9.9 COMPARISON OF SURFACE LAYER TURBULENCE IN URBAN AND SUBURBAN DOMAINS DURING JOINT URBAN 2003

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1. INTRODUCTION

During Joint Urban 2003 the Army Research Laboratory (ARL) deployed a number of measurement facilities in Oklahoma City. These included a Doppler lidar system, a mobile radiosonde system, a temperature/ moisture profiling microwave radiometer, and an array of sonic anemometers mounted on five 10-meter towers near and outside the central business district (CBD) in surrounding industrial (urban) and semi-rural (suburban) areas. In combination with the large number of in-situ and remote-sensing instruments operated by multiple agencies, it was anticipated that we would be able to characterize the effect of the city on the structure and dispersive properties of the atmospheric boundary layer at scales ranging from the whole metropolitan area to individual buildings. This presentation describes the wind and turbulence measurements obtained with two of the tower systems, emphasizing the similarities and differences in heat and momentum fluxes and turbulence intensities for the two types of domains.

2. TOWER LOCATIONS AND SETUP

The five towers were sited at the locations indicated on the map of Oklahoma City shown in Figure 1 (Yee *et al,* 2004). On each of the towers two R.M. Young Model 81000 sonic anemometers were mounted at levels 10 and 5 m above the ground. On two of the towers a third instrument was mounted at 2.5 m. Towers 1 and 3 were sited southwest and southeast of the CBD in relatively open areas belonging to the Metro Transit Station and the Trosper Park Maintenance Facility, respectively. Tower 1 was erected on a flat gravel parking lot with weeded patches and a small portable building to the southwest. Tower 3 was set up in a grassy area with a small house to the east and sloping ground to the south. Both sites were affected by the surrounding built-up suburban environment but were expected to exhibit little influence from the CBD under the generally prevailing southerly winds. Towers 2 (Bricktown) and 5 (Fleet Pride) were set up in industrial areas just east and west of the CBD. They were affected by nearby industrial buildings of one or two stories, by the Interstate highway and greater fetch of suburban area to their south, and under some wind directions, by the CBD itself. A photograph of Tower 5 looking east toward the CBD is shown in Figure 2. The branches of a large tree can be seen on the right, southwest of the tower. Tower 4 (First Christian Church) was sited in an open area about 5 km directly north of the CBD and was co-located with a sodar and a radiosonde launch site.

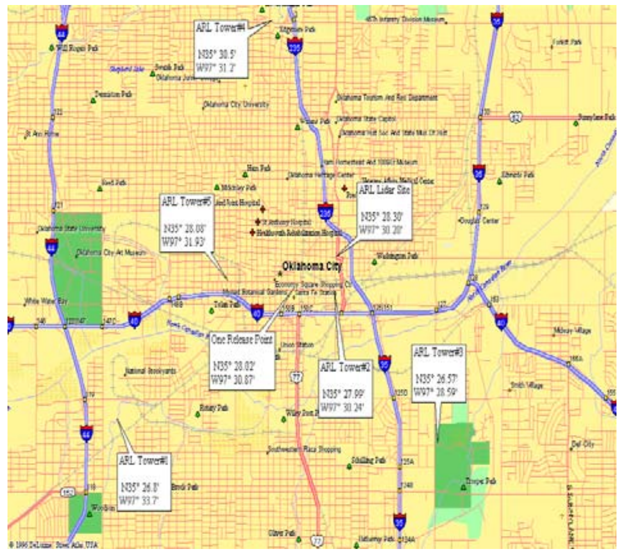

Figure 1. Map of central Oklahoma City showing locations of 10-meter towers. Scale is roughly 10 km north to south and 15 km west to east.

Figure 2. Tower 5 site near Fleet Pride building looking east toward Central Business District.

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3. SUBURBAN/URBAN TOWER DATA

We use the measurements from Tower 1 as representative of the suburban domain and those from Tower 5 as representative of the urban domain. Plots of the temperature, wind direction, wind speed, kinematic heat flux, kinematic momentum flux, and turbulent kinetic energy (TKE) for two levels on the two towers for the period 24 June through 01 August are shown in Figures 3 and 4. The values plotted are averages calculated for 10-minute blocks for which the average crosswind (v) and vertical velocity (w) were set equal to zero. Obvious in both sets of plots is the expected diurnal dependence of temperature, heat flux, and TKE; the wind speed and direction as well as the momentum flux also exhibit a diurnal dependence, but their time series are complicated by other factors.

3.1 Temperature

Because the accuracy of the temperatures obtained from the sonic anemometers is only on the order of 2C, gradients calculated from these temperatures on a single tower are not meaningful. Nor are they sufficiently precise to determine the existence of an urban heat island effect between the two sites. It can be seen from Figures 3 and 4, however, that the measured temperatures at 10m at both sites varied from about 22C to nearly 40C and that they correlated extremely well. The calculated correlation for the 10-min averages for times for which temperatures were obtained from both towers was found to be 0.997. Cooler conditions early in the field test, when no measurements were available from Tower 5, were a factor resulting in an average temperature at Tower 1 approximately 1C less than that for Tower 5, about 29C as opposed to about 30C.

3.2 Wind Direction

The measured wind directions at both towers were generally from the anticipated southerly quadrant. The 10-min mean directions at the two levels at each tower were in very good agreement, showing a correlation of 0.961 at Tower 1 and 0.978 at Tower 5. At 10m the average 10-min mean direction at Tower 1 was 181 degrees; that at Tower 5 was 173 degrees. The relatively low correlation between the wind directions at the two towers, 0.62, is due in part to times when the northerly winds were west of north at one tower and east of north at the other. A scatter plot for the wind directions at the two sites, however, does indicate that there are often times when the mean wind directions are significantly different. These times should be looked at to investigate possible turning due to local morphology.

3.3 Wind Speed

As is evident in Figures 3 and 4, the wind speeds measured at the two levels on each tower were also highly correlated, correlation values being about 0.99. Using the slope of regression lines fit to their respective scatter plots, the wind speeds at 5m on Tower 1 were about 88% of those at 10m; on Tower 5 the corresponding figure was just 80%. The average wind speed at 10m on Tower 1 was 3.73 m/s; that on Tower 5 was 2.56 m/s, an average reduction of 30% largely due to the drag induced by the roughness of the urban environment.

3.4 Heat Flux

The 10-min kinematic heat fluxes at the two levels on each of the towers were also highly correlated, values being 0.98 and 0.97 respectively. At Tower 1 the heat flux at 5m was 78% of that at 10m; at Tower 5 it was 84%. The average heat flux at 10m on Tower 1 was 0.071 K-m/s; that on Tower 5 was 0.073 K-m/s. It must be noted, however that these averages are calculated for the entire period using both the positive and negative values of the heat fluxes. It is barely discernible in Figure 4, but the heat fluxes at Tower 5 seldom went negative, while those at Tower 1 always became negative at night. The heat retention by the urban ground surface and surrounding structures at night are almost certainly responsible for this difference. The maximum positive heat flux during the day was always greater at the Tower 1 site, the surrounding gravel surface of the Metro Transit Station being largely responsible for 10-min kinematic sensible heat fluxes very often larger than 0.3 K-m/s.

3.5 Momentum Flux

The kinematic momentum fluxes at the two levels on each of the towers are not as highly correlated as the other variables, but still 0.92 and 0.85 on Towers 1 and 5, respectively. At Tower 1 the momentum flux at 5m was 70% of that that at 10m; at Tower 5 it was only 61%. The average momentum flux at 10 m on Tower 1 was negative 0.25 m^2/s^2; that on Tower 5 minus 0.30 m^2/s^2.

3.6 Turbulent Kinetic Energy

The TKE values at the two levels on each of the towers were better correlated than the momentum fluxes, greater than 0.97 in each case. On Tower 1 the TKE at 5m was 92% of that at 10m; on Tower 5 it was 77%. The average value at 10m on Tower 1 was 1.45 m^2/s^2; that on Tower 5 was 1.39 m^2/s^2. The difference in TKE at 10m at the two sites is can be seen graphically in a scatter plot (not shown) having a correlation of 0.87 and a slope of 0.81.

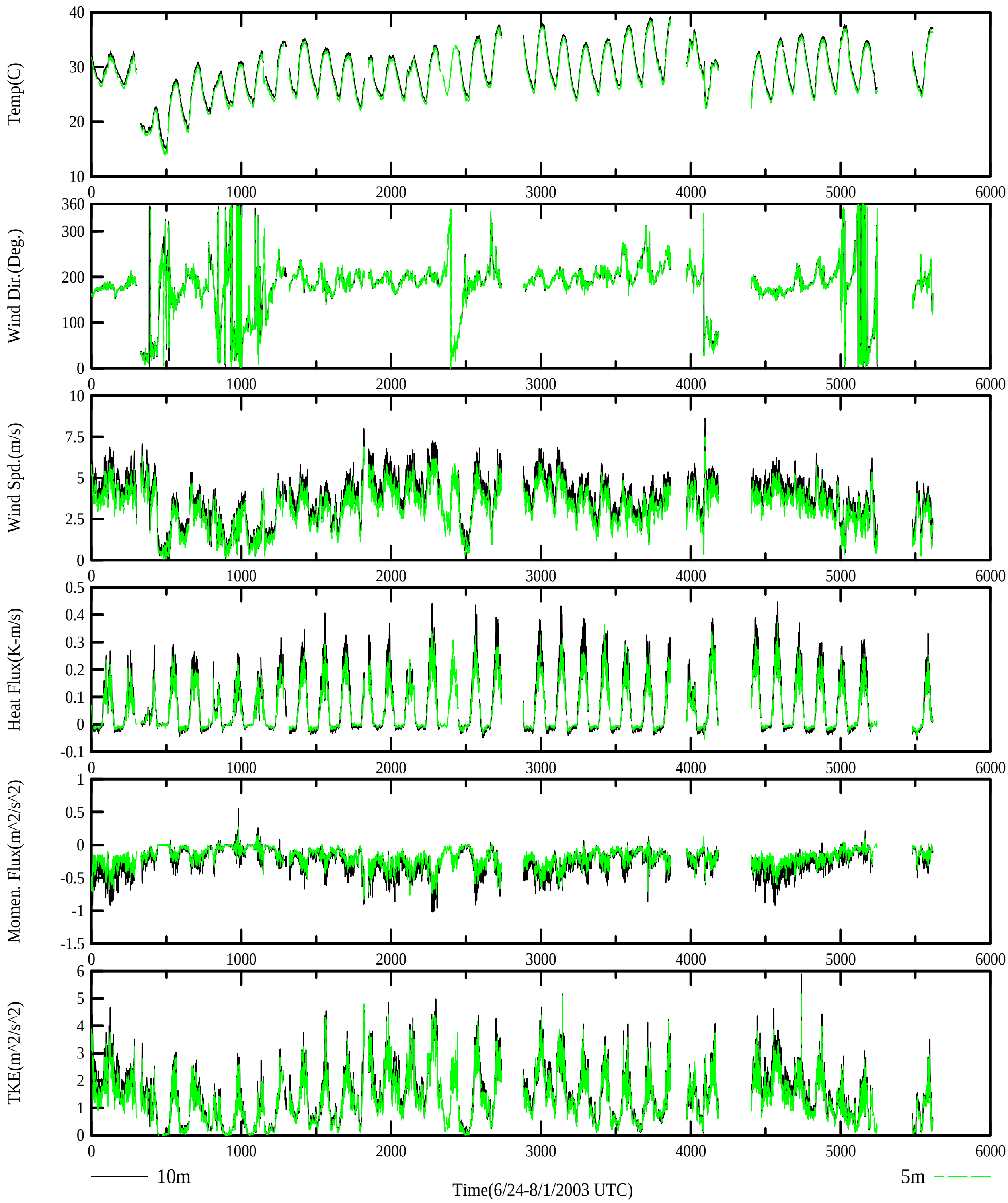

Figure 3. Ten minute average of temperature, wind direction, wind speed, heat flux, momentum flux, and TKE at 10m (solid) and 5m (dash) on Tower 1 (6/24/03--8/1/03).

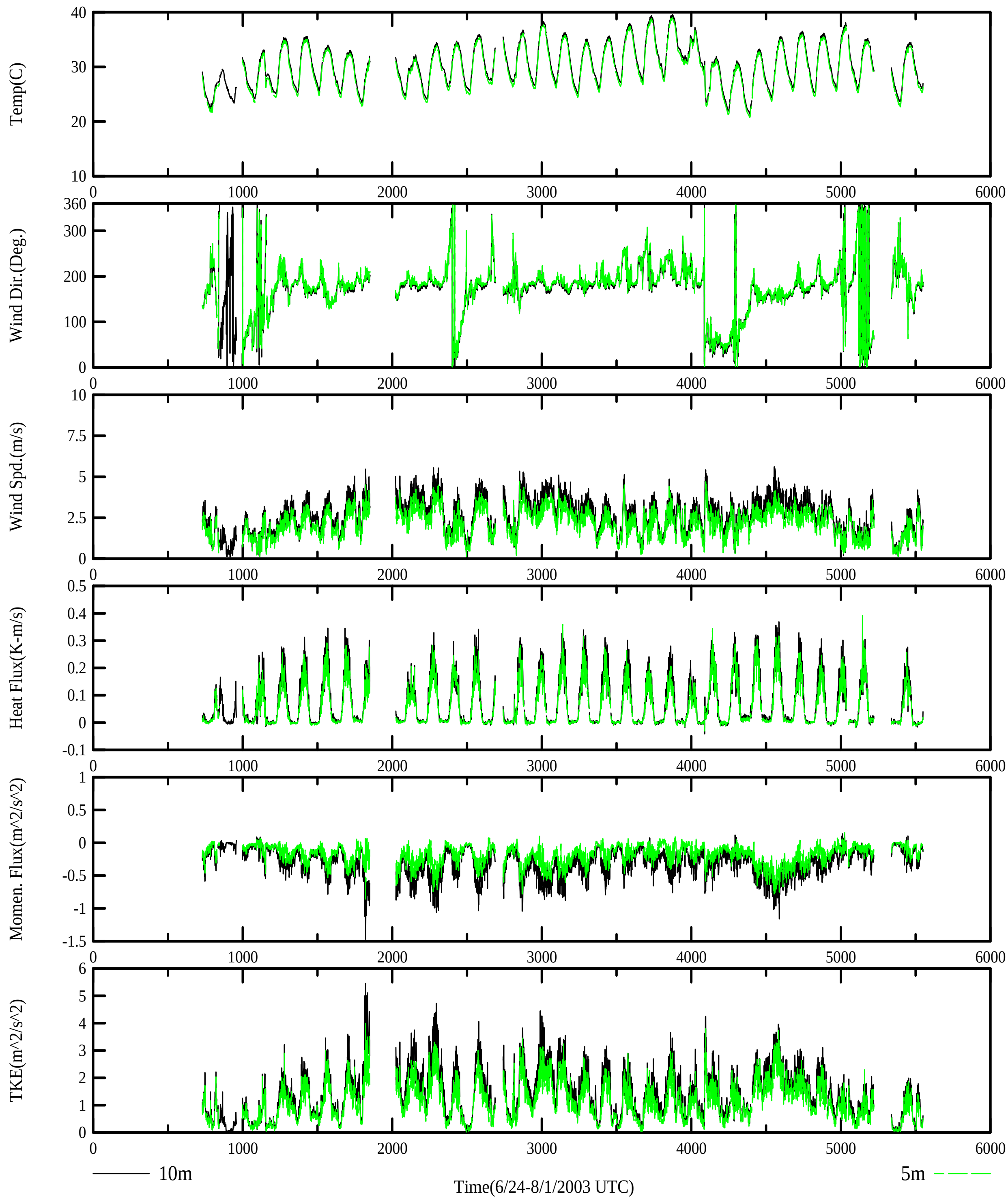

Figure 4. . Ten minute average of temperature, wind direction, wind speed, heat flux, momentum flux, and TKE at 10m (solid) and 5m (dash) on Tower 5 (6/24/03--8/1/03).

4. SUMMARY OF RESULTS

We first note that the correlation between values of any one of the variables derived from the sonic anemometers at the 5 and 10 m levels on either of the towers was very high, better than 0.96 for all variables except the kinematic momentum flux, where it dropped just below 0.85 on Tower 5. Both the heat flux and the momentum flux at these two levels on each tower, however, differed by more than the 10% nominal value often used to define the surface layer. Therefore, while the values measured at 10m can be used to describe surface layer characteristics at each site, caution must be exercised when surface layer vertical gradients of any of the variables are considered.

Table 1 below provides a summary comparison of the wind speed, heat flux, momentum flux, and TKE measured at 10m for the two sites. The first row of numbers is the average and the second row the standard deviation of each of these variables calculated for all times for which data is available. The last row shows both the correlation and the slope of the regression line for each of the variables at the two sites. The slope is calculated using the Tower 1 data as the independent (unaffected) value. The correlation is highest for the heat flux (a result that might be expected because of the dominant effect of solar heating), intermediate for the TKE and the momentum flux, and lowest for wind speed. The absence of a downward heat flux at night on Tower 5, already pointed out above, is not evident in these numbers, but the stronger positive heat flux during the day at Tower 1 manifests itself in the relatively small value of the slope of the regression line. The momentum fluxes at the two sites are on the average not greatly different, but because of the intermediate correlation value and the relatively large standard deviations, this variable needs to be investigated on an individual case basis to determine the relative effects of buoyancy and surface roughness for different conditions of wind and solar heating. The reduced wind speed for the more urban site (Tower 5) is borne out by both the average values and the slope of the regression line, though the correlation value for this line is only 0.74. The value of the slope is less than the ratio of the average value, 0.60 compared to 0.69. For TKE the corresponding values are 0.81 and 0.96, indicating a slightly reduced turbulent kinetic energy for the urban site. We note, too, that if the average values of the TKE are divided by the squares of the average wind speeds for the two sites, the magnitude of the normalized turbulence intensity for the urban site is about half that for the suburban site. Normalization of such average values, however, may not be very meaningful.

We conclude by pointing out that only average results and general differences for the two sites are discussed herein. Much more analysis of the data for all the sites stratified by time of day and by wind speed and direction remains to be done. Klipp *et al.* (2004) report on a method for distinguishing between necessary sonic anemometer tilt corrections and real directional dependencies on local slopes and structures. This is a necessary step in attempting to estimate directionally dependent diffusion coefficients for dispersion modeling. A limited spectral analysis of turbulence data for Towers 1 and 2 will be reported in an upcoming conference (Chang *et al.*, 2004). We emphasize that since a principal motivation for performing the field experiment was to relate the urban meteorological conditions to the resulting atmospheric dispersion in the boundary layer, future analyses will necessitate looking at all of the data obtained by the many investigators (e.g., Lundquist *et al,* 2004, and Grimmond, *et al,* 2004), concentrating particularly on times for which intensive operations were conducted.

5. ACKNOWLEDGMENTS

I want to add a note of appreciation to my colleagues at ARL not included as co-authors on this paper but who made our participation in this effort do-able. I also want to thank the citizens of Oklahoma City who so graciously accepted our interrupting their daily schedules and especially the many who actively supported the field experiment.

6. REFERENCES

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Table 1. Summary Comparison of Wind Speed, Heat Flux, Momentum Flux, and TKE at two sites.

u_T1	u_T5	<wT>_T1	<wT>_T5	<uw>_T1	<uw>_T5	TKE_T1	TKE_T5
3.73	2.56	0.071	0.073	-0.25	-0.30	1.45	1.39
1.37	1.06	0.105	0.087	0.18	0.20	0.93	0.87
Correl.	Slope	Correl.	Slope	Correl.	Slope	Correl.	Slope
0.74	0.60	0.93	0.76	0.80	0.97	0.87	0.81