AERODYNAMIC ROUGHNESS OF URBAN AREAS DERIVED FROM WIND OBSERVATIONS

C. S. B. GRIMMOND[1], T. S. KING[1], M. ROTH[2] and T. R. OKE[2]
[1]*Climate and Meteorology Program, Department of Geography, Indiana University, Bloomington, IN, 47405, USA;* [2]*Atmospheric Science Program, Department of Geography, University of British Columbia, Vancouver, BC, Canada*

(Received in final form 20 May 1998)

Abstract. This study contributes to the sparse literature on anemometrically determined roughness parameters in cities. Data were collected using both slow and fast response anemometry in suburban areas of Chicago, Los Angeles, Miami and Vancouver. In all cases the instruments were mounted on tall towers, data were sorted by stability condition, and zero-plane displacement (z_d) was taken into account. Results indicate the most reliable slow response estimates of surface roughness are based on the standard deviation of the wind speed obtained from observations at one level. For residential areas, winter roughness values (leaf-off) are 80–90% of summer (leaf-on) values. Direct comparison of fast and slow response methods at one site give very similar results. However, when compared to estimates using morphometric methods at a wider range of sites, the fast response methods tend to give larger roughness length values. A temperature variance method to determine z_d from fast response sensors is found to be useful at only one of the four sites. There is no clear best choice of anemometric method to determine roughness parameters. There is a need for more high quality field observations, especially using fast response sensors in urban settings.

Keywords: Roughness length, Urban area, Zero-plane displacement length.

1. Introduction

Accurate knowledge of the aerodynamic characteristics of cities is vital to describe, model, and forecast the behaviour of urban winds and turbulence at all scales. Methods to determine roughness parameters can be generalized into those that require observations of wind (anemometric or micrometeorological), and those that are based on the morphology and spatial arrangement of surface roughness elements (referred to as morphometric analysis).

Grimmond and Oke (1998) reviewed more than fifty studies that provide anemometric based estimates of roughness length (z_0) in cities. They assessed each study by applying criteria, adapted from Wieringa (1993) and Bottema (1997), which consider: site characteristics (ideally horizontal terrain and extensive fetch with no anomalous structures nearby); tower exposure (slender and open structure to avoid wake effects); measurement height (above roughness sublayer but low enough to be in an adjusted boundary layer); instrumentation (response characteristics, spacing if profiles are used, and sampling period); atmospheric stability (neutral, or

Boundary-Layer Meteorology **89:** 1–24, 1998.
© 1998 *Kluwer Academic Publishers. Printed in the Netherlands.*

Figure 1a.

Figure 1. (a) Aerial photographs of each of the study sites. All photographs oriented with North at the top of the page. Site location indicated with white dot, site code name to the right. (b) Oblique photographs of residential areas at each of the sites (next page in the same order as Figure 1a).

stability corrected); and, inclusion of zero-plane displacement (for full details see Grimmond and Oke, 1998). Only seven studies were found to be acceptable (listed here in alphabetical order of the original author): Clarke et al. (1982); Duchêne-Marullaz (1979); Högström et al. (1982); Jones et al. (1971); Karlsson (1981, 1986); Oikawa and Meng (1995); and Yersel and Gobel (1986). Most studies were excluded because the displacement length (z_d) had not been included, and consequently the reported z_0 is too large. Hanna (1969) demonstrated the importance of this with a re-analysis of the results of Ariel and Kliuchnikova (1960). These authors reported a z_0 of 4.5 m based on wind speed observations at 24 and 48 m in Kiev whereas Hanna (1969) obtained a z_0 of 1.5 m after including a z_d of 10 m.

Figure 1b.

Unfortunately the original value and others with similar problems have been widely quoted (e.g., Landsberg, 1981). Grimmond and Oke (1998) also note that some values quoted as anemometric are in fact morphometrically-based (e.g., Wieringa (1993) quotes Steyn (1980)). A further difficulty is that many studies do not provide sufficient information about the measurement site and its vicinity to allow others to relate them to sites in other cities.

The objective of the present study is to contribute to the sparse literature on anemometrically determined urban roughness parameters. Anemometric methods, derived from the logarithmic wind profile equation under neutral conditions, can be divided into those determined from slow and fast response instruments. Both approaches are used here to obtain estimates of z_0 and z_d in suburban areas of Chicago, Los Angeles, Miami and Vancouver (Figure 1). In all cases the instruments were mounted on tall towers, data were sorted by stability condition, and zero-plane displacement was taken into account, so that these data meet the criteria of Wieringa (1993), Bottema (1997), and Grimmond and Oke (1998).

2. Anemometric Methods for Roughness Length

2.1. Slow Response Anemometry

Two methods are considered here: the first requires observations of mean wind speed at multiple levels; the second wind speed (U) and the standard deviation of wind speed (σ_U) at one level.

To implement the Lettau wind profile method (referred to hereafter as Lw) for typical urban roughness conditions a minimum of three to four anemometers are required in the profile (more as the roughness becomes less) (Wieringa, 1993). Data should represent only times of near neutral conditions, which meet stationarity requirements (i.e., not near sunrise or sunset). With such observations, Lettau (1957) proposed a method to determine the zero-point displacement D (where $D = z_0 - z_d$) for the condition of the minimized sum of error squares:

$$\sum_{i=1}^{N} \epsilon^2 = \sum_{i=1}^{N} \left[(U_i - \overline{U_N}) - \frac{u_*}{k} (\ln(z_{si} + D) - \overline{\ln(z_{si} + D)}) \right]^2 \tag{1a}$$

$$\frac{u_*}{k} = \frac{\sum_{i=1}^{N} [U_i - \overline{U_N}][\ln(z_{si} + D) - \overline{\ln(z_{si} + D)}]}{\sum_{i=1}^{N} [(\ln(z_{si} + D)) - \overline{\ln(z_{si} + D)}]^2} \tag{1b}$$

where U_i is the mean wind speed at level z_{si} of which there are N levels, u_* is the friction velocity, and k is von Karman's constant (here assumed to be 0.4) and the overbar indicates the mean for the N levels. Given the logarithmic wind profile equation, and using the D and u_*/k value with the wind speed at one level, z_0 and z_d can be determined:

$$\begin{aligned} \text{Lw} \quad z_0 &= (z_s + D) \exp\left(-\frac{U_z k}{u_*} \right) \\ z_d &= z_0 - D. \end{aligned} \tag{2}$$

This method has the advantage of solving for z_d and z_0 simultaneously.

The second method, the ratio referred to here as Su, uses the neutral value of $\phi_u = \sigma_u / u_*$, where σ_u is the standard deviation of the wind speed. It requires only one level of wind speed data (Beljaars, 1987):

$$\text{Su} \quad z_0 = (z_s - z_d) \exp\left(-\frac{U_z \phi_u k}{\sigma_u} \right) \tag{3}$$

where ϕ_u is generally assumed to be 2.4–2.5 when using fast response sensors in neutral conditions over rural terrain (Lumley and Panofsky, 1964; Panofsky and Dutton, 1984). Roth (1993) presents a table of values of σ_u/u_* for urban sites, which has a mean value of 2.4. Beljaars (1987) notes that because a slow response anemometer acts as a low pass filter it is necessary to adapt the value for the averaging period of the instrument. He recommends it be adjusted to 2.2 for 10 min averages (this is considered further in Section 4.2). In addition, Beljaars recommends that at least 20 values are required to determine z_0. This method is limited to the same neutral conditions with stationarity as Lettau's method.

2.2. Fast response anemometry

If fast response three-dimensional anemometry is available (e.g., $\geq$10 Hz sonic anemometer), then it is possible to determine u_* directly:

$$u_* = (\overline{-u'w'})^{1/2} \tag{4}$$

where u and w are the rotated longitudinal and vertical velocity components, respectively; the prime indicates a departure from the mean. Thus z_0 can be determined directly from the logarithmic wind profile (the eddy correlation stress method, Es) in neutral conditions:

$$\text{Es} \quad z_0 = (z_s - z_d) \exp\left(-\frac{U_z k}{u_*}\right). \tag{5}$$

With measured σ_u/u_* it is also possible to use Equation (3) (Lumley and Panofsky, 1964), or to use σ_w/u_* (Panofsky, 1984) with $\phi_w = 1.25$ (Panofsky and Dutton, 1984). The mean ϕ_w value for urban areas in the studies reviewed by Roth (1993) is 1.29. However, since one normally has u_* and can use Equation (4) under these circumstances, these methods are not pursued here.

3. Displacement Length

Except for the Lw method, all approaches also require a value of the displacement length. One approach to determine z_d using turbulence data, is the temperature variance method (Tv) developed by Rotach (1994), which he considers to be applicable to source areas which are thermally homogeneous. This approach is based on the $-1/3$ dependence of σ_Θ/Θ_* on the dimensionless stability parameter z'/L, where $z' = z_s - z_d$, σ_Θ is the standard deviation of potential temperature (Θ); $\Theta_* = -\overline{w'\theta'}/u_*$, and L, the Obukhov length scale is defined:

$$L = -\frac{\bar{\theta} u_*^3}{kg\overline{w'\theta'}} \tag{6}$$

where $\bar{\theta}$ is mean potential temperature, and g is acceleration due to gravity. Rotach (1991) and Roth (1993) demonstrate this relationship to be valid above urban surfaces, and show that data compare favorably to those obtained for rural sites (Wyngaard et al., 1971; Tillman, 1972). Tillman (1972) proposed the following formulation which assumes σ_Θ/Θ_* approaches a constant for neutral conditions:

$$\frac{\sigma_\Theta}{\Theta_*} = -C_1\left(C_2 - \frac{z_s - z_d}{L}\right)^{-1/3} \tag{7}$$

where $C_2 = -(C_1/C_3)^3$, when C_3 is the neutral limit of the function. Previous investigators have obtained values of C_3 ranging from -1.77 and -2.5 (Tillman, 1972) to -3.5 (Beljaars et al., 1983). C_1 is often accepted as 0.95 from Wyngaard et al. (1971). Since σ_Θ/Θ_* depends on height, z_d can be determined as the height at which the temperature variations are a function of the dynamic roughness of the surface. The value of z_d associated with the minimized root-mean-squared (rms) deviations between the predicted and observed values of σ_Θ/Θ_* (Equation (7)) for a range of estimated z_d values corresponds to z_d (Tv).

For z_0 methods (fast and slow response) which require a value of z_d explicitly (i.e., they do not calculate it), the morphometric method of Bottema (1995) is used:

$$\frac{z_d}{\overline{z_H}} = \left(\frac{\sum A_{rb} + \sum(1-p)A_{rt}}{A_T}\right)^{0.6} \tag{8}$$

where A_{rb} is the area of buildings, A_{rt} is the area of trees, A_T is the total area, and p is the porosity of trees. This method takes into account both the height and area of the roughness elements and provides a reasonable fit to wind tunnel estimates of z_d (Grimmond and Oke, 1998). The model is used to determine a value of z_d by wind direction, for each season, for each site. The porosity coefficient is set to 0.6 in winter, 0.4 in the fall and spring, and 0.2 in summer (see Grimmond and Oke, 1998, for further details).

4. Meteorological Observations and Site Description

The field studies used to determine the z_0 and z_d reported in this paper were parts of other urban climate studies: see Roth and Oke (1993), Grimmond et al. (1994, 1996), Grimmond and Oke (1995), and King and Grimmond (1997). Observations were conducted in suburban areas of Chicago (two sites), Los Angeles, Miami and Vancouver (Figure 1; Table I). The experimental details reported here just refer to those aspects of the field projects necessary to calculate the roughness parameters. In all cases instruments were mounted at a height that was greater than two times the height of the roughness elements (Table I) (criteria used by Grimmond and Oke, 1998). At each site, data have been stratified to exclude any directions where the instruments themselves or the tower may have influenced the measurements (Table I). Differences in land cover around the sites can be identified on Figure 1a. For each site, the data are stratified by land cover to separate values that are only for residential (R) areas (Figure 1b) from those representative of commercial (C), institutional (I), and urban parks (P).

4.1. CHICAGO

Observations were collected at two sites located within 1.1 km of each other on Chicago's northwest side (Grimmond et al., 1994; King and Grimmond, 1997) (Figure 1). Measurements in 1992, referred to hereafter as C92w (w indicates wind profile tower), involved slow response anemometry; those in 1995, C95u, (u indicates upper level data) used fast response sensors.

At the C92w site, measurements of wind speed and temperature were conducted from July 1992 until June 1993 (Grimmond et al., 1994). The instruments were mounted on a 101 m tall triangular lattice tower. Anemometers (R. M. Young wind sentry) and temperature sensors (the aspirated model of Grant and Heisler (1994) and Gill radiation shielded Vaisala HMP35C) were located at three levels (z_1 = 24.6, z_2 = 43.1, and z_3 = 69.5 m) on booms 0.05 m in diameter, which extended 6 m from the tower. Data were 15 minute averages determined from 0.2 Hz samples. All instruments were compared before and after the study, and the data reported here are corrected for inter-instrument differences.

For this analysis, data were selected to include only those hours with near-neutral stability; defined here as $|Ri| < 0.01$. The Richardson number, Ri, was calculated between the two lowest levels:

$$Ri = \frac{g}{\bar{T}} \frac{\Delta\bar{T}/\Delta z}{(\Delta\bar{u}/\Delta z)^2} \tag{9}$$

where T is temperature (K). This method has the advantage that it does not require a z_d value *a priori* to determine which hours should be analyzed. The wind profile data were screened to ensure they conformed, within ±1%, to the logarithmic profile. The data were stratified by season to account for variations in leaf cover and porosity of the trees, and by wind direction to exclude sectors potentially influenced by the tower and/or instruments (Table I).

Turbulence data were collected during June/July 1995 at the C95u site (King and Grimmond, 1997) from instruments mounted at 27 m on a guyed mobile triangular lattice tower (Aluma Tower Co model TM-51-35-SS/T-100). A three dimensional sonic anemometer-thermometer (Applied Technology Instruments, model SAT-211/3k) sampled the wind velocity components and virtual temperature at 100 Hz. Corrections were made for transducer shadowing and sonic temperature (Kaimal, 1990). Data were block-averaged, non-overlapping in real time to 10 Hz to minimize the effects of aliasing high frequency information back into the lower frequency portion of the turbulence spectrum. Post processing was conducted on

TABLE I

Location of study sites, sensor heights (z_s), and ratio of sensor height to roughness element height (z_H). Directions included are those without instrument or tower interference (see Table II for further breakdown analysis of land cover).

	Chicago, IL					Arcadia, LA, CA		Miami, FL	Vancouver, B.C.
Code	C92w	C92w	C92w	C92w	C95u	A94w	A94	Mi95	Vs89
Latitude & Longitude		41° 57′ N 87° 48′ W			41° 57′ N 87° 48′ W	34° 08′ N 118° 03′ W		25° 44′ N 80° 22′ W	49° 15′ N 123° 04′ W
z_s (m)	24.6–69.5	24.6	43.1	69.5	27.0	32.8	32.8	40.8	22.5
$z_{s\ max}/z_{s\ min}$	2.8	na	na	na	na	na	na	na	na
z_s/z_H	3.1–8.7	3.1	5.4	8.7	3.1	2.8	3.2	5.9	3.8
Directions included (°)	150–210 270–90	0–90 150–360	0–210 270–360	0–90 150–360	0–20 75–360	0–150 (L)[1] 165–360 (L) 0–150 (I)[2] 220–360 (I)	0–40 70–110 130–360	60–210	135–304
N neutral[3]		2544			44	1950	3	63	2
N unstable[4]	na	na	na	na	v[5]	na	v	v	35
z_0 Method	Lw	Su	Su	Su	Es	Su	Es	Es	Es
Sampling rate (Hz)	0.2	0.2	0.2	0.2	100, 10*[6]	0.2	100, 10*	20.83	25, 10+[7]
Averaging period (min)	15	15	15	15	30	15	30	30	60

[1] (L) acceptable wind directions for long term observations.
[2] (I) acceptable wind directions for intensive observations.
[3] N number of data points.
[4] N unstable: number of data points used in Tv method.
[5] v number of hours varied depending on criteria evaluated (no results reported here).
[6] * data block averaged at 10 Hz.
[7] + data sampled at 25 Hz and low pass filtered at 10 Hz.

TABLE II

Summary of z_0 and z_d values for each study area stratified by land cover (R, residential; CR, commercial with residential; C, Commercial; I, institutional; P, urban park with trees; G, urban park with few trees). UTZ, urban terrain zones based on Ellefsen (1985), further details are provided in Grimmond and Oke (1998). Surface attributes are for the summer measurement periods except for A94w P, where winter values are reported.

Site	Land cover	UTZ	Density Classes	Directions	Method	Obs. Level (m)	λ_F	λ_P	z_H (m)	z_0 (m) summer Mean	s.d	Median	fall Mean	winter Mean	spring Mean	Number of observations summer	fall	winter	spring
A94w	R	Do3	Med	190–320	Su	32.8	0.31	0.52	11.7	1.02	1.13	0.63	0.94	0.89		600	172	417	
A94	R	Do3	Med	190–320	Es	32.8	0.31	0.52	10.3	0.72		1.02				3			
C92w	R	Dc3	Med	110–180	Su	43.1	0.27	0.44	8.0	0.57	0.73	0.38	0.66	0.47	0.61	235	34	171	58
C92w	R	Dc3	Med	150–180	Su	69.5	0.26	0.45	7.9	0.45	0.75	0.21	0.52	0.37	0.44	201	33	136	47
C95u	R	Dc3	Med	200–360	Es	27.0	0.33	0.44	8.0	1.32	0.45	1.32				20			
Mi95	R	Do3	Low	60–195	Es	40.8	0.18	0.41	6.9	0.46	0.60	0.30				63			
Vs89	R	Dc3	Low	281	Es	22.5	0.19	0.42	8.7	0.60		0.60				2			
C92w	CR	Dc3/Dc5	Med	180–250	Su	24.6	0.27	0.47	7.8	0.50	0.33	0.43	0.48	0.45		76	30	180	
C92w	CR	Dc3/Dc5	Low/Med	180–210, 270–60	Su	43.1	0.24	0.45	7.9	0.79	0.97	0.59	0.67	0.51	0.62	507	171	1195	174
C92w	CR	Dc3/Dc5	Low/Med	180–60	Su	69.5	0.25	0.41	8.7	0.81	0.77	0.50	0.72	0.44	0.67	599	203	1648	195
C92w	C	Do5	Low	250–60	Su	24.6	0.20	0.50	7.4	0.56	0.55	0.44	0.50	0.38	0.47	523	173	1468	180
C92w	I	Do4	Low	60–110	Su	43.1	0.16	0.41	8.6	0.61	0.86	0.30		0.40	0.77	139		111	25
C92w	I	Do4	Low	60–110	Su	69.5	0.20	0.43	8.7	1.09	1.34	0.62				66			
A94w	P		High	15–75	Su	32.8	0.27	0.52	17.9				1.46	2.23			44	84	
C95u	G		Low	0–20	Es	27.0	0.18	0.45	8.7	2.04		2.0				2			
										z_d (m)									
C92w	R	Dc3	Med	150–180	Lw	24.6–69.5	0.26	0.45	7.9	4.62	1.48	4.45	5.34	4.48	4.33	124	27	108	39
Vs89	R	Do3	Low	135-304	Tv	22.5	0.18	0.36	8.5	4.5						35			
C92w	CR	Dc3/Dc5	Low	180–210, 270–60	Lw	24.6–69.5	0.23	0.46	7.9	3.73	1.55	3.05	3.88	3.77	3.43	403	137	966	137
C92w	I	Do4	Low	60–90	Lw	24.6–69.5	0.17	0.41	8.6	3.05	1.35	2.46				39			

30 minute intervals of raw data. All data were linear detrended and velocity components corrected for sensor separation for each calculation interval (Chahuneau et al., 1989). In addition, three-dimensional coordinate rotation was applied to align the instrument coordinate system with the local mean streamline winds (McMillen, 1988). The number of runs available for analysis and the directions used are listed in Table I.

4.2. Los Angeles

In Los Angeles both slow response (A94w) and fast response (A94) observations were conducted at the height of 32.8 m on a triangular lattice tower (Rohn model ss100d70exc, 0.4 m on a face at the top) in the Arcadia area of San Gabriel Valley (Figure 1) (Grimmond et al., 1996). The data were collected from August 1993 to August 1994.

Instruments were installed on booms extending 1 m from the tower at three levels (32.8, 21.3 and 11.5 m). Anemometers (R. M. Young wind sentry) and aspirated temperature sensors (Vaisala HMP35C), installed at each of the levels, were sampled at 0.2 Hz and 15 min averages and standard deviations recorded. Because of the position of the instruments relative to the tower, data were excluded from the direction 150 to 165° for the long term observations. When the turbulence data were being gathered, and new instruments mounted (see below), the sector excluded was extended to 220° (Table I). The data were stratified for neutral conditions based on observations at the top two levels. Because of the heights of the sensors relative to the canopy, only the upper sensor is used to determine roughness length. This means method Lw is not applicable and only Su (Equation (3)) is used here. All instruments were compared before and after the field program and data were corrected accordingly. The data were stratified by season to account for variability in leaf cover.

During July/August 1994 turbulence data (A94) were collected using a three-dimensional sonic anemometer-thermometer (Applied Technology Instruments, model SAT-211/3k) mounted at 32.8 m on the same tower. These data were gathered over a 30 min period sampled at 100 Hz and block-averaged non-overlapping in real time to 10 Hz. This instrument was located 0.56 m from the wind sentry which allowed *in situ* comparison of the σ_U values determined using the two types of instrumentation. For this analysis, the wind sentry data were split into two sets to account for the difference in averaging periods (30 min for the fast response sensors; 15 min for the slow response sensors). One set had the first 15-min period in each 30-min period; the second, had the second 15-min period in each 30 min. The slope determined between the fast (x) and slow (y) response sensors for the two sets are: 0.908 (R^2 = 0.914) and 0.891 (R^2 = 0.930) respectively, for the combined set the slope is 0.900 (R^2 = 0.921). Therefore, to account for data collected with 15-min averages with a sampling rate of 0.2 Hz, the ϕ_U value is reduced to 2.16

(2.4 × 0.9). This is very similar to the value of 2.2 recommended by Beljaars (1987) for 10-minute averages.

4.3. MIAMI

In Miami (Mi95) a fast response sensor was mounted at 40.8 m on a guyed mobile pneumatic tower (Will Burt TMD-20-134-469) during May/June 1995. A three-dimensional sonic anemometer (Gill/Solent three-axis research model) was used to measure the three velocity components and temperature. The data were sampled at 20.83 Hz, detrended by removing a linear trend, and analyzed using an averaging length of 30 min. A three-dimensional coordinate rotation was applied to align the instrument coordinate system with the local mean streamline winds (McMillen, 1988). No additional filtering was performed. Wind directions in the sectors 60–210° were selected to avoid wake interference from other instruments mounted at the same height (Tables I, II).

4.4. VANCOUVER

In Vancouver (Vs89) an array of fast response sensors were mounted at z_s = 22.5 m. The three-dimensional wind field, as well as temperature and vertical velocity fluctuations used in the present study, were measured with a sonic anemometer (Kaijo Denki, model TR-61C) and one-dimensional sonic anemometer/fine-wire thermocouple system (Campbell Scientific Inc, model CA 27), respectively (Roth and Oke, 1993). The sensors were mounted on a rotatable boom extending 2 m from the tower. The position of the boom was adjusted for each run to ensure complete exposure of sensors to the approaching mean wind (135–304°). Signals were sampled at 25 Hz, low-pass filtered at 10 Hz, and a linear trend removed. Transducer shadow and flow distortion corrections were applied to the Kaijo Denki data. For the present analysis 37 60-min runs were selected. For full details of instrumentation and data processing see Roth and Oke (1993).

4.5. SURFACE CHARACTERISTICS OF THE SITES

The height at which a sensor is located will, in conjunction with the meteorological conditions, determine the ‘source area’ or ‘foot print’ of the observations (i.e., the upwind surface area that affects the measurements) (Schmid, 1997). Winds at different heights are affected by roughness elements located at different distances upstream from the measurement site; the greater the height, the larger the effective distance (Panofsky, 1984). For the sites where slow response anemometry was conducted (A94w, C92w), the surface characteristics are calculated for source areas radiating every 5° around the measurement site, using the mean wind characteristics for that direction and a stability of $z'/L = -0.04$. For C92w the source area surface characteristics were determined for all three measurement heights. For sites where fast response anemometry was employed, the characteristics are calculated for each observation period. As z_0 and z_d are needed as inputs for source area calculations, initial inputs were provided by the values calculated for 30° sectors around each site. Using the source area model of Schmid (1994, 1997) a source weight filter was determined for each hour's observations, overlain on a surface geographic information system for each site (see Grimmond and Souch, 1994), and used to determine the site characteristics.

The spatial variability of these characteristics at each site should be interpreted with the aid of Figure 1a. Since land cover varies around each site, in later analyses the data are stratified to ensure only directions with similar land cover are averaged together when designating mean or median characteristics for a site. In this paper, most attention is directed to residential land cover. However, data from other surface types, notably commercial-residential areas and urban parks are presented to illustrate the spatial variability of roughness parameters in suburban areas.

The following mean site characteristics for each source area are plotted by wind direction in Figure 2:

(a) Mean height of the roughness elements ($\overline{z_H}$) (this includes buildings and trees) based on the frontal area index weighting.

(b) Plan area index: $\lambda_P = A_P/A_T$ where A_P is the plan area of the roughness elements and A_T is the total area.

(c) Frontal area index: $\lambda_F = \overline{L_y}\,\overline{z_H}/\overline{S_x^2}$ where $\overline{L_y}$ is the mean breadth of the roughness elements perpendicular to the wind direction and $\overline{S_x}$ is the average inter-element spacing between element centroids, in the along-wind direction.

5. Results and Discussion

5.1. Roughness Length

5.1.1. *Slow Response Anemometry*

Two slow response anemometric methods (Lw, Su) were applied to the Chicago 1992 (C92w) data set. The data presented in Figure 3 are the mean ($\overline{z_0}$) values calculated for 10° sectors around the site. These are only reported if there are at least 20 values for a given sector (following the criteria of Beljaars, 1987). It is important to note that land cover around the C92w site varies (see top of Figure 3).

Even though continuous data were collected for almost a year, because of the existence of preferred wind directions and the strict criteria for accepting data, not all wind directions provide results for all seasons. For a given method there are considerably more data available for the winter than for other seasons, with 22 of the possible 36 sectors having enough data to fulfill the Beljaars (1987) criterion. For the 13 sectors where a direct comparison is possible between the seasons, the Su winter values are about four-fifths of summer ones. Variability of medians for all sectors with data is large, as exemplified both by winter sector values which range from 0.15 to 0.56 m, 0.13 to 0.56 m, and 0.19 to 0.43 m at the three levels ($n = 22$,

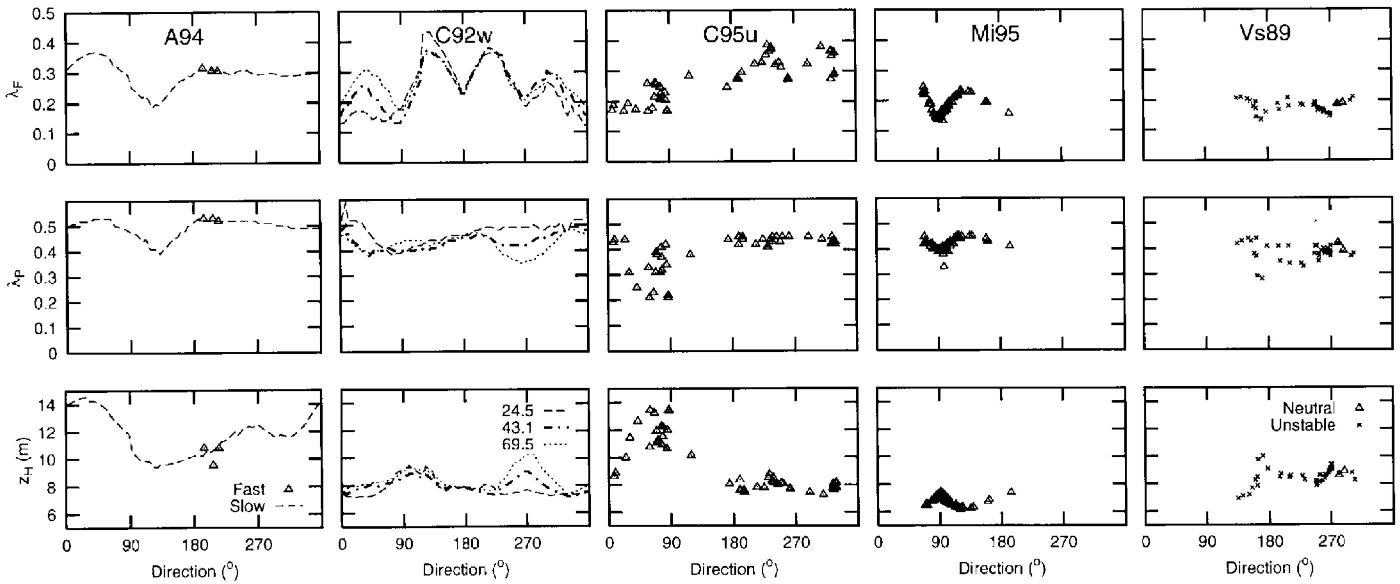

Figure 2. Morphometric characteristics for each of the study sites by wind direction: $\overline{z_H}$ mean height of the roughness elements; λ_P plan area of the roughness elements; and λ_F the frontal area index. For sites with slow response sensors values are calculated at 5° intervals, whereas for the sites with fast response sensors, values are calculated for the source areas of the observations (see text for further explanation).

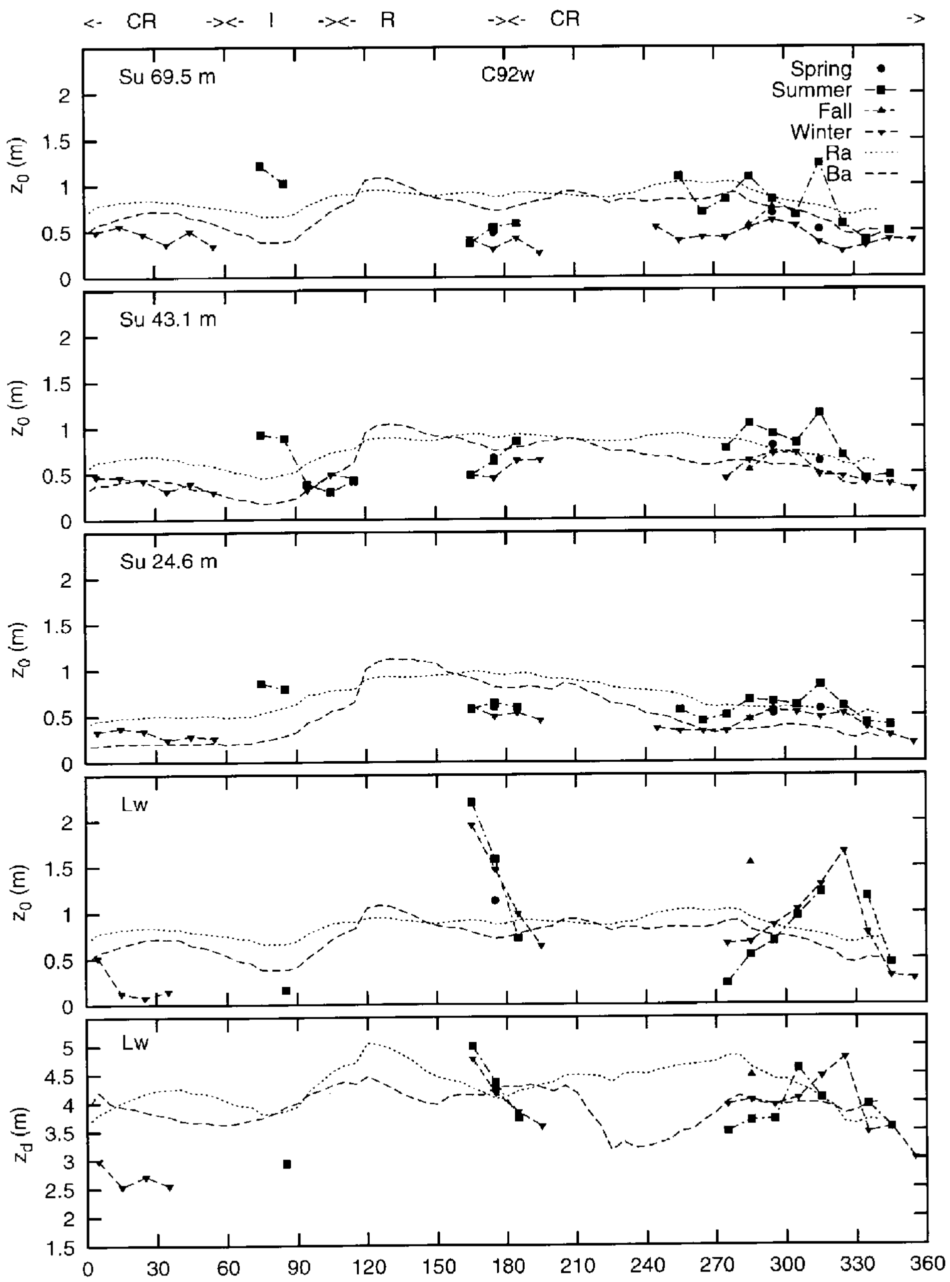

Figure 3. Mean values of $\overline{z_0}$ and $\overline{z_d}$ for 10° sectors by season using slow response methods for C92w. Morphometric methods (Ra, Ba) (see text for explanation) determined for every 5° around the site. Land cover around the site shown at the top of the diagram. (R, residential; CR, commercial with some residential; I, institutional).

21, 22 sectors, respectively); and for summer ($n = 13$, 11, 13 sectors respectively) when values range from 0.31 to 0.63 m, 0.19 to 0.84 m, and 0.17 to 0.97 m. For the residential areas (medium density)(from the 43.1 m level sensor), the mean winter value is 0.47 m, summer 0.57 m; while an area with mixed residential- commercial fetch has a winter mean of 0.51 m and summer mean of 0.79 m (Table II). The spatial variability determined from all levels is reasonably consistent between seasons. In general, the anemometrically determined results follow the same trends obtained from the two morphometric methods.

The values determined from the Lw method are quite different to those of Su (Figure 3). The differences in z_0 between the two methods are not systematic. If simple regressions are run between the median of the two sets, for the sectors where Lw data are available, at the lowest level there is an offset of 0.25 m and a slope of 0.18 (R^2 = 0.63); at the middle level the offset is 0.38 m, slope 0.07 (R^2 = 0.1); and at the upper level an offset of 0.285 m, and a slope of 0.01 (R^2 = 0.0); i.e., there is a lot of scatter in the relationship. As the height of the instruments changes so too does the source area/foot print of the anemometers. In general the land cover in the source areas around the site becomes more uniform with increasing height. In Chicago the Su z_{050} values determined from each level of measurement (24.6, 43.1, 69.5 m) are quite different. The lowest and middle levels are the most similar (the relation between the lowest level and the middle level has an offset of 0.05 m and a slope of 0.73 (R^2 = 0.58); between the middle and upper level an offset 0.12 m and slope of 0.96 (R^2 = 0.59); and between the lower and upper level the offset is 0.21 m and slope of 0.45 (R^2 = 0.29)). This suggests that when determining z_0 using the Lw method, problems may occur which are attributable to changes in surface characteristics at different distances away from the site, i.e., each of the sensors in the profile are affected by different surface characteristics. It follows that for Lw to be applicable the surface needs to be more spatially homogeneous than is found at the C92w site. The extremely small Lw values are for the wind directions 11–40°, an area with mixed commercial/residential fetch. In contrast, from the residential fetch in the 160–170° sector the Lw $\overline{z_0}$ values are much larger than those from Su (Figure 3). On average the Lw derived $\overline{z_0}$ values are 14% larger in winter than for summer. This is unexpected given the importance of deciduous trees in this area (Nowak, 1994).

Method Su requires z_d as an input whereas this is calculated by the Lw method. To evaluate the sensitivity of the $z_{0\,50}$ (median values) calculated by Su to the method used to determine z_d, winter $z_{0\,50}$ data for those sectors and times when Lw is also available were further analyzed. First Bottema's (1995) result (Equation (8)) was used to calculate z_d; second the simpler rule of thumb ($z_d = 0.7z_H$) was used. The Bottema method results in larger $z_{0\,50}$ values at all levels: of the order of 5% at the lower level, but less than 3% at the middle and top levels. All z_0 values for all sectors are systematically increased (offset $<$0.01 m, $R^2 > 0.99$). This suggests that the morphometric method used for z_d does not account for the differences in

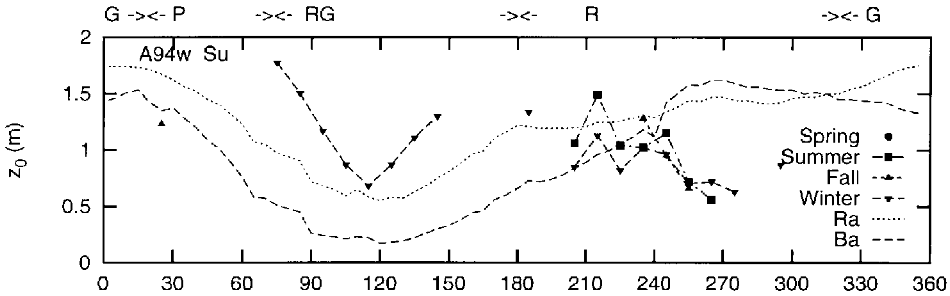

Figure 4. Mean values of z_0 for 10° sectors by season using the Su method for A94w. Morphometric methods (Ra, Ba) determined for every 5° around the site. Land cover around the site shown at the top of the diagram. (R, residential; P, urban park with a large number of trees; G, urban park which is predominantly grass with some trees; RG, residential with G type park in foreground).

results between the two methods, and furthermore that z_0 is not very sensitive to the z_d method used.

In Los Angeles (A94w) only the Su method could be used to determine z_0 (see Section 4.2). Data are available for some, although not all wind directions, encompassing different land covers (Figure 4). Again, there are more data available in winter than summer, with 18 data sets of 10° sectors ($N > 20$) providing mean values. The winter values around the site range from 0.63 (residential) to 1.77 m (urban park with high density trees) (Figure 4), with an overall mean of 1.02 m. The spatial variability around the site is very similar to that documented in Chicago. For the residential sector, the mean summer z_0 value (1.02 m) is approximately 15% greater than that for winter (0.89 m) (Table II). The mean z_0 value for the urban park is approximately 50% higher than that for the residential area (Table II).

5.1.2. *Fast Response Anemometry*

To estimate z_0 with measured u_* (method Es), z_d was calculated using Equation (8). It should be noted that because z_d is used in the determination of neutral conditions ($|z'/L| < 0.1$) the z_d estimate also influences which periods are analyzed. There are many fewer data points available at the individual sites for this analysis than from the slow response anemometric methods, because data were collected for shorter periods, and observations were only conducted in summer (Table I). At A94 and Vs89 so few data are available that only individual values can be reported. For C95u, the data are aggregated into 20° sectors, whereas in Mi95 10° sectors are used. In both Mi95 and C95u the medians reported are for sectors with a minimum of five values, rather than twenty values with the slow response data (Figure 5).

Table II summarizes the mean and median z_0 values obtained at the four sites using the Es method. The $z_{0\,50}$ values for the four 20° sectors for the C95u site, range from 0.57 to 3.35 m. The large $z_{0\,50}$ values (Figure 5) for the sectors 60–90° correspond to an area covered by a park and cemetery (i.e., a surface which is sparsely vegetated ('savannah type' structure) with large trees, interspersed with a

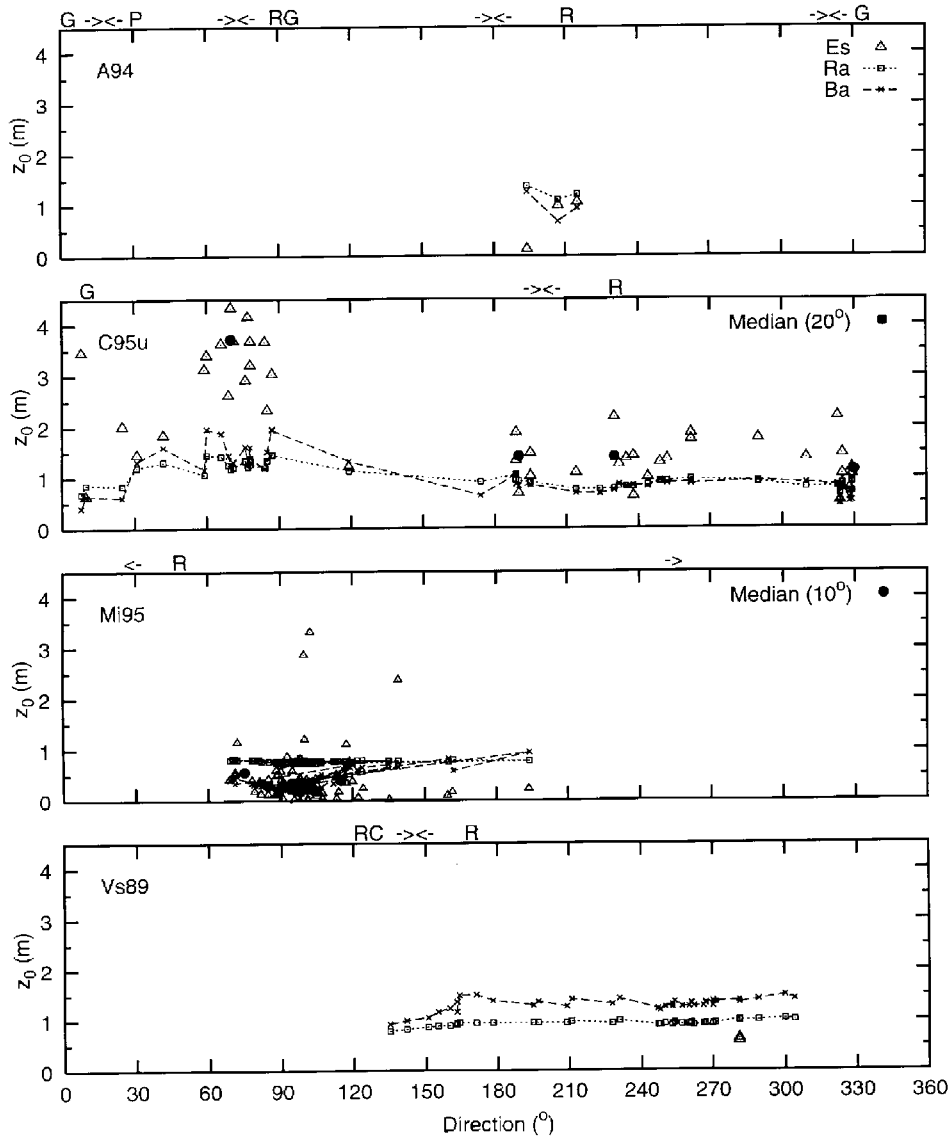

Figure 5. z_0 values from method Es for A94, C95u, Mi95 and Vs89 for individual periods. The median value for 20° and 10° sectors for C95u and Mi95 respectively are shown. Morphometrically (Ra, Ba) determined z_0 for source area characteristics for each observation period. Land cover around the sites are shown at the top of each diagram (R, residential; P, urban park with a large number of trees; RC, residential with some commercial; G, urban park which is predominantly grass with some trees).

few individual buildings). For the five 10° sectors in Mi95, $z_{0\ 50}$ ranges from 0.19 to 0.54 m. In all cases this is residential land cover. In Vs89 the mean of the two z_0 values is 0.6 m, and for the three in A94 it is 0.97 m. The coefficients of variation for C95u and Mi95 are much larger from the Es method than from the Su method. However, it is important to note that the number of data points considered in these analyses is much smaller.

5.1.3. *Comparison of the Methods*

Because (i) none of the anemometric methods for z_0 can be defined as 'the standard', (ii) not all methods were available at all sites, and (iii) estimates were restricted by limited wind directions, two morphometrically determined values of z_0 are plotted on all the figures. Morphometric methods provide one measure of the expected variability around each site due to changes in the size and spatial arrangement of the roughness elements (shown in Figure 2). Based on an assessment of several available methods (Grimmond and Oke, 1998) two methods are used: Raupach (1994, 1995) and the simplified Bottema (1995) method (Ra and Ba, respectively). Both methods determine z_0 and z_d as a function of frontal area index (λ_F) (see Section 4.5) and height. It is important to stress that the morphometric results are presented here to allow an interpretation of the consistency in patterns not as a basis to evaluate absolute values *per se.*

$\overline{z_0}$ values obtained from Su from both the C92w (3 levels) and A94w data sets are generally very similar to those determined morphometrically, whereas those using Lw data show greater variability (Figures 3 and 4). Based on this and the discussion in Section 5.1.1 we conclude that the Lw values at the C92w site are questionable.

At A94 and Vs89, the two Es sites where there are very few data points, the results reasonably agree with predictions using the morphometric methods (Figure 5). The one stray data point in the A94 set seems erroneously small, yet the source area characteristics it represents are almost the same (Figure 2). On the other hand, at the two sites with larger amounts of data we find that in one (C95u) the fast response data are almost all larger, and in the other (Mi95) somewhat smaller, than predicted by the morphometric methods.

Across all the sites and seasons z_0/z_H ranges from 0.02 to 0.24 (Figure 6), for λ_P in the range 0.40–0.52, and λ_F from 0.14–0.33. The C92w Lw data are not considered reliable and are not included. Table II presents a summary of results stratified by land cover class. Clearly, the data do not collapse on to a simple relation using either of the morphometric descriptors λ_P or λ_F (Figure 6), although most of the values do fall within the 'reasonable limits' proposed by Grimmond and Oke (1998). Wieringa (1993) suggests that after the peak in z_0/z_H when plotted against λ_P, data will show increased scatter because in skimming flow z_H is increasingly irrelevant as a length scale. Since the data collected here correspond to morphometric conditions beyond the peak in z_0/z_H proposed by Grimmond and Oke (envelope curves on Figure 6) we cannot comment on this directly; however,

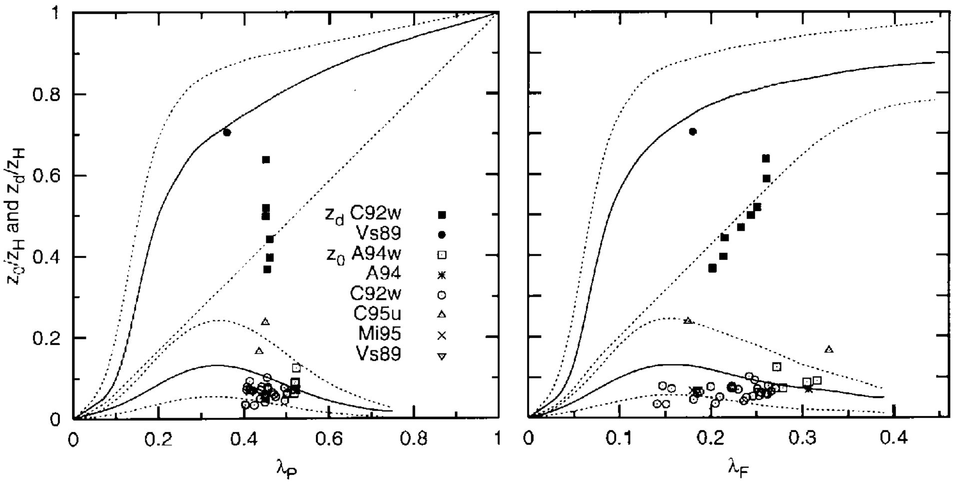

Figure 6. Height normalized z_0 and z_d versus morphometric parameters, frontal area index (λ_F) and plan area index (λ_P). Data plotted are from Table II with the appropriate morphometric characteristics for each season (only summer values are reported in Table II). Envelope curves are 'reasonable limits' (dotted) and approximate 'best estimate' (solid) based on heuristic arguments (Grimmond and Oke, 1998). The upper set of curves are for z_d/z_H and the lower set are for z_0/z_H.

the data do show increasing scatter at larger values of λ_P. The distribution of data on Figure 6 illustrate clearly that the morphometric parameter λ_F better captures the surface characteristics influencing z_d and z_0 than λ_P.

5.2. Displacement Length

5.2.1. *Slow Response Anemometry*

To determine z_d from slow-response wind sensors it is necessary to have a profile of instruments above the canopy. For the present study this was only available for the C92w data set. Using method Lw (Equations (1), (2)) both z_0 and z_d are obtained simultaneously. Based on the 17 data sets of 10° sectors with more than 20 individual data points (Figure 3), $\overline{z_d}$ values vary from approximately 2.5 to 5 m around the tower. The mean summer value for the residential land cover is 4.6 m, for the commercial/residential land cover 3.7 m, and for institutional land cover 3.0 m (Table II). Winter values are on average just slightly less (94%) than summer values. Data for both seasons show the same general spatial pattern around the site.

As with the z_0 plots, the Raupach and Bottema morphometrically determined z_d values are plotted for purposes of comparison (Figure 3). The Lw data do not show the same spatial pattern as the morphometric data in all directions. As noted above, the z_0 data determined simultaneously with these z_d values look questionable. Given their relative size, the same absolute error in each term will result in a larger relative error in z_0 (evident by greater relative variations in Figure 3).

5.2.2. *Fast Response Anemometry*

The displacement length at all four sites was determined using the Rotach (1994) Tv approach (see Section 2.2). The results obtained varied between sites and are discussed separately below.

The Vs89 data were analysed using two different empirical functions to calculate σ_Θ/Θ_*:

$$\sigma_\Theta/\Theta_* = -C_1[-(C_1/C_3)^3 - z'/L]^{-1/3} \tag{10}$$

$$\sigma_\Theta/\Theta_* = -C_1(-z'/L)^{-1/3} \tag{11}$$

C_1 was set constant at 0.95, and C_3 which defines the neutral limit, was set to -2.8, -3.0 and -3.5. When Equation (10) is used the z_d values corresponding to the minimum rms values were 2.1, 2.5, and 3.3 m, with the three C_3 values respectively. These are calculated for 35 unstable ($z/L < -0.2$) data points. At larger C_3 the fit is better because these data do not approach a limiting value near neutral stability (see Figure 6 in Roth, 1993). When Equation (11) is used, z_d is calculated to be 4.5 m which is larger than the mean for these periods determined from the Ra (2.9 m) and Ba (3.3 m) methods. However, it provides the better fit (the lowest rms value) to these observations. These results show the strong sensitivity of the calculated displacement lengths to the form of the empirical function and the value of the C_3 coefficient, and to the stability criterion for inclusion of data points at near neutral (not shown here).

Similar procedures were followed to implement the Tv method at the other three sites. First attempts used the coefficients C_1 = 0.95 and $C_3 = -3.5$ from Beljaars et al. (1983), based on the previous success of Rotach with these values in an urban environment. As is required, only data obtained during unstable conditions were used ($z'/L < -0.2$). In each case this produced displacement estimates that were the maximum possible (set at z_s) given the available range of heights input to the rms function. These values do not make sense physically since they exceed significantly the average height of the roughness elements.

The Tv method is not applicable for the A94, C95u, Mi95 data because the scaled temperature variance data do not coincide closely enough with the predicted values of the function given the range of possible displacement lengths. The variability of these observations make it difficult to formulate a function generalizing the trend of all the data. Feigenwinter et al. (1997) also encountered problems with the Tv method at the BASTA tower in Basel, Switzerland. They applied it to three levels (36, 50 and 76 m above ground level). The average height of the buildings was 24 m. For the lower two levels they obtain a z_d estimate of 22 m (i.e., $z_d \approx z_H$). However, it should be noted that their lowest observation level is at a height less than $2z_H$.

Feigenwinter et al. (1997) offer the possibility that their site does not meet the fetch requirements for horizontal thermal homogeneity mentioned by Rotach (1994). This may also be the case for the problem sites reported here. But perhaps more important is the possibility that many urban sites do not meet the essential assumption invoked by Rotach that the primary source/sink heights for both heat and momentum are co-located. In cities most momentum exchange is concentrated on the upwind vertical portions of the main roughness elements (buildings and trees) lying above the zero-plane. On the other hand, heat exchange occurs over the complete three-dimensional area of the surface (Voogt and Oke, 1997), with an effective anisotropy controlled by solar, not wind direction angles, and where large, open horizontal spaces (especially if they are dry) dominate the flux of sensible heat. Thus it seems very unlikely that the spatially-averaged primary site of momentum absorption and heat release are co-located, and therefore it is likely that z_{du} does not equal z_{dT}. Hence, before the validity of this method can be tested, it will be necessary to assess the extent to which this assumption holds.

Of course it is possible to fit values to the C_1 and C_3 coefficients using the observed data, but in order to do this a value of z_d must be assigned. This is a circular argument which only generates the initially assigned value of z_d.

6. Concluding Remarks

This study presents roughness and displacement lengths determined from fast- and slow-response anemometry for four suburban areas in North America. Table II summarizes the ‘best’ estimates of z_0 and z_d by land cover class with the associated morphometric attributes.

- In the urban environment, because of the large roughness elements and the nature of the surface determination of z_0, using multiple levels of measurements is problematic. Of the slow response methods, Su (Equation (3)) with adjusted ϕ_u (Section 4.2) and evaluated for neutral conditions at $z_S > 2z_H$ is favored. However, this approach has the inherent problem that z_d is not determined anemometrically.
- With respect to z_0, methods using fast response instruments yield results that are larger than those from slow response anemometry. At the one site where direct comparisons of methods are possible (A94/A94w), if the outlier Es value is removed, the resulting mean z_0 values are effectively the same.
- The Rotach (1994) Tv method in its original form is not found to be useful at three of the four urban sites. A slightly modified version produced reasonable estimates at one site.
- Based on slow response determinations (Su), winter time (leaf off) residential $\overline{z_0}$ are 82–87% of summer (leaf on) values. z_d values may be <5% smaller without leaves.
- Overall the roughness values measured in the four cities fall within a reasonable range when considered in relation to surface morphometric parameters (Figure 6), but the scatter is large. The magnitude of the differences around

the sites presented here are significant, and should be included via sensitivity analyses in applications where z_0 and z_d are needed.

There does not appear to be a clear choice of the ‘best’ anemometric method to determine z_0 and z_d. Even when wind observations are available, both the slow and fast response methods are capable of generating inconsistent data. Data were collected for a full year in Chicago and Los Angeles but because of stringent data requirements these sets still do not yield roughness parameters for all wind sectors. The need for more high quality field observations in cities, especially using fast response sensors, is obvious. The development of technology now makes it possible to measure almost continuously with fast response sonic anemometers. But careful attention must be paid to the choice of site and in order to properly interpret and generalize the results it is necessary to fully document the instrumentation, tower, and site characteristics.

Acknowledgements

The assistance of the many people who provided permission to use sites, and who aided with the fieldwork and the development of the morphometric databases is greatly appreciated. In particular, we would like to thank Trevor Newton, Andres Soux, Mark Hubble and Dr. Catherine Souch. Dr. Gordon Heisler provided the photograph of the Chicago site and Goshka Szczodrak the photograph of the Miami site. Helpful advice was given by: Dr. Mathias Rotach on the turbulence variance method; Dr. Hans Peter Schmid on the implementation of the source area model; and Dr. Marcel Bottema on his morphometric method. Funding was provided: to SG by Southern California Edison, USDA Forest Service co-operative research grants #23-526 & #23-546, and Indiana University Faculty Research Grant and Faculty Fellowships; to MR by the Swiss National Science Foundation #8220-042853; and, to TO by Natural Sciences and Engineering Research Council of Canada.

References

Ariel, M. Z. and Kliuchnikova, L. A.: 1960, ‘Wind over a City’, *Tr. Glav. Geofiz. Obs*. **94**, 29–32. (English translation by I. A. Donehoo. U.S. Weather Bur., Washington, D.C., 1961, 6 pp.)

Beljaars, A. C. M.: 1987, ‘The Measurement of Gustiness at Routine Wind Stations – A Review’, Koninklijk Nederlands Meteorologish Instituut Scientific Report WR87-11, 50 pp.

Beljaars, A. C. M., Schotanus, P., and Nieuwstadt, F. T. M.: 1983, ‘Surface Layer Similarity under Nonuniform Fetch Conditions’, *J. Appl. Meteorol.* **22**, 1800–1810.

Bottema, M.: 1995,.‘Aerodynamic Roughness Parameters for Homogeneous Building Groups – Part 2: Results. Document SUB-MESO **#23**, Ecole Centrale de Nantes, France, 80 pp.

Bottema, M.: 1997, ‘Urban Roughness Modelling in Relation to Pollutant Dispersal’, *Atmos. Environ.* **31**, 3059–3075.

Chahuneau, F., Desjardins, R. L., Brach, E., and Verdon, R.:1989, 'A Micrometeorological Facility for Eddy Flux Measurements of CO_2 and H_2O', *J. Atmos. Oceanic Technol.* **6**, 193–200.

Clarke, J. F., Ching, J. K. S., and Godowitch, J. M.: 1982, 'An Experimental Study of Turbulence in an Urban Environment', U.S. Environmental Protection Agency, Research Triangle Park, NC, Tech. Report EPA 600/3-8-062, 150 pp.

Duchene-Marullaz, P.: 1979, 'Effect of High Roughness on the Characteristics of Turbulence in Cases of Strong Winds', *Preprint 5th Int. Conf. Wind Eng.*, Fort Collins, paper II-8, 15 pp.

Ellefsen, R.: 1985, 'Urban Terrain Zone Characteristics', Tech. Monograph 18-87, U.S. Army Human Engineering Lab, Aberdeen Proving Ground, Maryland, 350 pp.

Feigenwinter, C., Vogt, R., and Parlow, E.: 1997, 'Vertical Structure of Turbulence above an Urban Canopy', Preprints of the Twelfth Conference on Boundary Layers and Turbulence, American Meteorological Society, Vancouver, British Columbia, July–August 1997, pp. 472–477.

Grant, R. G. and Heisler, G. M.: 1994, 'A Low Powered Radiation Shield for Air Temperature Measurements', in Preprints of the 21st Conference on Agriculture and Forest Meteorology, San Diego, CA, March 1994, pp. 203–206.

Grimmond, C. S. B. and Oke, T. R.: 1995, 'Comparison of Heat Fluxes from Summertime Observations in the Suburbs of Four North American Cities', *J. Appl. Meteorol*. **34**, 873–889.

Grimmond, C. S. B. and Oke, T. R.: 1998, 'Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form', *J. Appl. Meteorol.*, submitted.

Grimmond, C. S. B. and Souch, C: 1994, 'Surface Description for Urban Climate Studies: A GIS Based Methodology', *Geocarto Int.* **9**, 47–59.

Grimmond, C. S. B., Souch, C., Grant, R. H., and Heisler, G.:1994, 'Local Scale Energy and Water Exchanges in a Chicago Neighborhood', in E. G. McPherson, D. J. Nowak and R. A. Rowntree (eds.), *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*, USDA Forest Service Northeastern Forest Experiment Station, General Technical Report NE-186, pp. 41–61.

Grimmond, C. S. B., Souch, C., and Hubble, M.: 1996, 'The Influence of Tree Cover on Summertime Energy Balance Fluxes, San Gabriel Valley, Los Angeles', *Climate Research* **6**, 45–57.

Hanna, S. T.: 1969, 'Urban Micrometeorology', Proceedings American Nuclear Society Meeting, San Francisco, CA, ATDL Contribution 35, 21 pp.

Hanna, S. T. and Chang, J. C.: 1992, 'Boundary Layer Parameterisations for Applied Dispersion Modelling over Urban Areas', *Boundary-Layer Meteorol.* **58**, 229–259.

Högström, U., Bergström, H., and Alexandersson, H.: 1982, 'Turbulence Characteristics in a Near Neutrally Stratified Urban Atmosphere', *Boundary-Layer Meteorol.* **23**, 449–472.

Jones, P. M., deLarzinaga, M. A. B., and Wilson, C. B.: 1971, 'The Urban Wind Velocity Profile', *Atmos. Environ*. **5**, 89–102.

Kaimal, J. C.: 1990, *WPL Application Notes 1–4. Applied Technologies, Inc. Operator's Manual for SAT-211/3k Three-Axis Sonic Anemometer/Thermometer, Appendix D*, Applied Technologies, Inc. Boulder, CO, 14 pp.

Karlsson, S.: 1981, 'Analysis of Wind Profile Data from an Urban-Rural Interface Site', Report 58, Department of Meteorology, University of Uppsala.

Karlsson, S.: 1986, 'The Applicability of Wind Profile Formulas to an Urban-Rural Interface Site', *Boundary-Layer Meteorol.* **34**, 333–355.

King, T. S. and Grimmond, C. S. B.: 1997, 'Transfer Mechanisms over an Urban Surface for Water Vapor, Sensible Heat and Momentum', in Preprints of the Twelfth Conference on Boundary Layers and Turbulence, American Meteorological Society, Vancouver, British Columbia, July–August 1997, pp. 455–456.

Landsberg, H. E.: 1981, *The Urban Climate*, Academic Press, London, 275 pp.

Lettau H.: 1957, 'Compilation of Richardson Numbers, Classification of Profiles and Determination of Roughness Parameters', in *Exploring the Atmosphere's 1st Mile*, Vol. 1, pp. 328–336.

Lumley, J. L. and Panofsky, H. A.: 1964, *The Structure of Atmospheric Turbulence*, John Wiley and Sons, New York, 239 pp.

McMillen, R. T.: 1988, 'An Eddy Correlation Technique with Extended Applicability to Non-Simple Terrain', *Boundary-Layer Meteorol*. **43**, 231–245.

Nowak, D. J.: 1994, 'Urban Forest Structure: The State of Chicago's Urban Forest', in E. G. McPherson, D. J. Nowak and R. A. Rowntree (eds.), *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*, USDA Forest Service Northeastern Forest Experiment Station, General Technical Report NE-186, pp. 3–18.

Oikawa, S. and Meng, T.: 1995, 'Turbulence Characteristics and Organized Motion in a Suburban Roughness Layer', *Boundary-Layer Meteorol*. **74**, 289–312.

Panofsky, H. A.: 1984, 'Vertical Variation of Roughness Length at the Boulder Atmospheric Observatory', *Boundary-Layer Meteorol.* **28**, 305–308.

Panofsky, H. A. and Dutton, J. A.: 1984, *Atmospheric Turbulence, Models and Methods for Engineering Applications*, J. Wiley and Sons, New York, 397 pp.

Raupach, M. R.: 1994, 'Simplified Expressions for Vegetation Roughness Length and Zero-Plane Displacement as Functions of Canopy Height and Area Index', *Boundary-Layer Meteorol*. **71**, 211–216.

Raupach, M. R.: 1995, 'Corrigenda', *Boundary-Layer Meteorol*. **76**, 303–304.

Rotach, M. W.: 1991, 'Turbulence within and above an Urban Canopy', *Zürcher Geogr. Schrift.* **45**, 245.

Rotach, M. W.: 1994, 'Determination of the Zero Plane Displacement in an Urban Area', *Boundary-Layer Meteorol.* **67**, 187–193.

Roth, M.: 1993, 'Turbulent Transfer Relationships over an Urban Surface. II: Integral Statistics', *Quart. J. Roy. Meteorol. Soc.* **119**, 1105–1120.

Roth, M. and Oke, T. R.: 1993, 'Turbulent Transfer Relationships over an Urban Surface. I: Spectral Characteristics', *Quart. J. Roy. Meteorol. Soc.* **119**, 1071–1104.

Schmid, H. P.: 1994, 'Source Areas for Scalars and Scalar Fluxes', *Boundary-Layer Meteorol*. **67**, 293–318.

Schmid, H. P.: 1997, 'Experimental Design for Flux Measurements: Matching the Scale of the Observations to the Scale of the Flux', *Agric. For. Meteorol*. **87**, 179–200.

Steyn, D. G.: 1980, 'Turbulence, Diffusion and Daytime Mixed Layer Depth over a Coastal City', Unpubl. Ph.D. thesis, The University of British Columbia, Vancouver, 161 pp.

Tillman, J. E.: 1972, 'The Indirect Determination of Stability, Heat, and Momentum Fluxes in the Atmospheric Boundary Layer from Simple Scalar Variables during Dry Unstable Conditions', *J. Appl. Meteorol.* **11**, 783–792.

Voogt, J. A. and Oke, T. R.: 1997, 'Complete Urban Surface Temperatures', *J. Appl. Meteorol.* **36**, 1117–1132.

Wieringa, J.: 1993, 'Representative Roughness Parameters for Homogeneous Terrain', *Boundary-Layer Meteorol.* **63**, 323–363.

Wyngaard, J. C., Coté, O. R., and Izumi, Y.: 1971, 'Local Free Convection, Similarity, and the Budgets of Shear Stress', *J. Atmos Sci*. **28**, 1171–1182.

Yersel, M. and Gobel, R.: 1986, 'Roughness Effects on Urban Turbulence Parameters', *Boundary-Layer Meteorol*. **37**, 171–184.