9.2 A COMPARISON OF ROUGHNESS PARAMETERS FOR OKLAHOMA CITY FROM DIFFERENT EVALUATION METHODS

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ABSTRACT

The roughness parameters (displacement height, d, and momentum roughness length, z_o) are basic length scales for urban canopy flows. There are several methods to evaluate d and z_o. Burian et al. (2003) have used the morphometric method to obtain d and z_o values for Oklahoma City, Oklahoma. During the Joint Urban 2003 field experiment, a large amount of mean wind and turbulence data has been collected from the 83m pseudo tower of Lawrence Livermore National Laboratory (LLNL). With the LLNL data we have used different methods, including the mean wind profile method, the temperature variance method, and the spectral method to evaluate d and z_o for Oklahoma City. The results of our evaluation of the two parameters are presented.

1. INTRODUCTION

For urban canopy flows, the momentum roughness length (z_o) is a measure of the roughness of the urban surface. z_o represents the strength of the momentum sink for an urban area. The displacement height (d), also called the zero-plane displacement length is the level of mean momentum absorption (Thom, 1971). z_o and d are two basic length scales which affect the vertical structure of both mean wind and turbulence in the urban surface layer (Rotach, 1993; Roth, 2000). Values of these two roughness parameters are also necessary for urban airflow and dispersion modeling (e.g., Boybeyi, 2000). Although the importance of their evaluations has been recognized for a long time, there have been only a few credible estimations of urban z_o and d (Wieringa, 1993; Grimmond and Oke, 1999; Burian et al., 2003).

A major field experiment, the Joint Urban 2003 (JU2003) experiment, was a cooperative undertaking to study transport and dispersion in the atmospheric boundary layer in an urban environment. JU2003 was conducted in Oklahoma City in the summer of 2003 (Alwine et al., 2004). The Lawrence Livermore National Laboratory (LLNL) deployed a pseudo tower of 83m height, equipped with sonic anemometers at eight levels and located in a downtown site (Lundquist, et al., 2004; Gouveia, et al., 2006). A large amount of sonic anemometer data from the LLNL pseudo tower have been collected, processed, and archived. There are several methods to evaluate d and z_o (see next section).

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Burian et al., (2003) have used the morphometric methods to evaluate these two parameters for Oklahoma City. With the LLNL sonic anemometer data, we have used different methods, including the mean wind profile method, the temperature variance method, and the spectral method to evaluate d and z_o for Oklahoma City. Our evaluation results follow. A comparison of d and z_o between different evaluation methods is also briefly discussed.

2. METHODS

2.1 *Wind speed profile method*

This is a conventional method with a long history. In the surface layer (constant flux layer), the mean wind speed profile can be expressed as:

$$\bar{u}(z) = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_o}\right) - \psi\left(\frac{z-d}{z_o}\right) + \psi\left(\frac{z_o}{L}\right)\right] \quad (1)$$

where $\bar{u}(z)$ is the mean wind speed at a height of z. u_* is the friction velocity, k the Von Karman constant (0.4). ψ is a stability correction function, and L the Monin-Obukhov length. Under neutral conditions, L → ∞ and ψ = 0. Consequently for the neutral constant flux layer or called neutral inertial sublayer:

$$\bar{u}(z) = \frac{u_*}{k}\ln\left(\frac{z-d}{z_o}\right) \quad (2)$$

From (2)

$$y_i = \exp\left(\frac{k\,\bar{u}_i}{u_*}\right) = \left(\frac{1}{z_o}\right)z_i - \left(\frac{1}{z_o}\right)d \quad (3)$$

This equation provides a linear regression method to determine z_o and d from observed $\bar{u}_i$ and u_* (Schaudt, 1998). In principle, the two unknowns (z_o and d) can also be obtained if we have two measured wind speeds at two levels, $\bar{u}_1(z_1)$ and $\bar{u}_2(z_2)$, and the measured friction velocity, u_*.

$$z_o = \frac{z_2 - z_1}{y_2 - y_1}\ , \quad d = \frac{y_2 z_1 - y_1 z_2}{y_2 - y_1} \tag{4}$$

It should be emphasized that the calculated values of z_o and d are extremely sensitive to the measured values of $\bar{u}_i$ and u_*. In order to reduce sensitivity or uncertainty for d and z_o evaluation, multi-level measurements or statistical values of $\bar{u}_i / u_*$ have been suggested, see Lloyd et al. (1992). Wieringa (1993) and Grimmond and Oke (1999), for example. They have provided many caveats and criteria for data selection or data rejection.

2.2 *Temperature Variance Method*

Rotach (1994) has presented the temperature variance method to estimate the zero plane displacement height over urban surfaces. This method assumes that the classic Monin-Obukhov similarity formula for the temperature variance can be applied to the urban surface layer. Specifically, the non-dimensional temperature variance for the unstable roughness sublayer can be expressed as

$$\sigma'_T = \frac{\sigma_T}{|T_*|} = C_1\left[1 - C_2\left(\frac{z-d}{L}\right)\right]^{-\frac{1}{3}}, \tag{5}$$

where σ_T is the standard deviation of temperature and T_* denotes the temperature scale. Here

$$T_* = -\frac{H}{u_*} = -\frac{\overline{w'T'}}{u_*} \tag{6}$$

where u_* is the friction velocity, g the acceleration of gravity, H the kinematic heat flux, and L the Monin-Obukhov length. The constants C_1 and C_2 are estimated to be 2.9 and 28.4 respectively (De Bruin *et al.*, 1993, and Feigenwinter *et al.*, 1999). In order to obtain an estimate of d, the differences between the estimated value of σ_T' with a specific value of d from (5) and the measured value $(\sigma_T')_m$ are to be minimized from the following equation by varying the d value in (5).

$$E^2 = (1/N) \sum_{i=1}^{N} [\sigma'_T - (\sigma'_T)_m]^2_i\ , \quad i = 1, 2, \ldots N \tag{7}$$

where E represents the root-mean square error for a specific value of d, and N is the number of measurements. The value of d for the minimum E is adopted as the estimated value of d.

2.3 *Spectral Method*

Christen (2005) has proposed the spectral method to evaluate d, which can be expressed as

$$d = z - \frac{\bar{u}\, n_{\max}(u_i)}{f_{\max}(u_i)} \tag{8}$$

where z is the measurement height, $\bar{u}$ the mean wind speed at z, $n_{\max}(u_i)$ is the peak frequencies of the neutral and normalized power spectra of u_i, i= 1, 2, 3 ($u_1 = u, u_2 = v, u_3 = w$) for longitudinal, transverse, and vertical wind component, respectively. $f_{\max}(u_i)$ is the measured natural peak frequencies (Hz) of u_i in the inertial sublayer under neutral conditions. It is assumed that $n_{\max}(u) = 0.08, n_{\max}(v) = 0.22, n_{\max}(w) = 0.55$. Christen (2005) suggested that the spectra of w can provide most realistic estimates for d.

2.4 *Morphometric and other methods*

Grimmond and Oke (1999) have reviewed the morphometric methods for d and z_o evaluation. They have studied seven formulas to estimate d and nine to estimate z_o from morphological parameters. Using some of the most appropriate formulas in Grimmond and Oke, Burian et al., (2003) have calculated d and z_o for the Oklahoma City. We will use some of their calculated values of d and z_o to illustrate a comparison in the fourth section. In addition to the morphometric methods, other methods have also been proposed and studied, e.g., Kanda et al., (2002), Kastner – Klein and Rotach, (2004), Jasinski et al. (2005).

3. DATA

As mentioned earlier, the sonic anemometer data from the LLNL 83m pseudo-tower are used for our evaluation. Detailed information about the tower and sonic data has been provided by Lundquist et al., (2004) and Gouveia et al., (2006). The pseudo tower is a large crane-based system which provided a stable platform for eight sonic anemometers. Its location is 35^o 28.55' N and 97^o 31.07' W, just north of the central business district of Oklahoma City. Sonic anemometers were mounted at 7.8(A), 14.6(B), 21.5(C), 28.3(D), 42.5(E), 55.8(F), 69.7(G), and 83.2m(H) above the ground surface.

The sonic anemometers (R.M. Young model 8100) measure 3 wind components and sonic temperature at a sampling rate of 10 Hz. During the 34 days of measurements (from 28 June to 1 August, 2003), data recovery was 95% over that period. For sonic anemometer tilt correction, the traditional two angle rotations method (Kaimal and Finnigan, 1994) was applied for each time series of 30 minutes (1800 seconds, 18000 data points). After the tilt correction, the three components of the wind vector are u (stream wise), v (transverse), and w (vertical). As pointed out by Lundquist (2004), the time period with a mean wind direction between 315° and 45° were not used due to the pseudo tower 'shadow effect'. Based on the building heights (Fig. 3, Lundquist, 2004), the sonic data are grouped under three wind direction (WD) sectors: (1) 45° – 120°, (2) 120° – 210° , and (3) 210° – 315°, as indicated in Fig. 1.

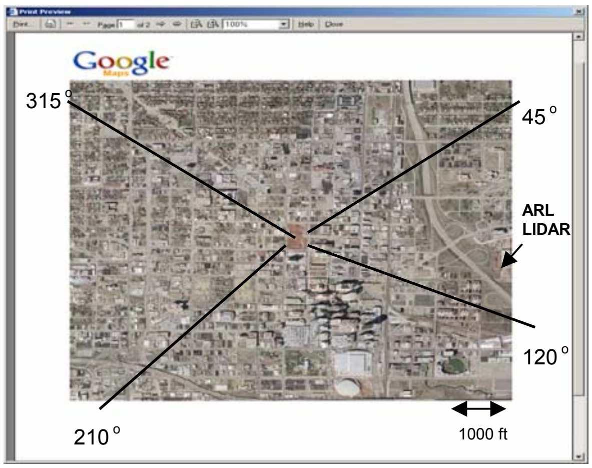

Figure 1. Wind direction sectors centered at the LLNL 83m pseudo tower over Oklahoma City's central business district.

4. RESULTS

In order to use the wind speed profile data of 8 levels from the LLNL tower, it is essential to locate the inertial sublayer first and then to use the data only from those levels which are in the inertial sublayer as required by the wind speed profile method. Fig. 2 is the vertical profile of the friction velocity (u_*, upper) and the kinematic heat flux (H, lower) for the wind direction between 120° and 210° under neutral conditions. The horizontal bars at each level (A through H) represent plus and minus standard deviation of u_* or H. The definition of neutral condition is $|z/L| < 0.01$. Fig. 2 (upper) shows that the friction velocity increases with height from the lowest level A(7.8m) until level G(69.7m), then it becomes almost constant. The corresponding vertical profile of the heat flux (H) on the lower of Fig. 2 demonstrates a general trend of decreasing with height. However, H are very small (less than 10 W m^{-2}) at all 8 levels as expected for the neutral surface layer. Also the heat flux at each level has a large standard deviation as shown by the horizontal bars. Consequently Fig. 2 indicates that the upper most two levels, G(69.7m), and H(83.2m) can be considered as in the inertial sublayer for this wind direction sector. For the other two wind direction sectors, similar profiles of u_* and H (not shown) indicate that the levels B, C and D for the 45° – 120° wind direction sector, and level C, D and E for the 210° – 315° wind direction sector can be considered as in the inertial sublayer.

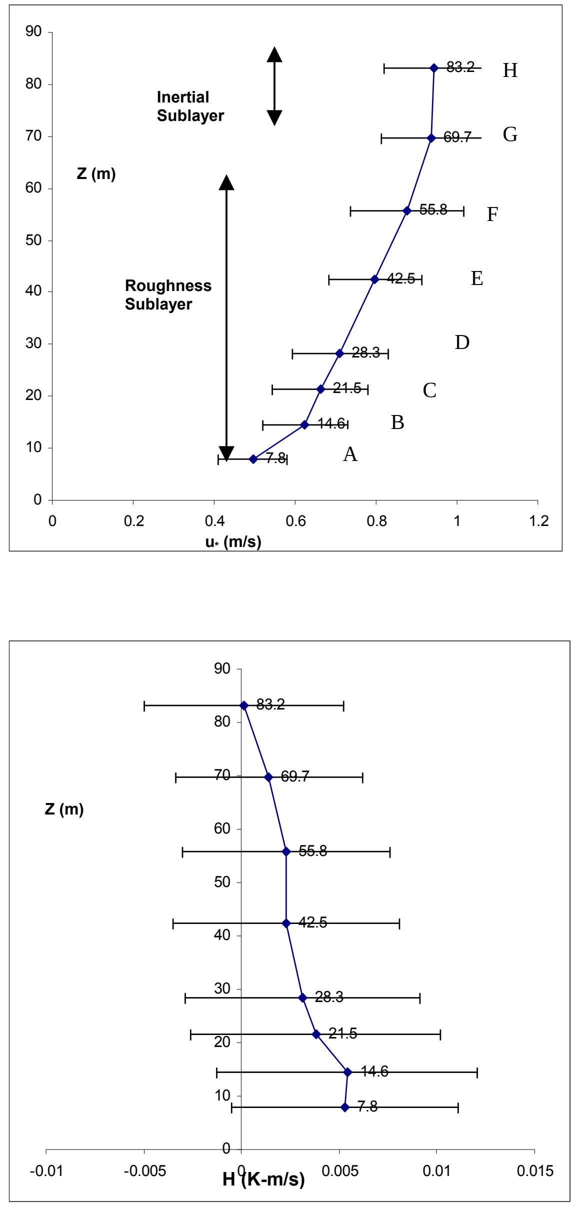

Figure 2. Vertical profiles of u_* (upper) and H (lower) for 120° ≤ WD ≤210° under neutral condition ($|z/L| < 0.01$). The horizontal bar at each level (A through H) represents one plus and one minus standard deviation of u_* and H, respectively.

As mentioned earlier, the values of d and z_o are extremely sensitive to the measured values of $\overline{u}_i$ and u_*. Therefore, statistical values of $\overline{u}_i / u_*$ were used for equations (3) and (4). Fig. 3 shows linear regression plots of 30 minute average values of u_* against wind speed for neutral conditions. The straight lines in the plots of Fig. 3 are regressions forced through the origin. Hence their slopes (b) are used to calculate statistical averages of $\overline{u}_i / u_*$.

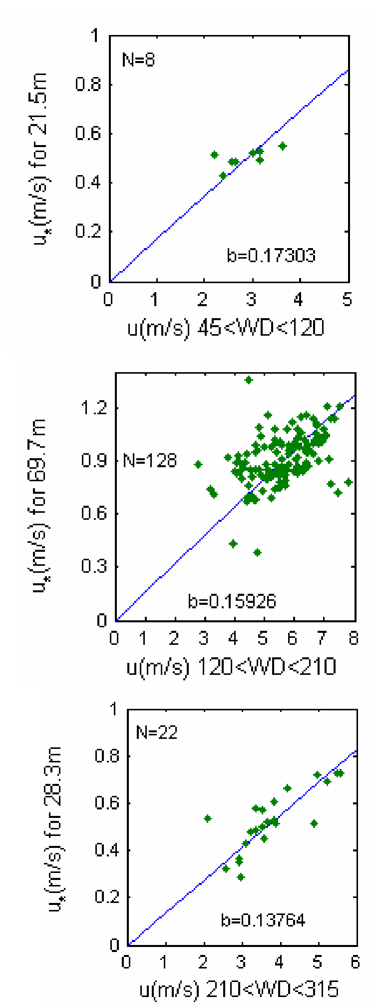

Figure 3. u_* plotted against wind speed for neutral conditions at levels C (top), G (middle), and D (bottom) for different wind direction (WD) sectors. The Lines are regressions forced through the origin.

The evaluated values of d and z_o with the average values of $\overline{u}_i / u_*$ are listed in Table 1. The largest values of d (19.93m) and z_o (4.04m) occur for the wind direction sector (120^o – 210^o) as expected since this sector includes almost all tall buildings of Oklahoma City's downtown area. The average displacement height and roughness length are 11.22m and 0.93m, respectively, for wind direction sector (1), and 14.65m and 0.66m, respectively, for wind direction sector (3).

	(1) 45<WD≤120		(2) 120<WD≤210		(3) 210<WD≤315	
Method	**Z_o (m)**	**d (m)**	**Z_o (m)**	**d (m)**	**Z_o (m)**	**d (m)**
Neutral Wind Profile	**0.93**	**11.22**	**4.04**	**19.93**	**0.66**	**14.65**
TVM						
A (7.8m)		**4.66**		**3.22**		**4.17**
B (14.6m)				**8.28**		**8.16**
C (21.5m)				**13.73**		
D (28.3m)				**19.80**		
E (42.5m)				**31.98**		
F (55.8m)				**44.11**		
Spectral		**6.01**		**13.88**		**4.23**
Morpho metric (Burian et al. 2003)	**0.31-1.17**	**Other Urban Area 2.45-5.85**	**1.05-3.70**	**Urban High-rise 11.75-20.30**	**1.11-2.91**	**Down town Core Area 9.70-15.59**

Table 1. Comparison of z_o and d evaluated from different methods for the three wind direction (WD) sectors: (1), (2), and (3).

As proposed by Rotach (1994), the Temperature Variance Method (TVM) uses the turbulence data only from the unstable roughness sublayer which is usually below the inertial sublayer. Therefore, we have used the data at levels A, A through F, A and B, for the wind direction sectors (1), (2), and (3), respectively. The results of TVM are also listed in Table 1. Generally, the values of d from TVM appear smaller than d values from the neutral wind speed profile method, as seen from Table 1. d values from the temperature variance data at E and F levels (31.98m and 44.11m, respectively) seem extremely high. The d values also seem to increase with the measurement height. This result is difficult to explain and needs further investigation.

The spectral method introduced and tested by Christen (2005) can be used for u, v, w, and T power spectra. We have applied this method only for w power spectra with limited data from the neutral inertial sublayer. Results of d values are also listed in Table 1 and should be considered as preliminary results. The d values for the three wind sectors (6.01, 13.88, and 4.23m) appear between the values from the neutral wind speed profile method and TVM. Hence, this relatively new method for d evaluation is useful.

Based on a three-dimensional building data set and detailed land use/land cover information, Burian et al., (2003) have calculated many building height characteristics and morphological parameters for Oklahoma City. These urban morphological parameters including building mean height, building plan area fraction (λ_p), frontal area index (λ_f) were used to compute d and z_o for the entire Oklahoma urban area ($27km^2$) and for different land use types (categories). Displacement heights and roughness lengths for different land use classes (7 categories) with standard equations are listed in their Table 14 through 19. It is difficult to compare their results with our results from 3 different methods. Our evaluated d and z_o values are for three non-overlapping wind direction sectors which have no clear-cut correspondences with the seven land use categories. For a broad comparison, however, we assume that the three wind direction sectors can be referred to as the Other Urban Area, Urban High-rise, and Downtown Core Area for wind direction sectors (1), (2), and (3), respectively. We have cited the values of d and z_o from their tables in our Table 1. Although the comparison between our results and the morphometric results from Burian et al., (2003) may not be totally appropriate, it can be useful in a broad sense of comparison. Generally speaking, the values of d and z_o from the morphometric method appear comparable with, and within a factor of 2 of, the values from the three methods.

5. SUMMARY

As pointed out by Grimmond and Oke (1999), there have been remarkably few credible and accurate values of roughness parameters for urban areas. This study represents an effort to provide reliable values of d and z_o for an urban area like Oklahoma City from three different evaluation methods: the neutral wind speed profile method, the temperature variance method, and the spectral method. In addition, we try to compare our evaluated results between the three methods and with the morphometric method by Burian et al. (2003). It can be said from Table 1 that the evaluated values of the roughness parameters from those four different methods are comparable although there are significant differences between them. It is difficult to tell, however, which result can be considered as the most credible and accurate one due to the fact that each of those evaluated values of d and z_o has some uncertainty or error. Also each method is based on its own assumptions and has inherent limitations. It is also difficult to say which method should be favored on the grounds of reliability and accuracy. Our results presented here are preliminary since we are still analyzing the large amount of the LLNL sonic anemometer data collected during the JU2003 field experiment.

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