Roughness Lengths for Momentum and Heat Derived from Outdoor Urban Scale Models

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ABSTRACT

Urban climate experimental results from the Comprehensive Outdoor Scale Model (COSMO) were used to estimate roughness lengths for momentum and heat. Two different physical scale models were used to investigate the scale dependence of the roughness lengths; the large scale model included an aligned array of 1.5-m concrete cubes, and the small scale model had a geometrically similar array of 0.15-m concrete cubes. Only turbulent data from the unstable boundary layers were considered. The roughness length for momentum relative to the obstacle height was dependent on wind direction, but the scale dependence was not evident. Estimated values agreed well with a conventional morphometrical relationship. The logarithm of the roughness length for heat relative to the obstacle height depended on the scale but was insensitive to wind direction. COSMO data were used successfully to regress a theoretical relationship between the logarithmic ratio of roughness length for momentum to heat, and Re*, the roughness Reynolds number. Values of κB−1 associated with Re* for three different urban sites from previous field experiments were intercompared. A surprising finding was that, even though surface geometry differed from site to site, the regressed function agreed with data from the three urban sites as well as with the COSMO data. Field data showed that κB−1 values decreased as the areal fraction of vegetation increased. The observed dependency of the bulk transfer coefficient on atmospheric stability in the COSMO data could be reproduced using the regressed function of Re* and κB−1, together with a Monin–Obukhov similarity framework.

1. Introduction

Monin–Obukhov similarity theory (MOST) is a theoretical basis to estimate momentum and scalar fluxes in the atmospheric surface layer and is commonly used in meteorological numerical modeling systems. In the MOST framework, roughness lengths for momentum and heat (zm and zh, respectively) are the key parameters identifying the aerodynamic features of underlying surfaces. Roughness lengths are often assumed to be constants that are a function of the surface type (e.g., Garratt and Hicks 1973; Garratt and Francy 1978). However, recent studies have suggested that the roughness length for heat over vegetated or even bare surfaces depends not only on the surface type but also on meteorological variables (e.g., Sun and Mahrt 1995; Brutsaert and Sugita 1996; Malhi 1996; Verhoef et al. 1997; Qualls and Hopson 1998; Sun 1999; Ma and Dagupaty 2000).

The roughness lengths of interest in this paper are those over urbanlike surfaces. Field and laboratory measurements of zm over various urbanlike geometries have been collated, and theoretical frameworks to determine zm have been well established (e.g., see review by Grimmond and Oke 1999). In contrast, zh data over urban areas are relatively rare (Voogt and Grimmond 2000; Sugawara 2001; Moriwaki and Kanda 2006).

Recent studies using urban canopy models (UCMs) have rapidly progressed (e.g., Masson 2000; Kusaka et al. 2001; Martilli et al. 2002; Kanda et al. 2005), mainly to estimate surface energy balances, and the computed energy budgets are more complicated than in the MOST framework. UCMs have a great advantage from...
the perspective of the energy balance in that the large heat capacity corresponding to the effective volume of urban materials and the resulting large thermal inertia can be well simulated. From an aerodynamic perspective, however, UCMs require local heat transfer coefficients beyond the assumptions that characterize a valid MOST framework. MOST is only valid for heat transfers in the surface layer, and application to the local heat transfer process within a canyon is physically incorrect. The MOST framework, when properly applied in the surface layer, can be a good check of the robustness of the bulk aerodynamic features in UCMs.

This study estimated momentum and heat roughness lengths using Comprehensive Outdoor Scale Model (COSMO) experiments for urban climate and considered the applicability of the conventional MOST framework to urbanlike surfaces. Outdoor scale models differ from field data in that they are simple and yet incorporate many of the real-life difficulties in estimating the spatial variability in material, geometry, and land use. Such scale models can provide supplemental information given realistic synoptic conditions of sunshine and wind fluctuations. The two models used in this study had different scales but similar geometries and concrete compositions and provided unique information on the scale dependence of physical parameters subject to realistic atmospheric stabilities. The scale of the lower structure of the atmosphere relative to each of the scale models differed by an order of magnitude.

2. Theoretical background

a. Roughness length for momentum and heat

Momentum flux in the surface layer is defined by the following bulk transfer equation:

\[ M = \rho u^2 = \rho C_m U^2 = \rho (U/r_{am}), \]

where \( M \) is momentum flux (kg \( m^{-1} \) \( s^{-2} \)), \( \rho \) is the air density (kg \( m^{-3} \)), \( u^* \) is the friction velocity (m \( s^{-1} \)), \( U \) is the wind velocity (m \( s^{-1} \)), \( C_m \) is the drag coefficient, and \( r_{am} \) is the aerodynamic resistance for momentum (s \( m^{-1} \)). Using MOST yields

\[ r_{am} = \frac{1}{C_m U} = \frac{1}{\kappa u^*} \left[ \ln \left( \frac{z - d}{z_m} \right) - \Psi_m \left( \frac{z - d}{L} \right) \right], \]

where \( \kappa \) is the von Kármán constant, \( z \) is the height (m), \( d \) is the displacement height (m), \( z_m \) is the roughness length for momentum (m), \( \Psi_m \) is the integrated stability function for momentum, and \( L \) is the Obukhov length (m).

Sensible heat flux is also described with a bulk transfer equation:

\[ H = -\rho c_p u^* T_w = \rho c_p C_h U(T_0 - T_w) = \rho c_p [(T_0 - T_w)/r_{ah}], \]

where \( H \) is the sensible heat flux (W \( m^{-2} \)), \( C_h \) is the bulk transfer coefficient for heat, \( c_p \) is the heat capacity of air at constant pressure (J kg\(^{-1}\) K\(^{-1}\)), \( T_0 \) is the air temperature (K), \( T_w \) is the aerodynamic surface temperature (K), \( T_a \) is the temperature scale (K), and \( r_{ah} \) is the aerodynamic resistance for heat (s \( m^{-1} \)). Heat transfer generally encounters more aerodynamic resistance than momentum does because heat transfer is significantly influenced by molecular diffusion near the surface of each roughness element. Momentum flux is more influenced by form drag. The excess of aerodynamic resistance \( r_{ah} \) accounts for this difference and is defined as

\[ r_{ah} = r_{am} + r_{bh} = \frac{1}{C_h U} \]

\[ = \frac{1}{\kappa u^*} \left[ \ln \left( \frac{z - d}{z_m} \right) - \Psi_h \left( \frac{z - d}{L} \right) \right] + \frac{1}{\kappa u^*} \ln \left( \frac{z_m}{z_h} \right), \]

where \( \Psi_h \) is the integrated stability function for heat and \( z_h \) is the roughness length for heat (m). The ratio between momentum and heat roughness lengths \( \kappa B^{-1} \) is introduced for convenience (Owen and Thomson 1963; Chamberlain 1968):

\[ \kappa B^{-1} = \ln(z_m/z_h). \]

b. Representative surface temperatures

The aerodynamic surface temperature \( T_0 \) in Eq. (3) is the temperature extrapolated logarithmically toward the level \( d + z_h \). In practice, the measurements of \( T_0 \) and \( z_h \) are difficult (Troufleau et al. 1997). However, it is possible to measure some other surface temperatures and to replace \( T_0 \) in Eq. (3). If the urban surface of interest is completely composed of \( n \) local facets, such as walls, the ground, and roofs, the major representative surface temperatures can be explicitly computed as below. First, the effective surface temperature \( T_{ef} \) can be derived from the conservation of local heat flux contributions from each facet (Kanda et al. 2005) as
where $T_H$ is the surface temperature (K) of facet $i$, $A(i)$ is the area ($m^2$) of facet $i$, and $C_m(i)$ is the local bulk transfer coefficient between facet $i$ and the reference height. Temperature $T_H$ is theoretically equivalent to $T_o$, and the physical meaning is clear but still very difficult to measure because a dataset of local bulk transfer coefficients is required. Second, the radiative surface temperature $T_R$ is defined as

$$T_R = \frac{\sum_{i=1}^{n} T_s(i)^4 W(i) A(i)}{\sum_{i=1}^{n} W(i) A(i)},$$

where $W(i)$ is the view factor from the radiometer to the unit area of facet $i$. Note that a complete derivation of $T_R$ must consider multireflection processes of longwave radiation within the canopy (e.g., Kanda et al. 2005). However, these are ignored in Eq. (7) for simplicity. Using both upward and downward measurements of longwave radiation and surface emissivity, $T_R$ is estimated directly. Such a technique has been widely used for various land surfaces, although computed values vary with the position and angle of radiometers. Third, the complete surface temperature $T_C$ is the area-weighted temperature (Voogt and Oke 1997),

$$T_C = \frac{\sum_{i=1}^{n} T_s(i) A(i)}{\sum_{i=1}^{n} A(i)}.$$

Equations (6)–(8) show that representative surface temperatures differ from each other except when local bulk transfer coefficients and local view factors for constituent facets are all the same. Therefore, the estimated $z_h$ differs depending on the representative temperature used. This is one of the reasons behind the variability in estimated $z_h$ (Malhi 1996; Voogt and Grimmond 2000). Screen temperature $T_s$, the “air” temperature at a screen level within the roughness layer, differs from these surface temperatures and is practically meaningless for estimating $z_h$, because it is unaffected by excess aerodynamic resistance between the air and the rigid surfaces. Values are used for later comparisons with other surface temperatures. Figure 1 shows a schematic of roughness lengths for momentum and heat, corresponding resistances, and related variables.

3. Outdoor scale model experiments

a. Experimental setup

The physical scale models were located on a portion of the campus of Nippon Institute of Technology, Saitama Prefecture, Japan (39°04’N, 139°07’E). The study site is on the northern outskirts of metropolitan Tokyo and is 100 km from the Pacific Ocean. Gentle terrain extends at least several tens of kilometers in all direction from the site. Land use is paddy field in summer and bare soil in winter. Dominant seasonal winds are northerly in winter (November–April) and southeasterly in summer (May–October). The scale models were designed such that the longer $x$ axes (street line) were roughly on a northwest–southeast line (Fig. 2). Hereinafter, wind direction (WD) is defined as follows: WD = 0° indicates the wind along the northwest–southeast experimental $x$ axis (from northwest to southeast in winter and from southeast to northwest in summer). Positive WD is a direction clockwise from this axis (Fig. 2c).

Two different scale models were constructed. Cubic concrete blocks 1.5 m per side, with 0.1-m-thick walls, composed the large scale model. The blocks were distributed in an aligned array such that the plane area density was 0.25 on the concrete pavement with dimensions of 100 m × 50 m. Cubic, solid concrete blocks 0.15 m per side composed the small scale model. Three 12-m towers were constructed at $x = 8, 50$, and 92 m
along the x axis [(i), (ii) and (iii) in Fig. 2a]. The smaller blocks were regularly distributed with a plane area density of 0.25 on flat concrete plates with dimensions of 12 m × 12 m (Fig. 2b). The two models were adjacent (Fig. 2a).

Measurement instruments were positioned in the horizontal and vertical directions with careful consideration to the fetch and internal boundary layer (IBL) height. Table 1 summarizes information on the internal boundary at measurement points. Measurements used to estimate roughness lengths in the large scale model were conducted at the center of the model [(ii) in Fig. 2a]. Preliminary experiments considered vertical profiles of turbulent statistics and temperature at the central tower and were used to estimate the heights of the internal boundary layer and roughness sublayer. In this setting, the IBL height relative to the obstacle height \( (H) \) ranged from 3.5 to 4. The IBL height-to-fetch ratio agreed with a typical value of \( \frac{1}{10} \) for smooth-to-rough roughness changes (e.g., Garratt 1992). Measurements in the small scale model were conducted alternatively at the two edges of the model.

**Table 1.** Information on the internal boundary at measurement points; FC: fetch, IBL: internal boundary layer height, RS: roughness sublayer height, H: obstacle height, \( z_{\text{sonic}} \) and \( z_{\text{rad}} \): measurement heights of sonic anemometers and radiometers, respectively.

<table>
<thead>
<tr>
<th>Obs point</th>
<th>FC/H</th>
<th>IBL/H</th>
<th>( z_{\text{sonic}}/H )</th>
<th>( z_{\text{rad}}/H )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large scale (ii) in Fig. 2</td>
<td>33</td>
<td>3.5–4.0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>model</td>
<td>50</td>
<td>1.5–2.0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Small scale (iv) in Fig. 2 (summer)</td>
<td>73</td>
<td>2.5–3.0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>model (v) in Fig. 2 (winter)</td>
<td>11</td>
<td>1.5–2.5</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
The minimum IBL height was 2.5H. Therefore, the reference height $z_{ref}$ was set to 2.0H within the IBL for the two models; turbulent fluxes and reference variables were measured at $z_{ref}$. For the large scale model, $z_{ref}$ was between the roughness and inertial sublayers, and for the small scale model $z_{ref}$ was in the roughness sublayer. Moreover, data for wind directions of $|\text{WD}| > 45^\circ$ were ignored (Fig. 2c) to ensure appropriate fetch conditions. A compact sonic anemometer with a sensor span of 0.05 m and a sampling frequency of 50 Hz (Kaijo TR90-AH), and an infrared CO$_2$/H$_2$O open-path analyzer (Li-Cor, Inc., LI-7500) with a sampling frequency of 20 Hz were installed at $z_{ref}$ for each model. The instruments estimated momentum and sensible and latent heat fluxes using eddy covariance (EC) methods. Air temperature was measured at a sampling frequency of 1 Hz by 50-μm bare thermocouples that were installed at $z_{ref}$ and 0.5H. Upward and downward shortwave and longwave radiance were separately measured at a sampling frequency of 1 Hz at 3H with a radiation-balancing meter (Eko MR-40).

The unique instrumentation for the COSMO allowed direct measurement of conductive heat flux and surface temperature for each unit of the constituent surface, that is, rooftops, vertical walls, and the floor/ground. This was achieved by using very thin and highly accurate heat plates that were coated with the same material used to make the obstacles. A total of 164 heat plates (Captec HF-50, 0.05 m × 0.05 m in size and 0.4 mm thick) were used to cover completely a unit of constituent surfaces in the large scale model. A total of 72 heat plates (Captec HF-300, 0.3 m × 0.3 m in size and 0.4 mm thick) were used to cover completely a unit of constituent surfaces in the small scale model. The sampling frequency was 1 Hz.

### b. Data processing

Turbulent statistics were calculated using coordinate axes rotation (McMillen 1988) and a linear detrend. The integration time for all relevant variables discussed below was typically 60 min, even though sampling frequencies varied from instrument to instrument. Note that 30-min averaging was not significantly different except that estimated turbulent statistics exhibited larger scatter. Observed data used in this analysis were recorded between December 2004 and December 2005. An exception was the heat plate measurement for the large scale model that recorded measurements only from October 2005 to December 2005. No data were available from August 2005 to October 2005 because of mechanical troubles caused by heavy rains. Data were used only from days on which precipitation did not occur and during hours for which the WD was always within 45° along the x axis, thereby optimizing data quality. This criterion of WD largely reduced the number of available data but guaranteed the appropriate fetch conditions and resulting high quality of turbulent statistics.

The surface energy balance in this experiment did not close, that is, the observed net radiation minus the conductive heat flux did not equal the sum of the sensible and latent heat fluxes (Kanda et al. 2004). Corrections, such as the Bowen ratio method, were not made to correct the energy imbalance. In this study, just the observed sensible heat flux was used to estimate roughness lengths so as to ensure consistency with fluxes estimated from field data, all of which lacked estimates of measured heat storage. Anomalous results due to small turbulent flux values were avoided by calculating roughness lengths for momentum and heat only for those cases where $M > 0$ kg m$^{-1}$ s$^{-2}$ and $|H/c_p\rho| > 0.02$ K m s$^{-1}$. As a consequence, stable cases were completely screened out because the downward sensible heat fluxes were always below this criterion, and unstable runs remained because stable cases were rarely only observed. The number of valid data values in the analysis was about 800 based on a 60-min averaging time.

### c. Procedure to estimate roughness lengths

The momentum roughness length $z_m$ was estimated iteratively using Eq. (9), which was derived from Eqs. (1) and (2),

$$\frac{1}{\kappa} \ln \left( \frac{z - d}{z_m} \right) - \Psi_m \left( \frac{z - d}{L} \right) = \frac{U}{u_a}. \quad (9)$$

Friction velocity $u_a$, temperature scale $T_\psi$, wind velocity $U$, air temperature $T_a$, and the Obukhov length $L = u_a^2 T_a/kg T_\psi$ were directly determined from measured values at $z = z_{ref}$ at the center of the large scale model [(ii) in Fig. 2a] and at the two edges of the small scale model [(iv) and (v) in Fig. 2b]. A morphometric method (Macdonald et al. 1998) was used to estimate the zero-plane displacement height $d$; the normalized value was 0.4 H. The integrated stability functions for momentum
and heat ($\Psi_m$ and $\Psi_h$) were the same as those in Paulson (1970). Roughness lengths for heat $z_h$ were estimated iteratively using Eq. (10), which was derived from Eqs. (3) and (4):

$$\frac{1}{\kappa} \ln \left( \frac{z - d}{z_m} \right) - \Psi_h \left( \frac{z - d}{L} \right) + \frac{1}{\kappa} \ln \left( \frac{z_m}{z_h} \right) = \frac{(T_0 - T_w)}{T_H}.$$  

(10)

Measured values were used as input variables in Eq. (10) and also in Eq. (9). In Eq. (10), $z_m$ was from Eq. (9), and several representative surface temperatures were used instead of $T_0$, as mentioned below.

Complete surface temperature $T_C$ was calculated from direct heat plate observations of the surface temperature [Eq. (8)]. The effective surface temperature $T_{H}$ was calculated using Eq. (6) and the observed surface temperatures and a local bulk transfer coefficient dataset (Kanda et al. 2005). Radiative temperature $T_R$ was calculated from observed upward and downward longwave radiation and an emissivity correction following Arnfield (1982). A uniform emissivity of 0.95 was assumed. Screen temperature $T_e$ was set to the air temperature measured at 0.5 H. These surface temperatures generally differ from each other and consequently can produce significantly different roughness lengths for heat (Malhi 1996; Voogt and Grimmond 2000). However, $T_C$, $T_R$, and $T_H$ were very well correlated in this experiment, with correlation coefficients exceeding 0.99 (figures not shown). Because of the reduced scale, there were only small spatial temperature variations among the constituent surfaces, which explains the close agreement in measured surface temperatures during the COSMO experiments. Another reason for the good correlation between $T_C$ and $T_H$ is that the current cube array yielded small variations of local bulk transfer coefficients among constituent surfaces (Table 2). The good correlation between $T_R$ and $T_H$ is unexpected given the larger view factor of the roof relative to those of the other surfaces (Table 2). Figure 3 shows the diurnal variation of temperatures of the constituent surfaces. The surface temperature of the roof was relatively cool, and comparable to that of sunlit walls. The relatively cool roof temperature was likely due to the fact that all of the cube surfaces are composed of the same material, with no insulation of the roof surface (as is used in real residences). Close values in the representative surface temperatures meant that the influence of representative temperature ($T_H$, $T_C$, and $T_R$) on the estimated roughness length for heat was small (Table 4). Therefore, results using $T_R$ are mainly discussed because that temperature had the most valid data (Table 4).

Figure 3 clearly shows that the two scale models were characterized by different diurnal variations in surface temperature because of different volumetric heat capacity. Consequently, surface energy balances also differed (Kanda et al. 2006). However, the difference in thermal inertia between the two scale models did not introduce problems in the estimation of $z_h$ as long as all

**Table 2.** Local bulk transfer coefficients $C_{lh}$ and view factors $W$ at the COSMO site. The values of $C_{lh}$ are from Kanda et al. (2005). Ensemble means for nocturnal and near-neutral conditions with various wind directions are used.

<table>
<thead>
<tr>
<th></th>
<th>Roof</th>
<th>Floor</th>
<th>Wall (windward)</th>
<th>Wall (leeward)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W/W(\text{roof})$</td>
<td>1</td>
<td>0.59</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>$C_{lh}/C_{lh}(\text{roof})$</td>
<td>1</td>
<td>0.98</td>
<td>1.21</td>
<td>0.71</td>
</tr>
</tbody>
</table>

**Fig. 3.** Diurnal variation of surface temperatures at constituent surfaces (data for 18 Dec 2005): (a) large and (b) small scale models; NW: northwest-facing wall; NE: northeast-facing wall; SE: southeast-facing wall; SW: southwest-facing wall; R: roof; F: floor.
measured variables in Eqs. (9) and (10) were used for each of the models.

4. Results

a. Scale effect

Figure 4 and Table 3 show that momentum roughness length relative to the obstacle height $\overline{z}_m (= z_m/H)$ was slightly different for the two scale models; $\overline{z}_m$ of the small scale model was 10% larger on average than that of the large scale model. The roughness Reynolds number $Re^* (= z_m \mu u^*/\nu$, where $\nu$ is a kinematic molecular viscosity of $1.46 \times 10^{-5}$ m$^2$ s$^{-1}$), is a good index to show scale dependence of turbulent flow characteristics over rough surfaces. When $Re^*$ exceeds a critical value $Re^*_{crit}$, normalized turbulent statistics such as $\overline{z}_m$ are free of scale effects. Scale model estimates of $Re^*$ were larger than 100 (see Fig. 6), which is well above the values of $Re^*_{crit}$ reported from indoor experiments [$Re^*_{crit} = 2.5$ from Snyder (1972); $Re^*_{crit} = 5.4$ from Uehara et al. (2003)]. Therefore, the $Re^*$ criterion suggests that $\overline{z}_m$ is free of scale effects. Two possible explanations exist for the different $\overline{z}_m$ results in the two models. First, a slightly different internal boundary layer height relative to the cube height (IBL/H) may have affected $\overline{z}_m$ (see Table 1). Indoor experiments by Cheng and Castro (2002) demonstrated that $\overline{z}_m$ significantly changed with IBL/H, especially when IBL/H < 10. A review of turbulent flows over rough walls (Jimenez 2004) suggested that roughness length can be variable when IBL/H < 50. The second possibility is the influence of outer-layer turbulence. The scale of the lower structure of the atmosphere relative to each of the scale models is different by an order of magnitude. It is possible that large eddies in the atmospheric boundary layer scale have different effects on IBL turbulence, especially when IBL/H is small.

Figure 4 also shows a systematic relationship between $\overline{z}_m$ and WD. Larger WD yielded larger values of $\overline{z}_m$. Unfortunately, no other data exist that describe the relationship between $\overline{z}_m$ and WD and that can be compared with Fig. 4. However, previous data describing the relationship between $\overline{z}_m$ and array types (aligned/staggered) are available (Macdonald et al. 1998; Kanda 2006). A staggered cube array has not been tested at the COSMO site. However, the present result of an aligned array with WD = 45° can be assumed to approximate a staggered cube array with WD = 0°, and such results can be compared with theory (Macdonald et al. 1998). Figure 4 includes two lines from a conventional morphometric relationship (Macdonald et al. 1998) for arrays of aligned and staggered cubes, respectively, for which relationship the plane area index was 0.25, and the frontal area index varied according to WD. Estimates of $\overline{z}_m$ changed from one line (aligned array) to the other (staggered array) as WD changed. A large-eddy simulation (Kanda 2006) has also shown that staggered cube arrays have drag coefficients that are 2 times those of aligned cube arrays.

The roughness length for heat relative to the obstacle height $\overline{z}_h (= z_h/H)$ is generally smaller by several orders of magnitude with more scatter than the roughness length for momentum. Thus, the logarithmic values of $\overline{z}_h$ rather than the normal values are often discussed. Figure 5a and Table 3 show that values of $\overline{z}_h$ depend on the scale but are insensitive to WD. The scale dependence of $\overline{z}_h$ arises from the fact that heat transfer is significantly influenced by molecular diffusion near each surface of the roughness elements. Momentum transfer, in contrast, is controlled more by form drag. The scale dependence of $\overline{z}_h$ thus reflects molecular effects, and the insensitivity of $\overline{z}_h$ to WD reflects the
lack of form drag. If screen air temperature \( T_e \) is used instead of \( T_R \) to estimate \( \ln z_h \), the influence of molecular diffusion can be excluded. Figure 5b shows no scale effects, and values of \( \ln z_h \) derived from \( T_e \) are much larger than those derived from \( T_R \). Much of the excess resistance to heat transfer occurred very close to the rigid surfaces.

b. A theoretical relationship

Brutsaert (1982) theoretically related \( \kappa B^{-1} \) to the roughness Reynolds number \( \operatorname{Re}^* \) for rough surfaces,

\[
\kappa B^{-1} = a(\operatorname{Re}^*)^{0.25} - 2.0, \tag{11}
\]

where \( a \) is an empirical constant.

Figure 6 shows \( \kappa B^{-1} \) versus \( \operatorname{Re}^* \) as derived from COSMO data. The two lines in Fig. 6 were derived from the theoretical relationship in Eq. (11) with different values of \( a \); one used the original value of 2.46 from Brutsaert (1982), the other used a best-fit value of 1.29 regressed from the COSMO data. Brutsaert (1982) wrote, “It must be noted that the available experimental data only cover Reynolds numbers, \( \operatorname{Re}^* \), smaller than 1,000. Thus, (4.133) [Eq. (11) in this article] may not be valid for very rough surfaces, for example, to describe heat transfer when \( z_m \) is order of a meter or more.” Such large values of \( z_m \) occur in urban areas. Moreover, the original value of \( a \) in the study by Brutsaert (1982) was derived using various data with different molecular diffusivities reduced to \( \operatorname{Re}^* = 10 \). Merlivat (1978) had tested these \( a \) results by an isotopic method that used a wavy water surface such that \( 0.02 < \operatorname{Re}^* < 10 \). The second constant covers \( 10 < \operatorname{Re}^* < 10,000 \) and was derived directly from heat transfer of the air over urbanlike obstacles. The constant from the COSMO experiments is therefore likely valid for urban settings.

There is little scatter of the data around the regressed function. Even though the data in this study included values during an entire year, scatter in the plot was smaller than from previous datasets over various real-world surfaces. This small scatter thus likely reflects the idealized setting of uniform material and geometry and the small spatial temperature variations among the constituent surfaces resulting from the reduced scale of the models. Different representative surface temperatures generally vary and consequently can force significant differences in \( z_h \) in the real world (Malhi 1996; Voogt and Grimmond 2000). Table 4 shows values of the constant \( a \) in Eq. (11) as regressed individually from each COSMO surface temperature. Representative surface temperatures were nearly equivalent, and thus there was little difference in the regressed \( a \) values, as shown in the shaded region of Fig. 6.

c. Seasonal and diurnal variations of \( \ln z_h \)

Large diurnal variations of \( \ln z_h \) (or \( \kappa B^{-1} \)) have been observed in the past for sparse vegetation (e.g., see review by Verhoef et al. 1997) and urban areas (Voogt and Grimmond 2000; Moriwaki and Kanda 2006). Explanations for this variation include either the vertical movement of the heat source through the day as the solar angle changes (Brutsaert and Sugita 1996) or the use of inappropriate surface temperatures. Some theoretical works have successfully shown the anisotropic effects of the vegetation canopy (Qualls and Hopson
1998; Massman 1999; Lhomme et al. 2000; Suleiman and Crago 2002). However, Verhoef et al. (1997) suggested that even bare soil produces large diurnal variations in \( \ln z_h \), and Ma and Daggupaty (2000) found that the variations in \( \ln z_h \) are not sensitive to measurement errors and are unlikely to follow a simple functional relationship. Therefore, controversy remains as how to interpret the large variations.

Figures 7 and 8 show seasonal and diurnal changes in \( \ln z_h \) and Re*, respectively. The magnitude of the scatter of \( \ln z_h \) both seasonally and diurnally was larger for the large scale model than for the small scale model, and \( \ln z_h \) was smaller in winter and larger in summer. In addition, a diurnal trend of \( \ln z_h \) was not obvious, but values were slightly smaller in the evening than in the morning. There was little diurnal variation in \( \ln z_h \) in the small scale model, and variations in the magnitude of \( \ln z_h \) and its scatter can be explained by the relationship with Re*. Larger scatter of \( \ln z_h \) with the large scale model arose because of larger values of Re* and the corresponding wider range of \( \kappa B^{-1} \), as predicted by Eq. (11) and Fig. 6. The seasonal trend also corresponds well to Re*.

The diurnal trend cannot be explained so straightforwardly, because smaller evening values do not match the trend in Re*. Brutsaert and Sugita (1996) suggested that the diurnal variation of \( \ln z_h \) over vegetated surfaces was related to the vertical movement of the heat source through the day as the solar angle changes. However, this study found no significant correlation between solar elevation and the estimated \( \ln z_h \) (Fig. 9).

### Table 4

<table>
<thead>
<tr>
<th>Surface Temperature</th>
<th>( a )</th>
<th>No. of datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_R )</td>
<td>1.24</td>
<td>1442</td>
</tr>
<tr>
<td>( T_C )</td>
<td>1.41</td>
<td>791</td>
</tr>
<tr>
<td>( T_H )</td>
<td>1.37</td>
<td>791</td>
</tr>
<tr>
<td>All</td>
<td>1.29</td>
<td>3024</td>
</tr>
</tbody>
</table>

The seasonal trend also corresponds well to Re*.
and the small spatial temperature variations among the constituent surfaces resulting from the reduced scale.

5. Discussion

a. Comparison with urban field data

Figure 6 shows $\kappa B^{-1}$ data from three different cities together with the COSMO data. Table 5 summarizes the sites and data processing for the urban data. The three sites are a light industrial area in Vancouver, British Columbia, Canada (VG; from Voogt and Oke 1997; Voogt and Grimmond 2000), a business district in Tokyo, Japan (SU; from Sugawara 2001), and a densely built residential area in Tokyo (MK; from Moriwaki and Kanda 2004, 2006). No other urban $\kappa B^{-1}$ data exist. Urban $\kappa B^{-1}$ showed large scatter but generally followed the theoretical function in Eq. (11) that used the constant regressed from the COSMO data.

The VG site included a wide range of $\kappa B^{-1}$ corresponding to various surface temperature representations ($T_R$ and $T_C$), and values were mostly larger than those predicted by Eq. (11). However, the use of complete surface temperature $T_C$ yielded the lowest values of $\kappa B^{-1}$ (Fig. 8 by Voogt and Grimmond 2000); such values force the VG data closer to values predicted by Eq. (11). The MK site had a narrower range of $\kappa B^{-1}$ corresponding to a single surface temperature representation ($T_R$) and a fairly homogeneous fetch. Values were mostly smaller than those by Eq. (11), possibly because MK included a larger areal fraction of vegetation (20%) and vegetated surfaces generally yield smaller $\kappa B^{-1}$ than do bluff surfaces. The SU site had a very large scatter of $\kappa B^{-1}$ corresponding to the variable fetch condition as seen in the wide range of the sky-view factor and green coverage (Table 5), and values were slightly smaller than those of Eq. (11), also likely due to the presence of vegetation (0%–33%).

Further insights are provided by intercomparisons of scale model data with results from three cities, which show the effect of surface geometry on $\kappa B^{-1}$. Values of the complete surface area index $\lambda_C$ from COSMO (2.0), VG (1.4), and MK (2.8) were correlated with relative values of $\kappa B^{-1}$ (COSMO middle, VG large, and MK

![Fig. 7. Seasonal evolution of (a) $\ln z_H$ and (b) $R_{e*}$. Open circles: large scale model (L), and crosses: small scale model (S).](image1)

![Fig. 8. Diurnal changes in (a) $\ln z_H$ and (b) $R_{e*}$. Open circles: large scale model (L), and crosses: small scale model (S).](image2)

![Fig. 9. The $\ln z_H$ vs solar elevation angle. Open circles: large scale model (L), and crosses: small scale model (S).](image3)
small). However, the SU site lacked $\lambda_C$ information. The wide range of the sky-view factor $\varphi_{\text{sky}}$ (0.16–0.75), instead of $\lambda_C$, indicated that SU covered various surface geometries related to the diversity of the source area investigated. However, no systematic dependence of $\kappa B^{-1}$ on $\varphi_{\text{sky}}$ was found at SU (Sugawara 2001), and the direct effect of surface geometry on $\kappa B^{-1}$ is questionable other than for indirect effects linked to the momentum roughness length of $Re^*$. An effect from vegetation cover on $\kappa B^{-1}$ was also shown. This is the most plausible effect to account for systematic deviations of $\kappa B^{-1}$ because it is well known that vegetation and permeable surfaces generally yield smaller $\kappa B^{-1}$ than do bluff surfaces (Garratt and Hicks 1973; Verma 1989; Brutsaert 1982; Brutsaert and Sugita 1996). In fact, Fig. 10 does show a systematic decrease of $\kappa B^{-1}$ with increasing areal fraction of vegetation $\lambda_{\text{veg}}$. However, the wide range of $\lambda_{\text{veg}}$ was mostly caused by SU, and scatter was large.

The above discussion suggests that using the regressed parameter $a = 1.29$ in the theoretical function in Eq. (11) can be useful for various urban surfaces with no vegetation cover.

### Variable roughness lengths for heat

The variable roughness length for heat computed in Eq. (11) could be verified for the MOST framework. Figure 11 shows observed relationships between the bulk transfer coefficient for heat $C_h$ and the nondimensional stability parameter $-z/L$, where $C_h$ was calculated in Eq. (11) for various urban surfaces with no vegetation cover.

#### Table 5. Site, instrumentation, and data processing at the three urban data collection sites.

<table>
<thead>
<tr>
<th></th>
<th>COSMO</th>
<th>VG (Voogt and Grimmond 2000)*</th>
<th>SU (Sugawara 2001)*</th>
<th>MK (Moriwaki and Kanda 2006)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane area index</td>
<td>0.25</td>
<td>0.38</td>
<td>0.01–0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>Complete surface area index</td>
<td>2.0</td>
<td>1.4</td>
<td>—</td>
<td>2.8</td>
</tr>
<tr>
<td>Sky-view factor</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Green coverage (%)</td>
<td>0</td>
<td>&lt;5</td>
<td>0–33</td>
<td>20</td>
</tr>
<tr>
<td>Averaging time (min)</td>
<td>60</td>
<td>15</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>Method of flux estimation</td>
<td>EC</td>
<td>EC</td>
<td>EC</td>
<td>EC</td>
</tr>
<tr>
<td>Surface temperature used</td>
<td>$T_R$, $T_C$, $T_H$</td>
<td>$T_R$, $T_C$</td>
<td>$T_R$</td>
<td>$T_R$</td>
</tr>
<tr>
<td>Obs period</td>
<td>1 yr (2004–05)</td>
<td>3 days (Aug 1992)</td>
<td>1 month (Aug 1998)</td>
<td>1 yr (2004–05)</td>
</tr>
</tbody>
</table>

* Urban data symbols are defined in the text.

**Fig. 10.** The $\kappa B^{-1}$ vs the areal fraction of vegetation. The symbols are the same as in Fig. 6. Open circles: large scale model (L), and open squares: small scale model (S). Open triangles (VG: light industrial area, Vancouver), crosses (SU: business district, Tokyo), and filled circles (MK: dense residential area, Tokyo) correspond to the urban data, see Table 5.

**Fig. 11.** Bulk transfer coefficient for heat $C_h$ vs the nondimensional stability parameter $-z/L$ for the (a) large scale model and (b) small scale model. Lines were derived by substituting constant values of $\kappa B^{-1}$ into the conventional MOST line of Eq. (4). Solid and dotted lines correspond to the observed maximum and minimum $Re^*$ using Eq. (11), respectively.
lated from Eq. (3) using the observed $H$, $U$, $T_r$, and $T_R$. Lines in Fig. 11 were derived by substituting the constant values of $\kappa B^{-1}$ into the conventional MOST line of Eq. (4). The observed maximum and minimum $Re^*$ values yield the $\kappa B^{-1}$ values in the figures using Eq. (11), and result in the solid and dotted lines, respectively. Observed plots of $C_h$ evolved gradually from one line to the other as $-z/L$ increased. Thus, the plotted curve looks steeper than the conventional lines. Therefore, the use of Eq. (11), instead of a constant value of $\ln \frac{z}{L}$, together with conventional MOST equations [e.g., Eq. (4)] is recommended to estimate $C_h$ for a default nonvegetated urban surface parameterization.

6. Concluding remarks

a. Summary

Comprehensive Outdoor Scale Model experiments for urban climate yield unique information about roughness parameters, especially the roughness length for heat. These model experiments are free of many of the uncertainties found in real cities related to spatial variations in material, geometry, and land use, yet include realistic synoptic conditions. The COSMO results are thus different from both field and laboratory data. A useful finding of this paper is the regressed function between $\kappa B^{-1}$ and $Re^*$ [Eq. (11), with $a = 1.29$] for urban settings. This regressed function shows reasonable agreement with data from three urban sites as well as the COSMO data, even though surface geometry differed from site to site. Use of the regressed function can introduce the variable $\kappa B^{-1}$ into the conventional MOST framework, leading to a good reproduction of the observed dependency of the bulk transfer coefficient on the atmospheric stability. The use of the regressed function between $\kappa B^{-1}$ and $Re^*$ together with the MOST framework is recommended to estimate $C_h$ for urbanlike surfaces with no vegetation.

b. Suggestions for practical applications

Some suggestions for practical applications of the present COSMO results are given below. The first suggestion involves coupling with a vegetation scheme. The $\kappa B^{-1}$ and $Re^*$ regressed function from the COSMO data [Eq. (11), with $a = 1.29$] can be used together with a vegetation scheme in applications for real cities with green space. A realistic way to calculate an area-averaged land surface parameter (LSP) in complex urban sites is a simple areal weighting of LSPs obtained from this function and from a vegetation scheme. Sophisticated theoretical schemes of $\kappa B^{-1}$ that consider various vegetation canopy structures are fortunately available (Blyth and Dolman 1995; Qualls and Hopson 1998; Massman 1999; Lhomme et al. 2000; Suleiman and Crago 2002). Coupling the function from this paper with a vegetation scheme is applicable to various real urban surfaces because results from three urban datasets generally followed this function and were insensitive to the surface geometries but sensitive to the areal fraction of vegetation.

The second suggestion involves effective surface temperature. The MOST framework using the $\kappa B^{-1}$ and $Re^*$ function requires effective surface temperature $T_H$ to estimate sensible heat flux. In practice, $T_H$ is difficult to measure, and radiometric temperatures $T_R$ are generally used instead. The measured $T_R$ and $T_H$ of COSMO showed good agreement because the spatial temperature variations among the constituent surfaces were small because of the reduced scale. Small seasonal and diurnal variations in roughness length for heat in the COSMO experiments relative to those of real world can also be attributed to the same reason. In the real world, however, $T_R$ is often different from $T_H$, and a conversion from observed $T_R$ to $T_H$ is necessary. Simple vegetation canopy models can be used to approximate $T_H$ of the vegetated surfaces (e.g., Cargo 1998; Suleiman and Crago 2002). Although the vegetation canopy is assumed to be one-dimensional only in the vertical direction because of its permeable nature, the urban canopy should be treated as three-dimensional because of multiple sources. Therefore, UCMs should be used instead for the estimation of $T_H$ of urban surfaces.

The third suggestion involves implementation of the $\kappa B^{-1}$ and $Re^*$ function into urban canopy models (UCMs). The MOST framework requires effective surface temperatures that can be predicted from UCMs. Adding $\kappa B^{-1}$ and $Re^*$ functions into UCMs will improve the accuracy of UCMs. Therefore, the MOST framework and UCMs are complementary, and knowledge of roughness lengths in urban areas is beneficial both for the MOST framework and for UCMs. Observations of $\kappa B^{-1}$ and $Re^*$ in real cities are still limited, and thus further studies at various real urban sites are warranted.

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