J3.1 A STUDY OF TURBULENT KINETIC ENERGY PRODUCED BY BUILDINGS IN AN URBAN CENTRAL BUSINESS DISTRICT

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1. Introduction

In an effort to learn more about the transport and dispersion of materials in urban atmospheres, a large field research study, Joint Urban 2003, was held in Oklahoma City in July 2003 as described by Allwine et al. (2004). The dataset from this experiment will be of great benefit for the development and testing of a new generation of transport and dispersion models. ITT under sponsorship of the Defense Advanced Research Projects Agency, DARPA, has been developing an urban airflow model, RUSTIC, (Burrows et al. 2004) to be used in conjunction with a dispersion model). To properly estimate dispersion rates it is necessary for RUSTIC to produce an accurate estimate of the turbulent kinetic energy, TKE, field. Approximately 140 sonic anemometers were deployed in Oklahoma City sampling at 10 Hz. These measurements allow a detailed view of the distribution of TKE throughout the central business district, CBD, of an urban environment with large buildings (up to 150 m in height).

2. Measurements

In this study the measurements from 45 sonic anemometers placed within the CBD were used, distributed as shown in Figure 1. Eleven were operated by ITT, twenty were operated by Dugway Proving Grounds, DPG, eleven were operated by the University of Utah, UU, and three by Arizona State University, ASU. In addition eight sonic anemometers operated by Indiana University, IU, were used to determine conditions upwind of the CBD.

For this study only data from July 9, 2003 were used. Wind direction and speed were fairly steady for this period.

For analysis purposes it was found useful to divide the anemometer data into three groups. One group consisted of data from anemometers that were located in exposed areas of the CBD either in open areas on the upwind edge of the CBD or on the roofs of buildings. Another group was from anemometers near street level close to buildings or within street canyon areas. The third group was the Indiana University anemometers located in a suburban area in the SE part of the city. Wind speed power spectra were computed for all anemometers and smoothed and averaged for the three groups.

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Comparisons of the spectra between the three groups were made for three release periods in IOP-4, 1600-1700 UTC, 1800-1900 UTC and 2000-2100 UTC.

During the first period from 1600 to 1700 UTC, as shown in Figure 2, all the spectra have a peak between .003 Hz and .01 Hz. The locations in the CBD show more energy at the higher frequencies than the suburban locations. This is especially pronounced for the locations within the street canyons.

From 1800-1900 UTC solar heating was at its maximum and the spectra in Figure 3 show a considerable shift in the peaks towards higher frequencies. The main change appears to be an increase coming from eddies with periods from 30 to 100 seconds presumably due to thermal convection. As before, the street canyon locations have more energy

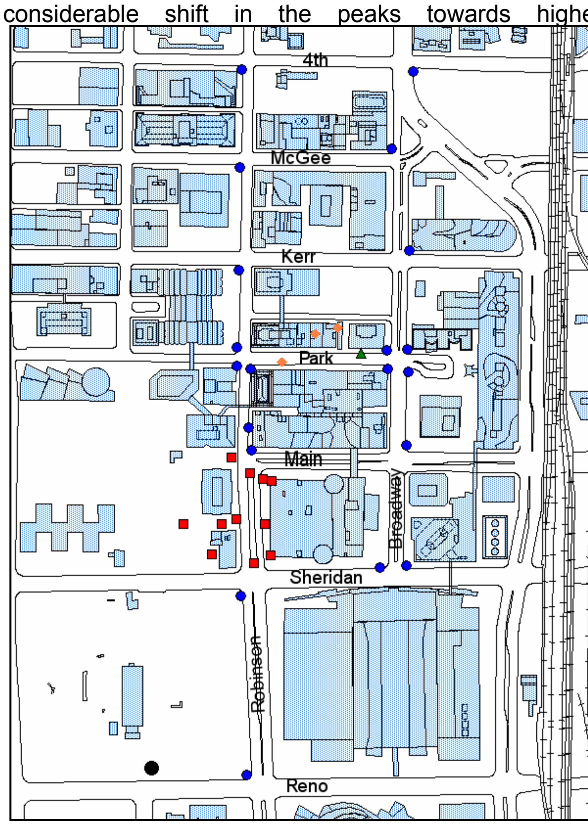

Figure 1. Location of sonic anemometers in the Oklahoma City CBD used in this study. Red squares are the anemometers operated by ITT, blue circles are those operated by DPG, orange diamonds are the towers with sonic anemometers operated by UU and the green triangle is the tower with three sonic anemometers operated by ASU. The black circle is the ANL mini-sodar.

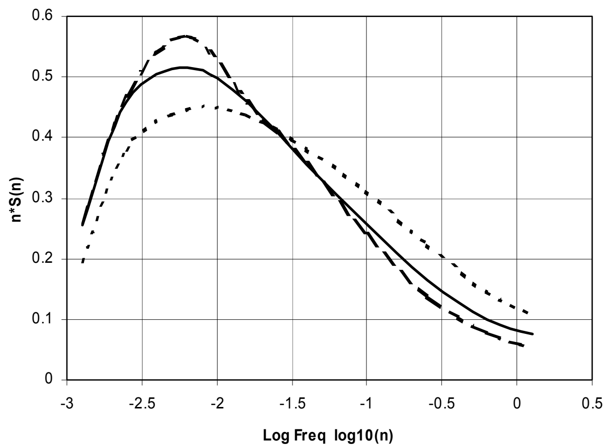

Figure 2. Wind speed spectra for 1600-1700 UTC July 9, 2003. Comparison of spectra from three different areas of the city:

- **a) solid line – Open areas and building tops in the CBD**
- **b) dotted line – Street Canyon locations**
- **c) dashed line - suburban upwind locations**

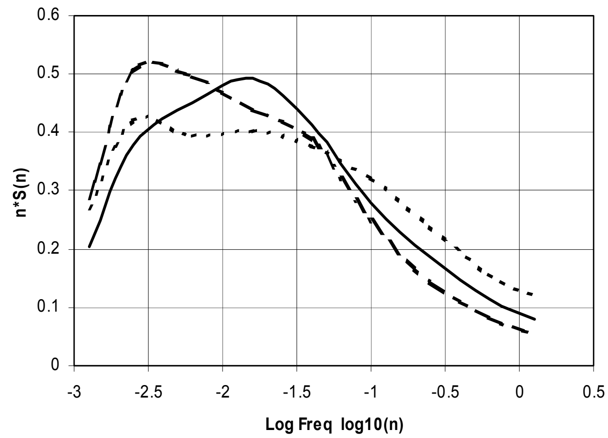

Figure 3. Wind speed spectra for 1800-1900 UTC July 9, 2003. Comparison of spectra from three different areas of the city:

- **a) solid line – Open areas and building tops in the CBD**
- **b) dotted line – Street Canyon locations**
- **c) dashed line - suburban upwind locations**

from higher frequency eddies compared to the other locations.

In the last release period from 2000-2100 UTC the solar heating is beginning to decrease, but the effects of thermal convection are still apparent in the spectra as shown in Figure 4. Again the street canyon locations have more of their energy from higher frequency eddies than the other locations.

The total TKE was computed for all the anemometers using a 20-minute averaging period. The results are displayed in Table 1. The TKE is about 50% greater for all locations during the 1800-1900 UTC as compared to 1600-1700 UTC, probably due to the onset of thermal convection. Little change is seen between the last two periods.

Also noticeable in Table 1 is that the TKE at the suburban sites is about 70% greater than at the CBD sites. In the open areas in the CBD only about 8% more TKE was present than in the street canyons, even though the frequency distribution of the eddies was quite different for the two locations.

3. Model Simulation

RUSTIC was run to simulate the release period from 1800-1900 UTC. To initialize the model the mean vertical wind speed profile from the Argonne National Laboratory, ANL, mini-sodar located at the south edge of the Myriad Botanical Gardens was used. The location of the mini-sodar is shown in Figure 1 and the wind profile is in Figure 5. Vertical heat flux values from the suburban anemometer locations were used for generation of the initial profile of TKE and specific dissipation. The mean vertical heat flux measured by the sonic anemometers in the CBD was used for the surface boundary values in the model. The model was run for wind directions from 170 to 195 degrees corresponding to the mean wind direction as observed by the mini-sodar.

The building shape data for Oklahoma City was obtained from the University of Oklahoma and the terrain data was 10 meter digital elevation data from the US Geological Survey. This data was used to generate a three dimensional grid with the open cells in the center of the grid of size, 5m x 5m x 5m. The size of the total domain was 1200 m x 1200 m x 200 m corresponding to grid cell numbers of 190 x 190 x 33. The model was run to near convergence.

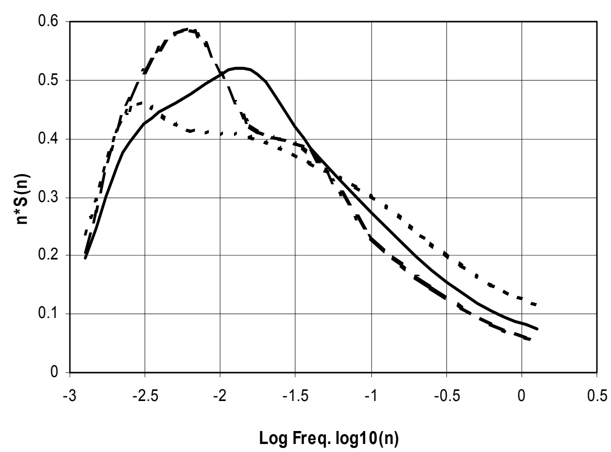

Figure 4. Wind speed spectra for 2000-2100 UTC July 9, 2003. Comparison of spectra from three different areas of the city:

- **a) solid line – Open areas and building tops in the CBD**
- **b) dotted line – Street Canyon locations**
- **c) dashed line - suburban upwind locations**

Time (UTC)	Suburban TKE (J/Kg)	Open Areas & Buildings TKE (J/Kg)	Street Canyons TKE (J/Kg)	Mean TKE (J/Kg)
1600-1700	**2.276**	**1.508**	**1.287**	**1.690**
1800-1900	**3.568**	**2.104**	**1.978**	**2.550**
2000-2100	**3.622**	**2.171**	**2.081**	**2.625**
Mean TKE (J/Kg)	**3.155**	**1.928**	**1.782**	**2.288**

Table 1. TKE computed using a 20 minute averaging time for sonic anemometers in each of the three city areas and for three different release periods.

For the study, the point anemometer measurements were compared to the mean TKE in the grid cell containing the anemometer. Table 2 shows the RUSTIC values for the two areas of the CBD compared with sonic anemometer measurements. The best correlation was found for the simulations with the wind direction from 190 and 195 degrees. The RUSTIC data used in Tables 2 and 3 for comparison is an average of these two simulations. To better understand the turbulent frequencies in the k-ω model predictions, TKE values were computed using six different averaging periods from 75 seconds to 40 minutes.

The mean TKE predicted by RUSTIC for the exposed locations in the CBD compares very closely with the mean TKE computed from the sonic anemometers using a 10 minute averaging period. For the street canyon locations the comparison is not as good. The RUSTIC predictions are low. The least difference occurs in comparison with values obtained using the shortest averaging period of 75 seconds.

When the RUSTIC predictions are correlated with the corresponding anemometer measurements the results are similar. The best correlation in the open areas and building tops areas was with TKE values computed using a 10 minute averaging period, although for this region the correlation is quite large and does not really differ much with the averaging period. In the street canyons the best correlation is with the TKE computed using a 75 second averaging period. As the correlation steadily increases with decreasing averaging period, it suggests that the correlation might be even better for an even shorter averaging period.

Averaging Time for TKE (sec)	Open Areas and Building Tops Mean TKE (J/Kg) (12 Sonics)	Street Canyons Mean TKE (J/Kg) (33 Sonics)
RUSTIC	**1.99**	**1.06**
75	1.39	**1.37**
150	1.64	1.54
300	1.84	1.72
600	**1.96**	1.84
1200	2.07	1.97
2400	2.12	2.00

Table 2. TKE predicted by RUSTIC and TKE computed from sonic anemometers using six different averaging times. Results for two different areas within the CBD are also compared.

Averaging Time for TKE (sec)	Open Areas and Building Tops Correlation Coefficient (12 Sonics)	Street Canyons Correlation Coefficient (33 Sonics)
75	0.786	**0.431**
150	0.794	0.386
300	0.801	0.326
600	**0.807**	0.319
1200	0.797	0.249
2400	0.794	0.266

Table 3. Correlation coefficients between TKE predicted by RUSTIC and TKE computed from sonic anemometers using six different averaging times. Results for two different areas within the CBD are also compared.

4. Discussion

Definite differences in the magnitude and frequency distribution of turbulence was found between the CBD of a city and the upwind suburban areas. The upwind areas were found to have about 70% larger TKE values with more of energy from low frequency eddies, primarily those with periods of greater than 30 seconds. Within the CBD both open areas and street canyons have similar magnitudes of TKE but the frequency distribution of the eddies is different. The open areas have more energy in eddies with periods of greater than 30 seconds than the street canyons.

Within the CBD, RUSTIC does very well in predicting TKE for the more exposed locations, but not so well within the street canyons. Although RUSTIC predicts the total TKE well in the exposed locations, in the street canyons it seems to predict only the contribution from the highest frequencies.

Further analysis and simulations for a greater variety of cases needs to be done to fully clarify the workings of RUSTIC's k-ω model in comparison with real world turbulence. In particular, a need exists to understand the interaction of the street canyon turbulence with the turbulence generated by the convective boundary layer.

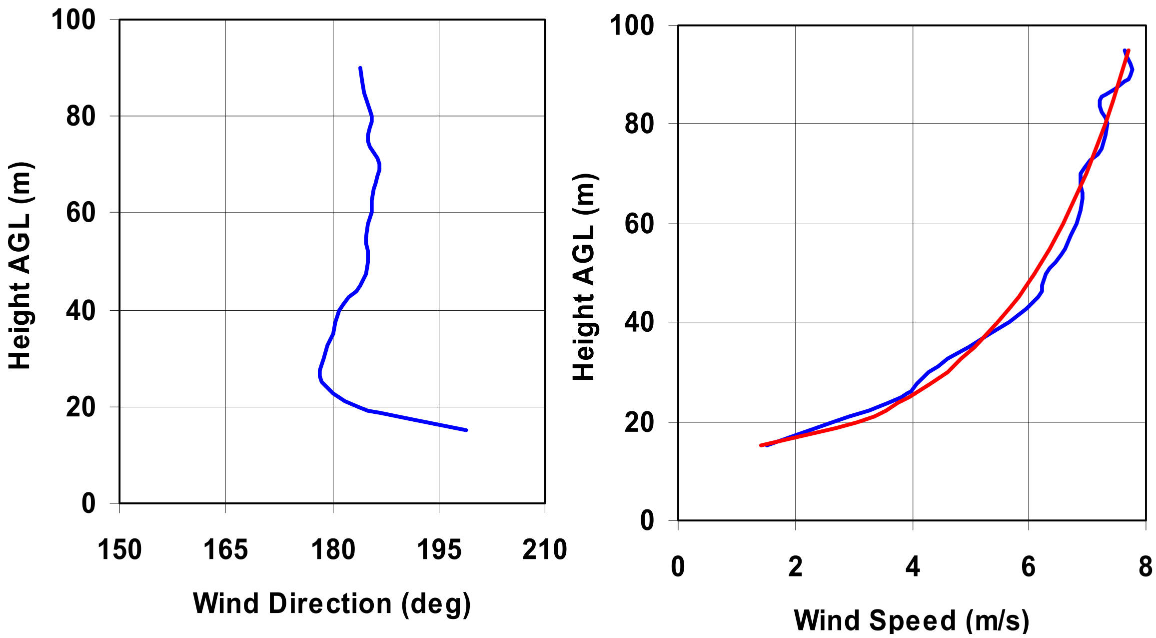

Figure 5. Vertical profiles of wind direction and wind speed from the ANL Botanical Gardens Mini-sodar. Profiles are an average of 4 observations at 1800, 1815, 1830 and 1845 UTC. Blue lines are the mini-sodar data and the red line is the profile used in the model simulations. Model profile calculated from u*=5.2 m/s, z_0=2.2 m and z_d=10.7 m

5. Acknowledgements

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6. References

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