15.2 AREA-AVERAGED PROFILES OVER THE MOCK URBAN SETTING TEST ARRAY

Matthew A. Nelson*, Michael J. Brown
Los Alamos National Laboratory, Los Alamos, NM

Eric R. Pardyjak, Joseph C. Klewicki
University of Utah, Salt Lake City, UT

1. INTRODUCTION

Urban areas have a large effect on the local climate and meteorology. Efforts have been made to incorporate the bulk dynamic and thermodynamic effects of urban areas into mesoscale models (e.g., Chin et al., 2000; Holt et al., 2002; Lacser and Otte, 2002). At this scale buildings cannot be resolved individually, but parameterizations have been developed to capture their aggregate effect. These urban canopy parameterizations have been designed to account for the area-average drag, turbulent kinetic energy (TKE) production, and surface energy balance modifications due to buildings (e.g., Sorbjan and Uliasz, 1982; Ca, 1999; Brown, 2000; Martilli et al., 2002). These models compute an area-averaged mean profile that is representative of the bulk flow characteristics over the entire mesoscale grid cell.

One difficulty has been testing of these parameterizations due to lack of area-averaged data. In this paper, area-averaged velocity and turbulent kinetic energy profiles are derived from data collected at the Mock Urban Setting Test (MUST). The MUST experiment was designed to be a near full-scale model of an idealized urban area imbedded in the Atmospheric Surface Layer (ASL). It's purpose was to study airflow and plume transport in urban areas and to provide a test case for model validation. A large number of velocity measurements were taken at the test site so that it was possible to derive area-averaged velocity and TKE profiles.

2. EXPERIMENTAL DETAILS

MUST was performed during the month of September 2001 in Utah's West Desert at US Army's Dugway Proving Ground (DPG) (Biltoft, 2001). MUST consisted of a 10 by 12 aligned array of shipping containers placed in relatively flat terrain surrounded by low shrubbery as seen in Figure 1. Each shipping container was 12.2 m long, 2.42 m wide, and 2.54 m high (*H*). The array had a plan area density (λ_p) of 0.096 and frontal area densities (λ_f) of 0.10 and 0.03 using the length and width respectively (Yee and Biltoft 2004). Various 2D and 3D sonic anemometers were placed around, above, and throughout the array on various towers.

**Corresponding author address:* Matthew A. Nelson, Los Alamos National Laboratory, Group D-4, MS K575, Los Alamos, NM 87545; e-mail: nelsonm@lanl.gov

Figure 1. Photograph of the MUST array taken from the southeast corner of the array (courtesy of C.A. Biltoft DPG, ret.).

Figure 2 is a schematic showing the relative location of the instrumentation and towers used in MUST. The array was aligned approximately 30° west of true north making winds with a bearing of 150° perpendicular to the length of the buildings. Table 1 lists the number of sonics at each height that have been used in this study. The type of sonic anemometer, the organization that operated the sonic anemometer, the relative position of the sonic anemometer, and the sampling frequency for the various sonic anemometers are also given. Note that there were two schemes for the placement of the 6 Handar 2D sonic anemometers. Area-averaged profiles were produced using scheme 1 with a high concentration of sonic anemometers in the southernmost urban canyon.

3. DATA PROCESSING

Five-minute averages were performed on the sonic measurements from the night of 9/24/2003 between 2020 and 2340 MDT. These data were then area-averaged by binning together measurements according to height above ground level as shown in Table 1. For this study, data analysis was only performed when inflow winds were within ±30° of perpendicular to the building array. Data from all instruments were weighted equally in determining the area-averaged profile. Although the instrument

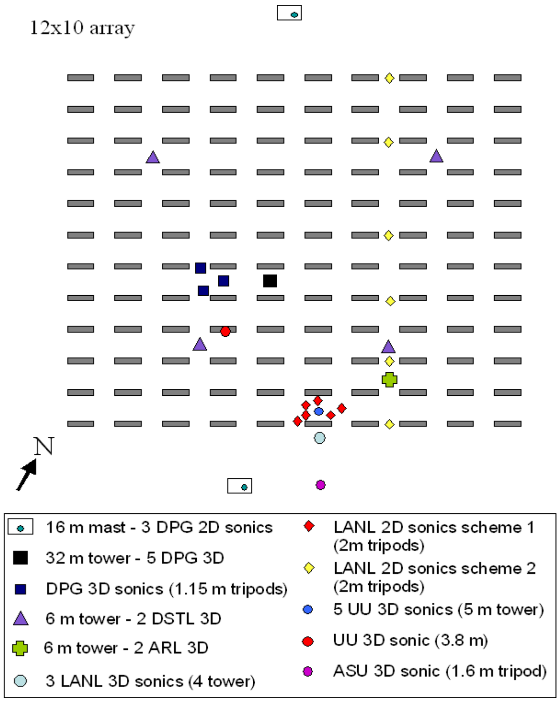

Figure 2. Schematic showing the relative locations of the sonic anemometers employed in MUST. Not to scale. Organizations: ARL (Army Research Laboratory); ASU (Arizona State University); DPG (Dugway Proving Grounds); DSTL (Defense Science Technology Laboratory); UU (University of Utah).

z(m)	# of Sonics	Organization & Type	Location in Array	SF (Hz)
0.6	1	1 UU 3D	F, z<H	20
1.1	5	1 UU 3D 4 DPG 3D	F,z<H M, z<H	20 10
1.9	6	1 UU 3D 5 LANL 2D	F, z<H F, z<H	20 0.5
2.5	3	1 UU 3D 2 DSTL 3D	F, z~H 1 F/1 B, z~H	20 10
3.9	3	2 UU 3D 1 DPG 3D	1 F/1 M, z>H M, z>H	20 10
6	3	3 DSTL 3D	2 F/1 B, z>H	10
8	1	1DPG 3D	M, z>H	10
16	1	1DPG 3D	M, z>H	10
32	1	1DPG 3D	M, z>H	10

Table 1 Height and number of sonic anemometers used for area-averaging with their relative location within the array. Note that the canopy height is 2.54 m. *F* signifies the front or southernmost rows of the array, *M* the middle of the array, and *B* the back or northernmost rows of the array. Organizations: UU(University of Utah); DPG (Dugway Proving Ground); LANL (Los Alamos National Laboratory); DSTL (Defense Science Technology Laboratory).

density was relatively high compared to other urban field experiments, the layout used in this study may introduce biases due to the inherent inhomogeneity of flow in the building array. In addition, bias in the area-averaged measurements will exist due to the high fraction of canopy measurements in the first row of the array where the canopy and urban roughness sublayer (URSL) are not fully developed. Utilization of inflow winds with bearings of 330º±30° would include fully-developed flow in the area-averaged calculations, however, few periods of northwesterly winds occurred during the operating periods of the MUST experiment. One should keep in mind these biases when making comparisons to real cities, idealized outdoor building arrays, and wind-tunnel experiments.

4. PRELIMINARY RESULTS

4.1 *Urban Canopy Area-Average Measurements*

Figure 3 focuses on the canopy region and roughness sublayer and shows the area-averaged building array wind speed profile has the inflection point that is typical in vegetative canopies. One can see that the area-average wind speed below canopy height is fairly uniform and then increases rapidly with height above building height. Note that in this plot the wind speed profiles are normalized by the area-averaged wind speed at building height.

Cionco (1965) suggested that the flow within vegetative canopies can be modeled as:

$$\frac{U(z)}{U_H} = \exp\left[-\alpha\left(1-\frac{z}{H}\right)\right] \qquad (1)$$

where α is a factor that depends on canopy element density. Using the formula proposed by MacDonald et al. (1998) for arrays of simple cubes, α=9.6λ_f, Eqn. 1 is compared to the normalized area-averaged wind speed profiles up to *z/H*~1.5. Figure 3 shows that

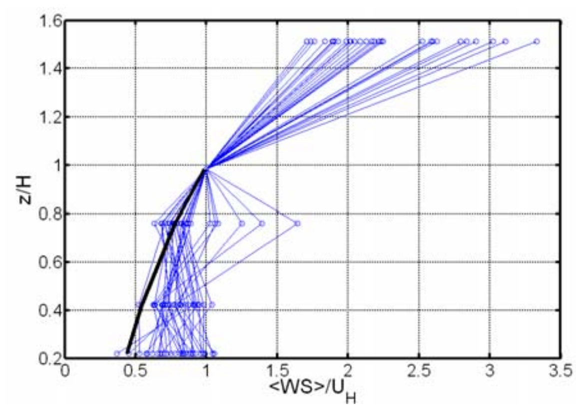

Figure 3. Area-averaged canopy wind speed profiles normalized by the wind speed at building height compared with the Cionco profile (shown as a solid black line).

Cionco's vegetative canopy formula provides a reasonable approximation to the wind speed within the canopy, however, it underestimates the magnitude and obviously cannot satisfy the no-slip boundary condition at *z*=0. Differences between the formula and data might be explained by biases due to instrument layout, the choice of α, and shortcomings in Cionco's formula, among other things.

Figure 4 shows the unscaled area-averaged turbulent kinetic energy versus height within and just above the canopy layer. There appears to be an elevated peak in TKE in most individual 5-minute average profiles. This agrees in a broad sense with the wind tunnel area-averaged measurements of Kastner-Klein et al. (2002). The peak in about half the cases (those with larger TKE magnitude) is below building height at about z/H = 0.8 and in the other half of cases at z/H = 1. Note that the vertical spacing of instruments is such that it is difficult to define the height of the TKE peak. Also of interest is that the TKE near the surface does not appear to fall off to rapidly for most cases. As noted before, the locations of the sensors relative to the buildings will impact the area-averaged calculations and so this should be kept in mind when interpreting results.

4.2 *Scaling with Atmospheric Surface Layer Parameters*

The local friction velocity (U_*) was computed using the Reynolds' stresses measured by the 3D sonic anemometers. In Fig. 5, the local friction velocity is seen to vary strongly with height, especially for z/H < 3 (Fig. 3). Figure 5 also shows that the constant stress layer occurs above *z/H*~6 for all the cases during the night in question and above *z/H*~3 for some cases.

The characteristic friction velocity and Monin-Obhukov length (*L*) used for normalization were determined by taking the mean of the two highest sonic anemometers. The uppermost sonic anemometer was not operational during a few of the observation periods and in these cases only the

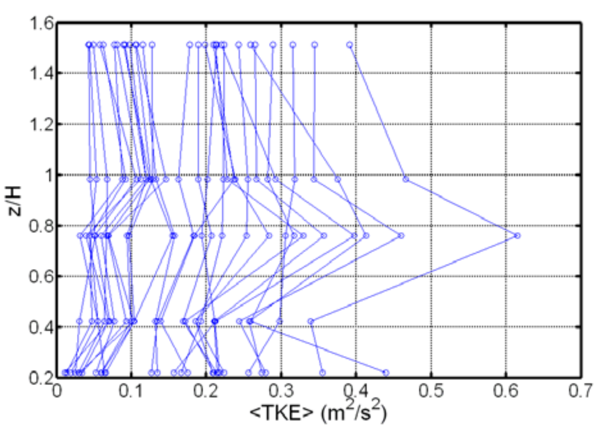

Figure 4. Unscaled area-averaged turbulent kinetic energy versus normalized height.

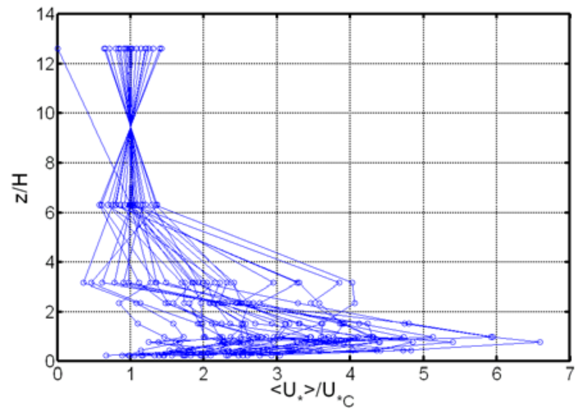

Figure 5. Area-averaged local friction velocity normalized by the characteristic friction velocity for the constant stress layer versus height normalized by building height.

values from the second highest anemometer were used.

Figure 6 depicts the area-averaged TKE profile normalized by the TKE at *z/H*~1. This plot is seen to have a great deal of scatter at high elevations. Figure 7 shows the area-averaged TKE profile normalized by characteristic friction velocity from the constant stress layer aloft. This collapses the data onto similar trends with the peak value of TKE near *H*. Thus it appears that the interaction of the building generated turbulence and the ambient turbulence from the incoming boundary layer is important.

The area-averaged wind profiles are shown through the depth of the MUST tower measurements in Figure 8. The data appear to collapse into two distinct patterns, one with faster winds aloft apparently due to differences in the upstream flow conditions.

Integration of the relations found by Businger et al. (1971) and Dyer (1974) provide corrections to the logarithmic wind profiles for the diabatic ASL based on the Monin-Obhukov stability parameter (*z/L*). 5-minute averaging periods have been found to be insufficient for producing statistically converged

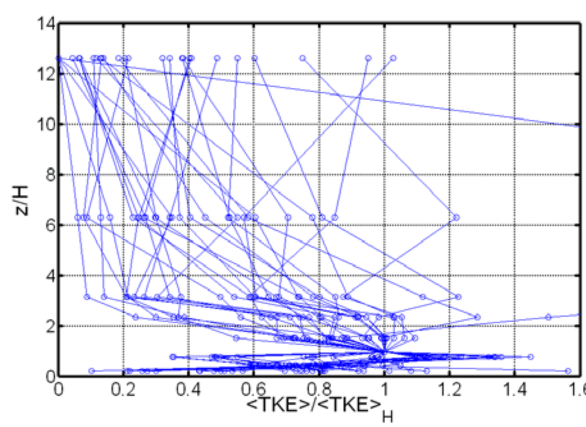

Figure 6. Area-averaged TKE normalized by the TKE at *H* versus *z/H*.

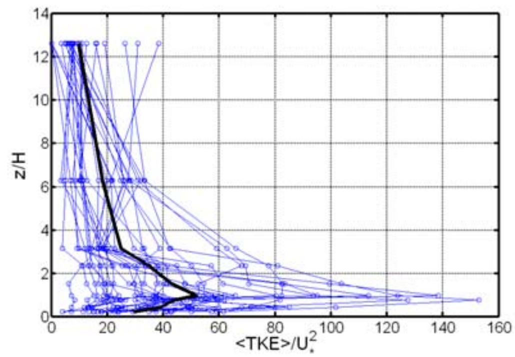

Figure 7. Area-averaged TKE profiles normalized by U_*^2. The ensemble average of all of these normalized profiles is shown as the solid black line.

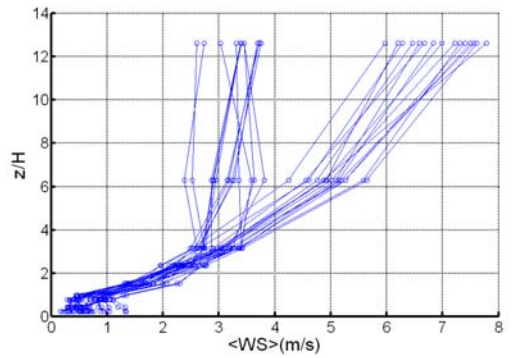

Figure 8. Area-averaged wind speed versus vertical distance above ground level normalized by building height.

values for *L* aloft in most cases. As such a comparison of the area-averaged wind speed profiles with the Businger-Dyer relations will not be presented in this manuscript but is to be performed after statistically converged values of *L* have been obtained.

5. CONCLUSIONS

Area-averaged measurements have been presented. While there is a bias in the averages due to the layout of instruments, the instrument density of the layout employed to derive these area-averaged profiles is relatively good compared to prior experiments. Since the MUST array was imbedded in the ASL complex meteorological phenomena may be present, making the interpretation of results more difficult.

The Cionco canopy profile was found to provide a reasonable approximation for the wind speed within the canopy although it underestimates the magnitude.

Local values of TKE and friction velocity were found to peak at $z=H$, which agrees with previous work. The interaction of ambient turbulence from the incoming boundary layer and the building generated turbulence was found to be important.

Further analyses will be performed with larger averaging periods to achieve statistical convergence of the characteristic length and velocity scales aloft, making the comparison of the area-averaged measurements of the MUST array to functional relationships found in previous work more conclusive.

6. REFERENCES

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