8.3 SPATIAL VARIABILITY OF TURBULENCE CHARACTERISTICS OBSERVED DURING JOINT URBAN 2003

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ABSTRACT

We present analyses of turbulence measurements made with sonic anemometers on five meteorological towers during Joint Urban 2003. We focus on the spatial variability of turbulence characteristics observed in the Oklahoma City metropolitan area. Inter-comparisons of turbulence statistics observed at the five tower locations and between urban and suburban domains demonstrate significant heterogeneity of turbulence characteristics in the surface layer over the city. Comparisons between our results and previously documented similar analyses are also presented.

1. INTRODUCTION

The Joint Urban 2003 was a cooperative undertaking to study transport and diffusion in the atmospheric boundary layer in an urban environment. It was conducted in Oklahoma City in the summer of 2003 (Allwine *et al.*, 2004). The Army Research Laboratory (ARL) deployed a number of measurement facilities, including an array of sonic anemometers mounted on five meteorological towers in the metropolitan area. See Yee *et al.* (2004) for detailed information on the ARL measurements. The large amount of sonic data was processed using available quality control software (Vickers and Mahrt, 1997).

Various turbulence parameters have been computed and their statistics analyzed. This paper focuses on the analysis of turbulence variances in the urban surface layer. Other results, including spectral analyses of u, v, w, and T in urban and suburban locations, are presented elsewhere (Chang *et al.*, 2004; Garvey *et al.*, 2004; Klipp *et al.*, 2004).

2. DATA COLLECTION AND PROCESSING

Ultrasonic anemometers (R. M. Young, Model 81000) were mounted on towers of ten meter height at three levels (10 m, 5 m, and 2.5 m above the ground) for Towers #2 and #3 and at two levels (10 m and 5 m) for Towers #1, #4, and #5. Instruments below the 10 m level were mounted due south of the towers at the end of 2 m booms in anticipation of the prevailing southerly winds in Oklahoma during the summer. Anemometer elevations (heights above the ground) were accurate to about +/- 0.1 m for 10.0m and 5.0 m instruments, and about +/- 0.05 m for the 2.5 m instruments.

Table 1. Geographic information for the five ARL meteorological towers. z is the anemometer height (AGL).

Tower	Lat.(N)	Long.(W)	Location	Elev(m)	z(m)
No.1	35 26.87'	97 33.67'	SW 20th & S Miller	307.85	10,5
No.2	35 27.99'	97 30.24'	Sheridan Ave & S Byers	381.91	10,5,2.5
No.3	35 26.57'	97 28.59'	SE 22nd & Eastern Ave	377.34	10,5,2.5
No.4	35 30.49'	97 31.16'	NW 36th & N Walker St	349.61	10,5
No.5	35 28.08'	97 31.93'	W Main St & N Klein Ave	368.81	10, 5

Relevant geographic information for the five towers is provided in Table 1. Figure 1 shows the locations and immediate surroundings of these 5 towers. As indicated in Figure 1(b), the immediate vicinity around Tower #1 is quite open; there were no houses or trees within a distance of 50 m except for a small portable trailer (3.3 m in height) to the south-southwest. There were a number of buses with a height of about 3.5 m to the west of the tower. The average height of houses in the surrounding area was estimated to be about 6 m. Tower #2, on the other hand, was surrounded by industrial buildings with an average height of 10 m within a distance of 30-50 m, as indicated by Figure 1(c). Tower #3, Figure 1(d), has an open fetch to the south, and the ground slopes off in this direction. There are trees with heights of 10-15 m east and west of the tower, with a small house near the trees to the east. As seen from Figure 1(e), Tower #4 was located near a highway, with a school building on the west and open ground for distances more than 50 m north, east, and south. Figure 1(f) shows that Tower #5 was surrounded by buildings on the east, south and west sides, with building heights between 6-8 m. There was a line of fairly tall trees across the alley to the north.

Generally speaking, Towers #2 and #5 can be considered typical of industrial or warehouse urban areas while the other three tower locations typify suburban areas. Lundquist *et al.* (2004) have estimated the mean building height for the urban area of Oklahoma City as 5-15m. Measurements by our sonic anemometers, conducted outside the central business district, can therefore be considered to represent the urban roughness sub-layer (Roth, 2000) at specific locations. The sonic anemometer data consist of three wind components (u, v, w) and sonic temperature (T). In this study, we use the data from the 10m sonic

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anemometers only. Mounted on the top of the five towers, these sensors should not exhibit a “tower shadow “ effect for any wind direction. The sampling

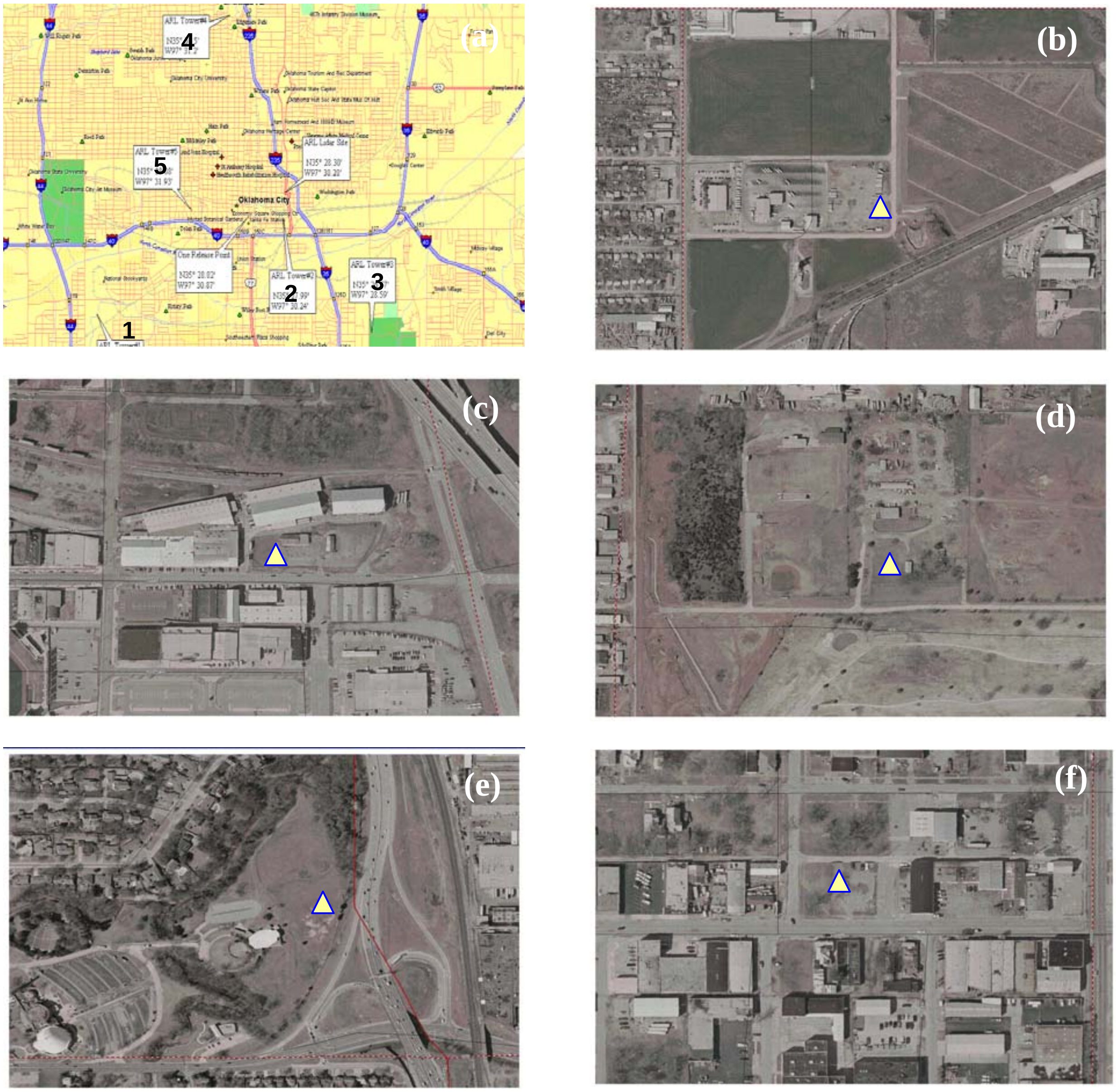

Figure 1. Locations (a) and surroundings of the ARL 5 met towers indicated by triangles. Aerial photos for Tower No. 1 (b), No. 2 (c), No. 3 (d), No. 4 (e), and No. 5 (f). Aerial photos available from U.S. Geological Survey, EROS Data Center, Sioux Falls, SD. (http://seamless.usgs.gov)

rate of the sonic anemometers was 10 Hz. For sonic anemometer tilt correction, the traditional two angle rotation method (Kaimal and Finnigan, 1994) was used for each time series of 30 minutes (18000 data points). After the tilt correction, the three components of the wind vector are u (streamline), v (transverse), and w (normal) with $\overline{v} = \overline{w} = 0$, where the over-bar indicates the 30-minute average. For our analysis we adopted the Analysis Package for Time Series (APAK) developed at Oregon State University by Vickers and Mahrt. (http://blg.coas.oregonstate.edu/Software/software.html)

3. RESULTS

3.1 Zero Plane Displacement Height (d)

Rotach (1994) has presented the temperature variance method to estimate the zero plane displacement height (d) 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 surface layer can be expressed as

$$\sigma_T' = \sigma_T / |T_*| = C_1[\,1 - C_2\,(z-d)/L\,]^{-1/3} , \qquad (1)$$

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

$$T_* = -H / u_* = -\overline{w'T'} / u_* \;; \qquad (2)$$

$$u_*^2 = \left((\overline{u'w'})^2 + (\overline{v'w'})^2 \right)^{1/2} \;\text{; and} \qquad (3)$$

$$L = -u_*^3 / [\,k\,(g/\overline{T})H\,] , \qquad (4)$$

where u_* is the friction velocity, k the von Karman constant, 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 (Wyngaard *et al*., 1971, Tillmann, 1972, 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 (1) and the measured value $(\sigma_T')_m$ are to be minimized from the following equation by varying the d value in (1).

$$E^2 = (1/N) \sum_{i=1}^{N} [\sigma_T' - (\sigma_T')_m]^2_i \;, \quad i = 1,2, \ldots N \qquad (5)$$

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. Table 2 lists estimated values of d for the 5 tower locations.

Table 2. Estimated values of d (m) with respect to the wind direction for the five ARL tower locations. The number in the parentheses denotes N in Equation (5). The last line indicates the N-weighted values of d for all wind directions.

Wind Dir. (degree)	Tower #1 d (N)	Tower #2 d (N)	Tower #3 d (N)	Tower #4 d (N)	Tower#5 d (N)
0 - 90	1.4 (44)	4.7 (64)	6.8 (30)	4.8 (46)	5.7 (57)
90 - 180	1.7 (68)	5.7 (106)	1.8 (48)	4.0 (49)	4.2 (138)
180 - 270	2.9 (253)	5.6 (273)	6.6 (183)	2.5 (221)	5.3 (186)
270 - 360	5.3 (13)	5.9 (16)	5.3 (8)	6.1 (13)	7.4 (14)
0 - 360	2.6 (378)	5.5 (459)	5.7 (269)	3.2 (329)	5.0 (395)

As emphasized by Rotach (1994), the zero plane displacement (d) at an urban site can vary considerably with wind direction. From Table 2 we see that d varies with wind direction at each location. For example, depending on wind direction, d can vary from 1.4 m to 5.3 m for the Tower #1 site and from 4.7 m to 5.9 m for the Tower #2 site. Feigenwinter *et al.* (1999) have also found significant variation of d values with wind direction over the city of Basel, Switzerland. These authors used eight wind direction sectors. We felt we had too few data points in some of the sectors to present a corresponding analysis here.

The reason for the significant variation of d with wind direction for the five tower sites is generally understandable if we examine the significant variation of urban roughness elements (buildings, structures, and trees) with wind direction at the five sites shown in Figure 1. Fig 1(b), for example, shows that there were many more roughness elements to the west of Tower #1 than to the east. Consequently, the d values are larger for westerly winds than for easterly winds. Likewise, the d values are larger for the sites at Towers #2 and #5 than for the sites at Towers #1 and #4 due to the fact that the former two were more closely surrounded by taller buildings, as seen from Fig. 1 (c,f and b,e) and discussed earlier. The large values of d for northeasterly and southwesterly winds (6.8 m and 6.6 m, respectively) for the Tower #3 site (Figure 1(d)) are believed to be due to the effects of the nearby trees; we speculate that if a southerly sector had been chosen for analysis, a smaller value of d would have resulted.

The measurements by the sonic anemometers at the 5 towers do not allow us to estimate the roughness length z_0 for the 5 locations because the heights of the instruments are not high enough to be considered in the inertial (constant flux) sub-layer (Roth, 2000). Grimmond and Oke (1999) have reviewed several methods to determine the aerodynamic characteristics of a surface, including the zero plane displacement height d and roughness length z_0. An approximate relation between z_0 and d can be derived as a simple rule of thumb. Based on the common morphometric approach, z_0 can be expressed as a fraction of d, say $z_0 = C_z * d$, where C_z is about 0.1 - 0.2; see section 2 of Grimmond and Oke (1999). Hence we can estimate the values of z_0 for the five locations from the d values in Table 2. Burian *et al.* (2003) have estimated the values of d and z_0 for the Oklahoma City downtown core area as around 13m and 2.5m, respectively, as cited by De Wekker *et al*. (2004). Because the downtown core area has taller buildings than the rest of the city, the values of d and z_0 from Burian *et al.* are significantly larger than our estimated values for the five ARL tower sites, which are not in the downtown area.

3.2 Normalized standard deviations

The standard deviations of longitudinal (σ_u), transverse (σ_v), and vertical (σ_w) wind velocity components normalized by the friction velocity (u_*) for unstable conditions can be expressed as (Roth, 2000)

$$\sigma_v' = \sigma_v / u_* \sim \sigma_u' = \sigma_u / u_* = C_3 [1 - C_4 (z-d)/L]^{1/3} ; \quad (6)$$

$$\sigma_w' = \sigma_w / u_* = C_5 [1 - C_6 (z-d)/L]^{1/3} ; \quad (7)$$

where C_3, C_4, C_5, and C_6 are empirical constants. Over flat terrain,

$$C_3 = 2.2, \quad C_4 = 3.0, \quad C_5 = 1.25, \quad C_6 = 3.0 \; ; \quad (8)$$

see, e.g., Panofsky and Dutton (1984); De Bruin *et al.* (1993). Based on the d values for the five tower locations at the four quadrants in Table 2, the measured normalized standard deviations for the three wind velocity components and for the temperature are plotted versus (z-d)/L in Figure 2. The solid lines in Figure 2 represent the empirical relations of equations (1), (6), and (7) using the empirical constants we have cited. Figure 2 shows that σ_w' (third row in Fig. 2) over Oklahoma City seems to exhibit the same behavior as over flat terrain, where d in Equation (7) is close to zero. The reason is probably that the vertical velocity fluctuations are produced by small eddies, the diameters of which are of the order of the reduced height (z-d) over the urban area instead of the height above the ground (z) over flat terrain. In contrast, the normalized standard deviations of the horizontal wind components (σ_u' and σ_v') are primarily produced by large quasi-horizontal eddies. Their diameters are typically a few hundred meters and tend to be influenced and distorted by urban buildings and trees. Consequently, σ_u' and σ_v' over an urban area are larger and more scattered, especially under unstable conditions, as compared to their counterparts over flat terrain. The mean values of the normalized standard deviations for near-neutral conditions, defined as |(z-d)/L| < 0.05, are listed in Table3.

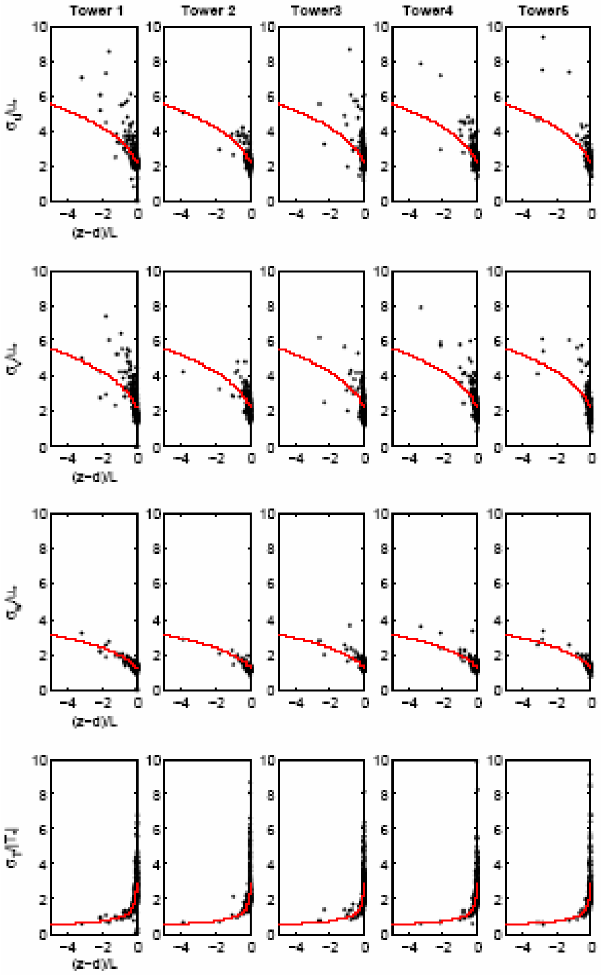

Figure 2. Normalized standard deviations from 5 ARL tower measurements. The lines show the empirical relations of (6) and (7) with (8) for (u,v,w) and of (1) for (T), respectively.

Table 3. Mean values and their standard deviations (in parentheses) of the normalized standard deviations for near neutral condition defined as |(z-d)/L|<0.05 measured at five ARL towers. N is the number of data points.

Tower	N	σ_u / u_*	σ_v / u_*	σ_w / u_*	$\sigma_T / \lvert T_* \rvert$
No. 1	182	2.15 (0.37)	1.80 (0.42)	1.25 (0.21)	2.73 (1.00)
No. 2	304	2.13 (0.22)	1.93 (0.35)	1.19 (0.10)	2.69 (1.23)
No. 3	386	2.31 (0.41)	1.84 (0.38)	1.32 (0.14)	2.70 (0.92)
No. 4	276	2.15 (0.23)	1.84 (0.29)	1.34 (0.12)	2.69 (1.01)
No. 5	255	2.23 (0.26)	1.73 (0.32)	1.21 (0.11)	2.73 (1.36)

All	1403	2.20	1.84	1.27	2.71
Panofsky & Dutton		2.39	1.92	1.25	

As the surface layer similarity theory suggests, the normalized standard deviations for the three wind components (σ_u', σ_v', σ_w') under neutral conditions are “constants”. From Table 3 we obtain values of 2.20, 1.84, and 1.27 when measurements from all five towers are considered. These values are very close to the corresponding values over flat terrain (Panofsky and Dutton, 1984), as indicated in Table 3. It is seen, too, that near-neutral values of these normalized standard deviations are very similar among the five tower locations.

Finally, the σ_T’ data are plotted using the calculated d values and compared to equation 1, shown in the bottom row of Figure 2. The good agreement between the two is reassuring. As pointed out by Roth (2000), large variations in σ_T’ are expected at near-neutral stability, where the heat flux becomes close to zero but production of temperature fluctuations does not cease. As a result of this, the estimated neutral limit values of σ_T’ are dependent more on the definition of near-neutral than on the initial choice of parameters in Equation 1, since the d values only affect the z/L scaling, not the magnitudes of σ_T’. Our estimates in Table 3 are based on $|(z-d)/L|<0.05$. Further restricting the definition of near-neutral stability results in larger values for the neutral limits of σ_T’ and in larger standard deviations.

4. SUMMARY

A considerable amount of sonic anemometer data from the Army Research Laboratory’s five meteorological towers during the Joint Urban 2003 Oklahoma City field experiment has been collected and processed. Using the temperature variance method, the displacement heights (d) for the five tower locations have been estimated. The estimated values of d exhibit significant heterogeneity and depend strongly on wind direction, as shown by Table 2; and so does the roughness length. On the other hand, the normalized standard deviations for the three wind components and for the temperature appear to follow more or less the empirical relations derived for flat terrain (rural area). In particular, the near neutral values of these normalized standard deviations are very close to the values observed over flat terrain as documented in the literature.

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