small in Kugahara and Basel sites as shown in chapter 3.

The Simple Urban Energy Balance for Mesoscale Simulation (SUMM) assumes a simple building array and simulates energy balance and surface temperature at constituent faces (i.e. a roof, a floor, and four vertical walls). The features of SUMM are briefly explained below. Detailed description of SUMM is given in the reference[5].

(1) Model geometry

Figure 1 illustrates the surface geometry of SUMM. The model explicitly considers three-dimensional urban surfaces composed of six local faces (a roof, a floor, and four vertical walls). Each building has a square horizontal cross section and is regularly arranged. Such a simple three-dimensional surface geometry can be identified using only two geometrical parameters such as the plane area index (λ_p) and frontal area index (λ_f), which are defined as,

$$\lambda_P = W^2/(W+L)^2 \quad (2)$$

$$\lambda_f = W\,H/(W+L)^2, \quad (3)$$

where W is the horizontal dimension of building, H is the height of the buildings, and L is the width of the streets respectively.

(2) Theoretical radiation scheme

SUMM theoretically solves the multi-reflection of shortwave (direct and diffuse components) and longwave radiation among the six faces by assuming Lambertian surfaces and using view factors and sunlit/shadow distributions[11]. This unique theoretical radiation scheme greatly reduces the computational costs.

(3) Top-down parameterization for bulk transfer coefficient

The sensible and latent heat fluxes of the six faces are calculated using the network of resistance formulation as well as other simple models[1),2)]. As is well known, bulk transfer coefficients of local faces ($C_H(i)$), are key parameters in this formulation. However, $C_H(i)$ are currently difficult to arrange in a simple formulation[12]. Monin-Obukhov similarity theory (MOST) is valid only for the whole surface layer and the application of MOST to a local surface is physically incorrect. SUMM uses a 'top-down' approach to determine $C_H(i)$. First, the surface layer bulk transfer coefficient (C_H) is determined by the MOST framework (**Figure 2(a)**) and then the value of C_H is distributed to local values of $C_H(i)$ (**Figure 2(b)**).

(4) Room temperature prediction

Room temperature (T_{in}) is predicted by solving the following energy-conservation equation for the room air:

$$c_p \rho V_{in} \frac{\partial T_{in}}{\partial t} = G_{in} A_{lot} \quad (4)$$

where, $c_p\rho$ (J m^{-3} K^{-1}) is the volumetric heat capacity of air, V_{in}(m^3) is the volume of the room, G_{in}(W m^{-2}) is the conductive heat flux of the room wall, and A_{lot} (m^2) is the area of the unit lot area.

(5) Vegetation model

In order to take into account the vegetation effect on urban canopy, SUMM predicted such effect using slab-type model vegetation. Urban surface layer is divided into an non-urban (vegetated) fraction (A_{veg}) and an urban fraction ($1- A_{veg}$). These assumptions resulted on the weighted area average fluxes (WRF) concept which applied into sensible heat (H) as well as latent heat flux (LE). Sensible and latent heat weighted by area average is formulated into the following equations :

$$H_{WRF} = H_{summ}(1 - A_{veg}) + H_{veg} A_{veg} \quad (5)$$

$$LE_{WRF} = LE_{summ}(1 - A_{veg}) + LE_{veg} A_{veg} \quad (6)$$

Surface temperature (T_{SURF}) is derived as a weighted C_H and area averaged temperature, as :

$$T_{SURF} = \frac{C_H T_H (1 - A_{veg}) + C_{Hveg} T_{Hveg} A_{veg}}{C_{HWRF}} \quad (7)$$

where C_{HWRF} is the total bulk transfer coefficient of whole surface. C_{HWRF} is calculated from equation 8.

$$C_{HWRF} = C_H (1 - A_{veg}) + C_{Hveg} A_{veg} \quad (8)$$

3. SITE DESCRIPTION

Two cities in different country and continent, i.e. Kugahara (Japan) and Basel (Switzerland) were chosen as evaluation site, since both sites provide one year measurement data. Overview condition of two sites was described on **Table 1**. Here we present a brief overview of the observation sites.

(1) Kugahara

Kugahara is a suburban area located in densely populated low story houses in Tokyo (35°34'N, 139°41'E). The vegetation is scattered in backyards and playgrounds in the residential area. Gentle terrain and rows of houses homogeneously extends at least 1-km to the south, west, and north from the tower. The terrain within 200-m to the east is gently slanting down with an inclination angle of 5.7°. At the foot of the slope, light industrial factories and higher multistory apartments are mixed with residential homes but their roof level is almost same as the canopy top around the tower[13]. Anthropogenic heat were reported 13 W/m^2, 20.6 W/m^2, and 13.16 W/m^2 on April 2002, December 2001 and July 2001 respectively.

(2) Basel

Basel is located in north-west Switzerland on the river Rhine, consider as Switzerland's third most populous city. The tower measurement surrounding is characterized by a typical European urban surface with residential row houses, enclosing large inner courtyards. The backyards are either open (green spaces) or built-up by one-storey garages, parking lots and flat commercial-industrial buildings. The neighborhood has a high population density between 200 and 300 inhabitants ha^{-1}. The shape of the roofs is a mixture of approximately 50% flat and 50% pitched roofs. Estimation of annual average anthropogenic heat was around 20 W/m^2 [14].

Table 1 Description of Kugahara and Basel sites

Site	Kugahara [13]	Basel [14]
Location	35°34'N,139°41'E	47°33'N, 7° 35'E
Height of Tower (m)[a]	29	32
Date of Measurement	May 01- Apr 02	Nov 01- Jul 02
Building Height (m)	7.3	14.6
Plan Area Index (λ_p)	0.326	0.54
Frontal Area Index (λ_f)	0.3	0.272 [b]
Vegetation Ratio	0.20	0.16

[a] Height of tower also represented measurement height

[b] Calculated from plane area index and complete aspect ratio data.

4. EVALUATION OF SUMM

(1) Simulation days

Almost a year data were provided by two sites, except autumn season for Basel (**Table 1**). Three days data on Feb 3rd , April 2nd , and May 31st, 2002 were chosen from Basel representing winter, spring and summer, respectively. Kugahara provides ensemble data during May 2001- April 2002. Data of December 2001, April 2002, and July 2001 were simulated representing winter, spring and summer.

(2) SUMM forcing data

Five forcing data were provided from corresponding site : incoming shortwave radiation ($S^{\downarrow}$), incoming longwave radiation ($L^{\downarrow}$), wind velocity (U_a), humidity (q_a), and air temperature (T_a). They are given at the top column of SUMM. The conductive heat flux ΔQ_S, is computed as the residual of the measured energy balance and thus errors in any of the other fluxes accumulate in this part.

(3) Input parameter

Table 2 shows input radiative and thermal properties of SUMM. Facet albedo was determined so as to best fit simulated net shortwave radiation to observed value, because it is difficult to obtain value of facet albedo from measurement site. Thermal properties setting in Basel were obtained from Martilli et al. (2002)[3].

The zero plane displacement height (z_d) and roughness length for momentum (z_0) were predicted from the geometric parameters (λ_p, λ_f) using the morphometric method of Macdonald (1998)[16]. The roughness length for heat (z_T) was predicted using the following experimental formula of the natural logarithm of the ratio of the roughness length for momentum to heat (κB^{-1}; Kanda et al., 2006) [16]

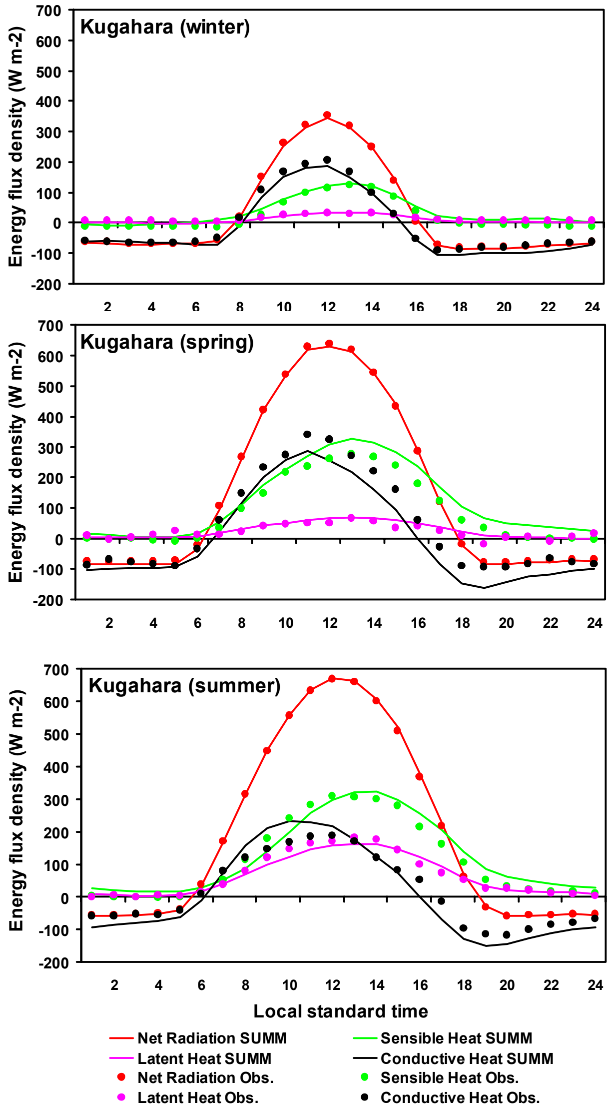

Fig. 3 Energy Balance in Kugahara

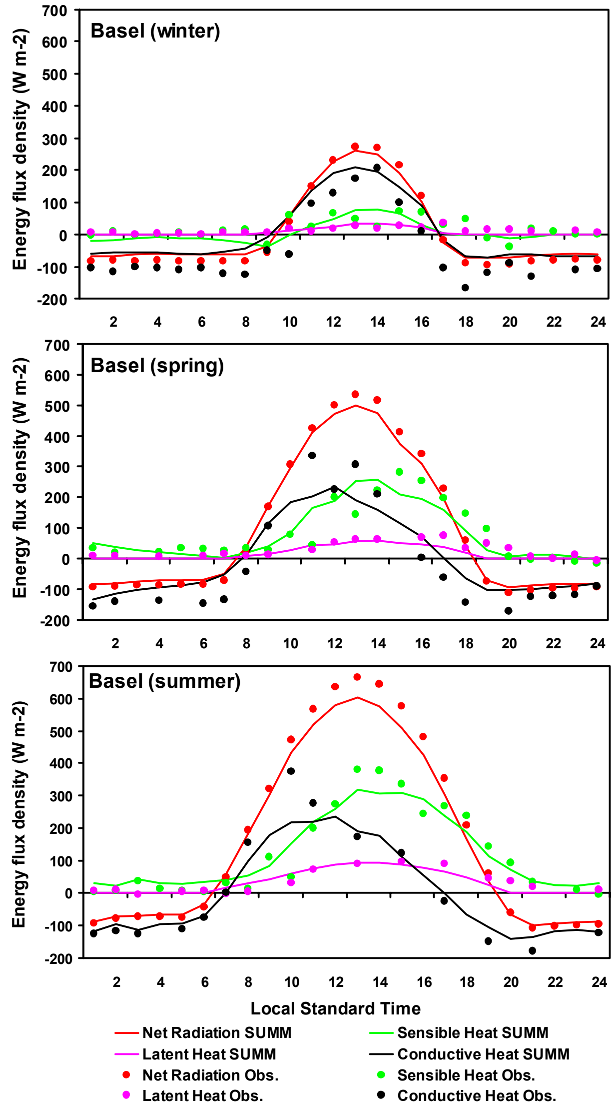

Fig. 4 Energy Balance in Basel

$$\kappa B^{-1} = 1.29 \mathrm{Re}^{*-0.25} - 2 \quad \left(\mathrm{Re}^* = \frac{u^* z_0}{\nu} \right) \tag{9}$$

In the formula above, Re* is the roughness Reynolds number, u^* is the friction velocity at the reference height, and ν is the molecular diffusivity of air. Equation (6) generally follows the data from three urban sites as well as from COSMO. The relative values of bulk transfer coefficients of local faces ($C_H(i)/C_H(roof)$) were set to unity, because we have no enough dataset for local bulk transfer coefficient[12]. Note that $C_H(i)/C_H(roof)$ is not sensitive for the surface layer energy balance and surface temperature[9].

5. RESULTS AND DISCUSSION

Evaluations were performed for surface layer energy balance and radiative temperature (T_R). T_R was calculated from upward long-wave radiation

Table 2 Thermal and radiative parameter of both sites

Parameter	Faces	Kugahara	Basel
Volumetric heat capacity ($c_p\rho$) (10^6) ($\mathrm{Jm^{-3}\,K^{-1}}$)	Roof	2.5	1.0[17]
	Wall	2.5	1.0[17]
	Road	2.5	1.4[17]
Thermal conductivity (λ) ($\mathrm{W\,m^{-1}\,K^{-1}}$)	Roof	1.01	0.67[17]
	Wall	1.01	0.67[17]
	Road	1.01	0.40[17]
Emissivity (ε)	Roof	0.98	0.90[17]
	Wall	0.98	0.90[17]
	Road	0.98	0.95[17]
Albedo	Roof	0.18	0.12
	Wall	0.18	0.12
	Road	0.18	0.12

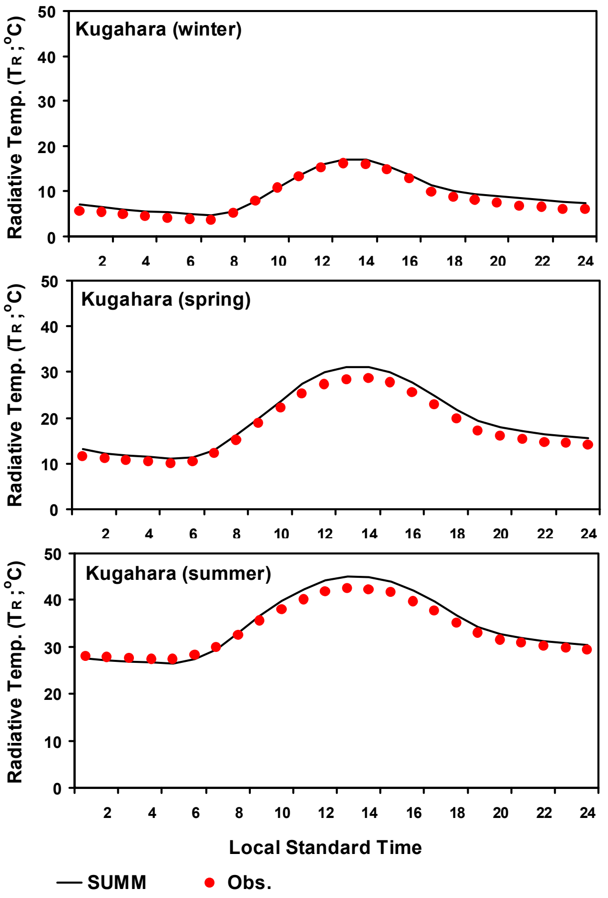

Fig. 5 Radiative temperature in Kugahara

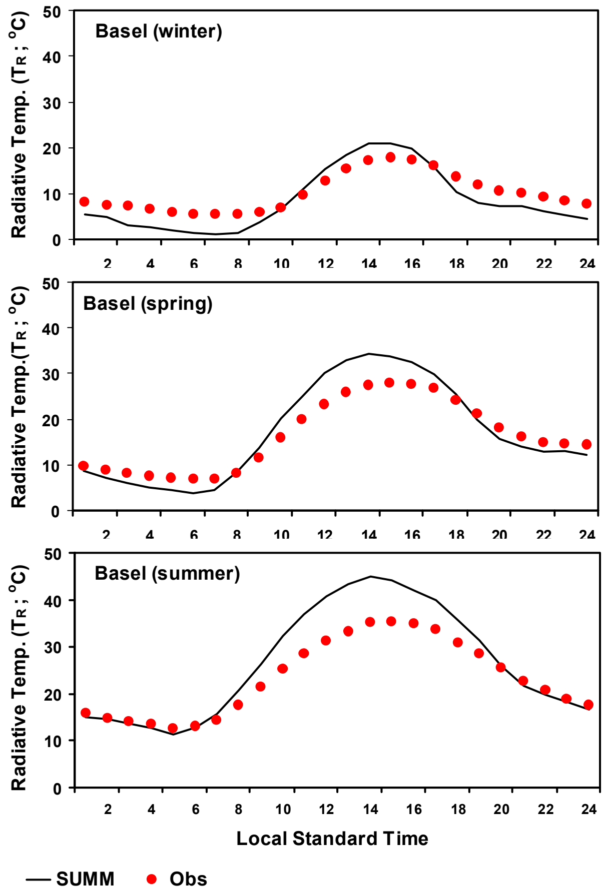

Fig. 6 Radiative temperature in Basel

with the corrected emissivity of 0.95[18)].
T_R is defined as :

$$T_R = (L^{\uparrow} / \varepsilon\sigma)^{0.25} \quad (10)$$

where ($L^{\uparrow}$) is the longwave upward radiation, ε is the emissivity, and σ is the Stefan-Boltzmann constant.

(1) Results

a) Energy Balance

Figure 3 shows evaluation results of diurnal variation of energy fluxes at Kugahara site in winter, spring and summer. SUMM simulated diurnal variation of each component of energy fluxes quite well. The bias of storage heat was slightly larger than the other energy fluxes.

Figure 4 is the same figure as figure 3, but for Basel site. In Basel, SUMM also simulated the energy fluxes generally well. However, SUMM slightly underestimated the net radiation especially in summer.

b) Radiative Temperature

Figure 5 shows an evaluation result of the radiative temperature (T_R) at Kugahara site. In Kugahara, SUMM also simulated diurnal variation of the T_R well. SUMM slightly over estimated the T_R in daytime especially in spring and summer. However, looking overall, biases were quite small.

Figure 6 is the same figure 5, but in Basel site. The biases of the T_R are larger than in Kugahara site. SUMM underestimated the T_R in nighttime and overestimated the T_R in the daytime.

(2) Discussion

Overall, SUMM simulated energy balance and radiative temperature well. However, there were small biases in net radiation and relatively large biases in radiative temperature in Basel site (**Figure 4** and **Figure 6**). One possible reason of these biases is addressed to representatives of radiation measurement in Basel site. As shown in **Table 1**, the ratio of measurement height of Q^* to the building height (Z/H) is about 2 in Basel, while the measurement height of Q^* is Z/H=3.5 in Kugahara. In Basel site the radiometer was also installed above the street canyon. Therefore, the contribution of canyon floor to the measured upward longwave radiation became larger than the area representative value. In the daytime, the surface temperature of floor (road) is lower, since the floor has a large fraction of shadow areas. On the contrary, the nighttime temperature of canyon floor became higher than the other constituent faces because of infrared multi-reflection within the street canyon. This lead to the lower T_R in the daytime and the higher T_R in the nighttime, respectively, compared with the area representative T_R.

The disagreement of Q^* between SUMM and the observation in Basel is also attributed to the same reason, since the smaller value of the daytime T_R lead the larger value of the daytime Q^*.

Parameterization of bulk transfer coefficient might be one of the other possible reasons of the biases. Under calm wind condition, SUMM tends to underestimate bulk transfer coefficient[9)]. Lower value of bulk transfer coefficient would underestimate sensible heat flux and create higher surface temperature in the daytime.

6. CONCLUSION

The new version of SUMM which is incorporated with vegetation scheme, simulated the urban energy balance in Kugahara quite well. The energy balance in Basel is presented by SUMM with some disagreement. Location of Basel measurement site, (i.e., the street canyon and the low measurement height) might be one of possible reasons of the disagreements.

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