J7.6

OBSERVATIONS OF TURBULENT KINETIC ENERGY DISSIPATION RATE IN THE URBAN ENVIRONMENT

Julie K. Lundquist *, J. H. Shinn, F. Gouveia
Atmospheric Science Division
Lawrence Livermore National Laboratory, Livermore, CA, 94550

1. INTRODUCTION

A major field experiment, Joint Urban 2003 (JU2003) experiment, was conducted in Oklahoma City in July 2003 to collect meteorological and tracer data sets for evaluating dispersion models in urban areas. The Department of Homeland Security and the Defense Threat Reduction Agency were the primary sponsors of JU2003. Investigators from five Department of Energy national laboratories, several other government agencies, universities, private companies, and international agencies conducted the experiment. Observations to characterize the meteorology in and around the urban area complemented the observation of SF6 dispersion.

Many of the *in situ* meteorological observations during JU2003 were within the urban canopy layer, at or below roughly the mean height of the buildings in a local area. At one location, a pseudo-tower, fitted with sonic anemometers at eight levels, extended turbulence observations to 80m. This level was well above the mean building height of the Oklahoma City central business district (CBD) but below the height of the two tallest buildings (approximately 120 m). Using these observations, we explore the variability of turbulent kinetic energy (TKE) budgets, and especially the dissipation term, within the urban canopy and urban surface layers. These calculations of TKE dissipation rate will eventually be compared with those used in dispersion models to guide improvements in those models.

2. DATA AND DATA PREPROCESSING

A pseudo tower (Figure 1) was constructed just north (downwind in typical summertime southerly flow situations) of the central business district. The upstream “fetch” of this tower varied with wind direction. Figure 2 depicts building heights (gridded to a 2m grid) as a function of distance from the crane for all buildings within the southerly 30 degree sector from the crane; note that spaces with no buildings are not represented on this plot. For this sector, the mean building height is approximately 13 m. The mean and maximum building heights for all sectors are seen in Figure 3. The built-up CBD, which is located south to south-east of the crane, is apparent in Figure 3.

Figure 1: The pseudo-tower, outlined in red, supported by a crane to the north of the pseudo-tower. The view is to the south-west. Most winds during the JU2003 experiment were from the south. (Photo courtesy of M. Leach, LLNL.)

On the crane, R.M. Young model 81000 sonic anemometers were mounted at 7.8, 14.6, 21.5, 28.3, 42.5, 55.8, 69.7, and 83.2 m above the surface. The sonic anemometers recorded data at 10 Hz throughout the experiment. For the dissipation calculations discussed below, 300-second time series were used. For calculations of turbulent fluxes, such $u'w'$ and $v'w'$, 30-minute time series were used to ensure adequate sampling of large scale motions. Of the 11520 30-minute time periods (at all levels) examined for this study, 413 were rejected because of instrument failure. Because the pseudo-tower was supported by a large crane to the north, time periods with a mean direction between 315° (north-westerly) and 45 ° (north-easterly) were rejected from analysis. Using this criterion, another 1000 30-minute segments were rejected from study. In total, 10107 30-minute time series, or 87.7% of the original data, were considered.

To adjust for any tilting of the sonic anemometer, the planar-fit correction described by Wilczak et al. (2001) has been applied to the data. The data have been rotated into a right-handed natural coordinate system: the streamwise

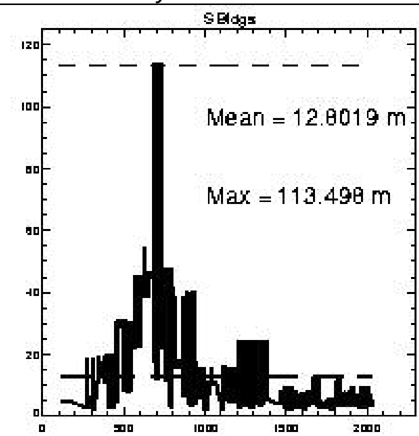

Figure 2: The variation of building height with distance from the tower for the 30 degree (165-195 degrees in meteorological coordinates) arc south of the tower.

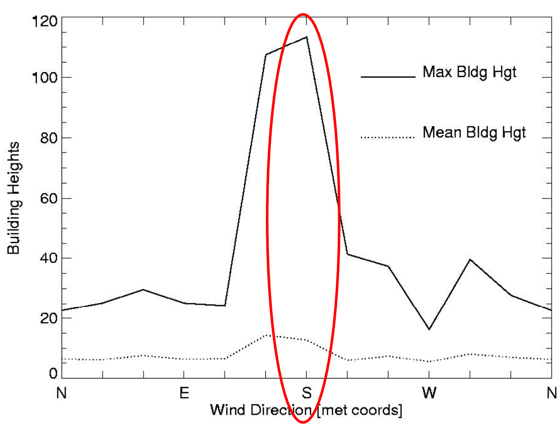

Figure 3: The variation of building heights in the fetch upstream of the tower, presented as a function of wind direction. Although the mean building height varies only slightly, from 5-15m, the maximum height varies considerably. The central business district is south and southeast of the crane. The red oval emphasizes the data points from the 30-degree arc displayed in more detail in Figure 2.

coordinate u is aligned with the mean horizontal wind; the transverse component v is perpendicular to u in the horizontal plane, and the normal component w is perpendicular to u in the vertical plane.

3. CALCULATIONS

The dissipation of turbulent kinetic energy is estimated from the frequency spectrum in the inertial frequency subrange. Dissipation ε is given by

$$\varepsilon = \frac{2\pi}{U}\left(\frac{f^{5/3}S_u(f)}{\alpha}\right)^{3/2}, \qquad (1)$$

where U is the mean streamwise wind speed, α is the Kolmogorov constant for the velocity component (here, 0.53), and $f^{5/3}S_u(f)$ is the mean compensated spectral intensity in the inertial subrange of the streamwise component of the winds. To define the inertial subrange, we must look at the spectra of each component of the sonic anemometer data.

3.1 *Spectral behavior: defining the inertial subrange*

Figure 4 shows an example of an energy spectra, in this case for a two hour time period 0100-0300 LDT 9 July 2003, measured by the 83.2m sonic. Winds were southerly at this time. These spectra are typical of spectra throughout the Joint URBAN 2003 field experiment – little variability was observed between daytime and nighttime**.** As expected, the streamwise component contains more energy at lower frequencies than either the normal or the transverse component. For frequencies greater than 0.2 Hz, the three spectra generally converge to one line, proportional to frequency to the five-thirds power, characteristic of the inertial subrange. These sonic anemometers were not able to directly observe the dissipative range, which would be represented by a dropoff of energy at the highest frequencies.

Equation (1) requires an estimate of the compensated spectral intensity in the inertial subrange. For the time series shown in Figure 4, this value was approximately 8×10^{-2} $m^2 s^{-8/3}$.

3.2 *Spectral behavior: isotropy in the inertial subrange.*

Previous studies of turbulence in an urban environment have suggested that turbulence within the roughness sublayer is rarely isotropic, and must be considered three-dimensional (Roth and Oke, 1993). In an isotropic turbulent flow, the ratio between the transverse spectrum S_v and the streamwise spectrum S_u (and similar between S_w and S_u) should be 4:3 (Frisch 1995). In Figure 5, we see the spectral ratios for the data from the 83.2 m level depicted in Figure 4. At the highest level on the tower, the turbulence only approaches isotropy.

Mean values of the spectra ratios for all heights during this nocturnal period appear in Figure 6**,** while Figure 7 shows the spectral ratios for a daytime period. The turbulence observed with the sonic anemometers never achieve the 4:3 ratio in both *v* and *w* required for isotropy. All levels on the tower are within the urban roughness sublayer. A constant flux layer, as required for Monin-Obukhov similarity theory, cannot be assumed to be present, and the turbulent field must be considered three-dimensional.

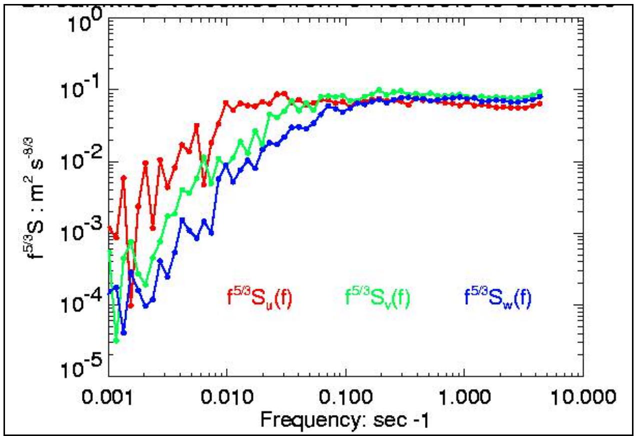

Figure 4: Streamwise (red), transverse (green), and normal (blue) compensated spectra from the 83.2m sonic from 0100-0300 LDT 9 July 2003. The inertial subrange begins near 0.2 Hz.

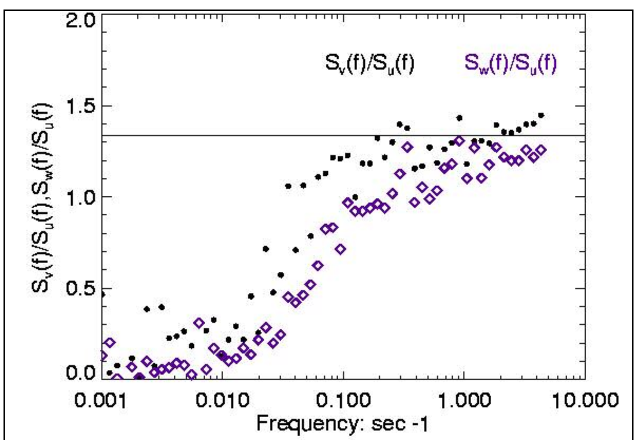

Figure 5: Ratios between the *v* and *u* spectra (dots) and *w* and *u* spectra (diamonds) from the **83.2m sonic** from 0100-0300 LDT 9 July 2003 depicting the approach to the 4:3 ratio required by isotropy.

3.3 *Time series of dissipation*

Using Equation (1), turbulent kinetic energy dissipation rates can be calculated for each level of the tower. Figure 8 shows one time

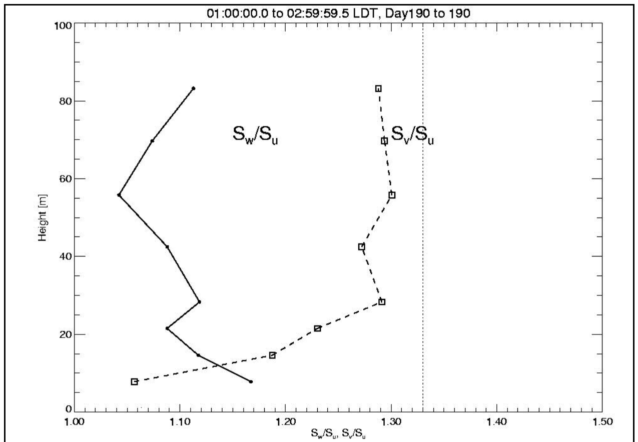

Figure 6:Mean spectral ratios (for frequencies greater than 0.1 Hz) for all levels from the data collected from 0100-0300 LDT 9 July 2003. The dotted line at 1.33 depicts the ratio required for isotropy.

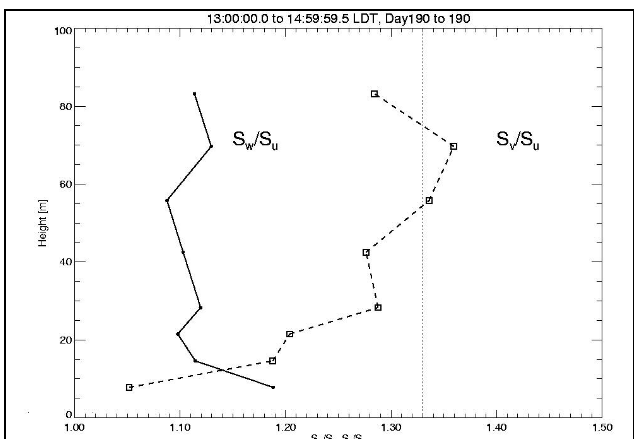

Figure 7: Mean spectral ratios (for frequencies greater than 0.1 Hz) for all levels from the data collected from 1300-1500 LDT 9 July 2003. The dotted line at 1.33 depicts the ratio required for isotropy.

series for a 24-hour period in dimensional units, while the normalized dissipation,

$$\phi_\varepsilon = \varepsilon \frac{kz}{u_*^3}, \quad (2)$$

is seen in Figure 9. Here, friction velocity $u*$ is defined as

$$u_*^2 = \sqrt{\overline{u'w'}^2 + \overline{v'w'}^2}, \quad (3)$$

and is calculated using 30-minute averages as noted above.

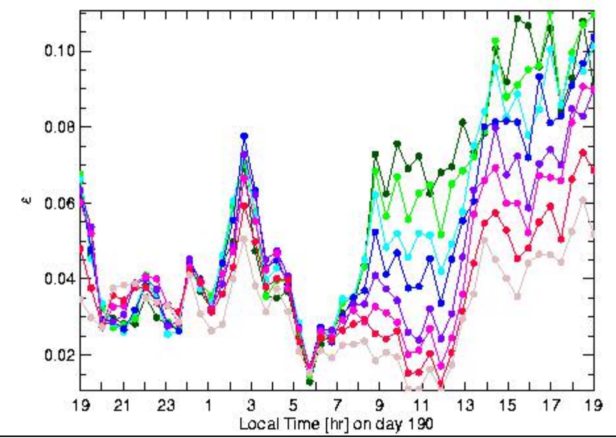

Figure 8: Turbulent kinetic energy dissipation (units of m^2s^{-3}) as a function of time for 24 hours beginning at 1900 LDT 8 July. All eight levels are shown in a spectrum ranging from dark green (7.8m) to light pink (83.2m level). Dissipation decreases with height from 8:30am local time to 12:30pm local time.

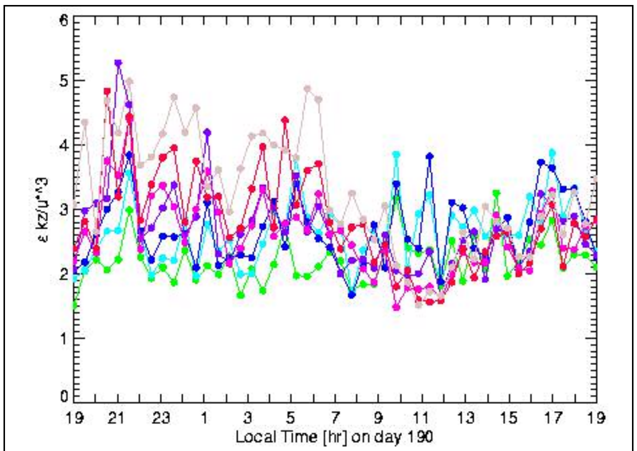

Figure 9: Normalized TKE dissipation rate as a function of time for the same period seen in Figure 8. Note that the 7.8m level (dark green) is offset from the other levels, due to its significantly smaller values of $u*$.

The values for dissipation shown here are consistent with those observed by Piper (2001) based on observations in the surface layer at a rural site. Normalized dissipation rate ϕ_ε is in the same range observed by Roth and Oke (1993) in suburban Vancouver, and by Sjöblom and Smedman (2003) in the marine boundary layer. Clear evidence of nocturnal bursts (around 0300 local time in Figure 8) is seen on the night pictured in Figure 8 and on many other nights (not shown here).

3.4 *TKE Budgets*

Evaluating all terms of the TKE budget equation is beyond the scope of this preprint, but budgets will be discussed in the accompanying presentation. A simplified budget, omitting the advective term and the pressure transport term but including storage, production, buoyancy, turbulent transport, and dissipation, can be expressed as:

$$S + P - B + T - \varepsilon = r, \quad (4)$$

where, in the streamwise coordinate system,

$$S = \frac{\partial e}{\partial t}, \quad (5)$$

$$P = \sqrt{\overline{u'w'}^2 + \overline{v'w'}^2}\,\frac{\partial u}{\partial z}, \quad (6)$$

$$B = \frac{g}{T_o}\overline{w'T'}, \quad (7)$$

$$T = \frac{\partial \overline{w'e'}}{\partial z}, \quad (8)$$

g is gravity, z is height, the vertical derivatives are calculated with third order spline fits to observations, and T_o is a reference temperature.

Total TKE, e, is calculated as $\frac{1}{2}(u'^2 + v'^2 + w'^2)$.

Each term in equation (4) can of course be normalized as in equation (2). Ideally, the residual r would be zero, but as it must necessarily include an advective term and the pressure transport term that cannot be calculated here, it is rarely zero. Also note that some errors are expected from the vertical derivatives of u and $w'e'$ as each level is rotated into streamwise coordinates independently.

The budget, as defined in equation (4), can be calculated for all levels throughout the experiment. We anticipate a large residual r due to the role of the central business district upstream. If more production occurs at higher frequencies in urban areas, as suggested by Roth and Oke

(1993), then we might expect that TKE dissipation would be larger downstream, perhaps even larger than TKE production.

4. SUMMARY

We have explored the general nature of turbulence observed on an 84m pseudo-tower in Oklahoma City during the Joint URBAN 2003 atmospheric dispersion and tracer study. Although the tower is well above the mean building height in the upstream area, isotropy is not observed even at the highest levels.

Most terms of the TKE budget, including production, storage, buoyancy, turbulent transport, and dissipation, can be calculated from this dataset. Future research will quantify whether or not TKE budgets balance in this unique environment. Numerical models of atmospheric flow in the urban environment must account for the variability thus observed.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. The pseudo-tower crane was constructed by William Ralph of LLNL with assistance from Allied Steel of Oklahoma City, Ron Pletcher of LLNL, and Marshall Stuart of LLNL. The building database was provided by May Yuan and Mang Lung Cheuk of the University of Oklahoma.

References

Frish, U., 1995. *Turbulence: The Legacy of A. N. Kolmogorov*. Cambridge University Press, 296 pp.

Oncley, S.P., C.A. Friehe, J.A. Businger, E.C. Itsweire, J. C. LaRue and S.S. Chang, 1996: Surface-layer fluxes, profiles, and turbulence measurements over uniform terrain under near-neutral conditions. *J. Atmos. Sci.*, **53**, 1029-1044.

Piper, M., 2001: The Effects of a Frontal Passage on Fine-Scale Nocturnal Boundary Layer Turbulence. Ph.D. dissertation, University of Colorado at Boulder, Dept. of Astrophysical, Planetary, and Atmospheric Sciences, 217 pp.

Pope, S. B., 2000. *Turbulent Flows.* Cambridge University Press, 771 pp.

Roth, M. and T. R. Oke, 1993: Turbulent transfer relationships over an urban surface. I: Spectral characteristics. *Quart. J. Roy. Meteorol. Soc.*, **119**, 1071-1104.

Sjöblom, A., and A.-S. Smedman, 2003, Vertical Structure in the Marine Atmospheric Boundary Layer and its Implications for the Inertial Dissipation Method. *Bound.-Layer Meteorol.* **109**, 1-25.

Wilczak, J.M., S.P. Oncley, and S.A. Stage, 2001: Sonic anemometer tilt correction algorithms. *Bound.-Layer Meteorol.* **99**, 127-150.