3.18

OBSERVATIONS OF BOUNDARY-LAYER WINDS IN AN URBAN ENVIRONMENT

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1. INTRODUCTION

It is well documented that large cities have important effects on both mean atmospheric flows (e.g. Angell et al. 1974, Kropfli and Kohn 1978) and atmospheric turbulence (e.g. Roth 2000). Previous studies, such as the Metropolitan Meteorological Experiment (METROMEX; Changnon 1981), the Regional Air Pollution study (Schiermeier 1978) and Etude de la Couche Limite dans l'Agglomération Parisienne (CLAP; Dupont et al. 1999) have focused on large urban areas. The Joint Urban 2003 (JU2003) field study was designed to provide insight into atmospheric dispersion and turbulence in the downtown core of a moderately sized city using state-of-the-art instrumentation.

2. JOINT URBAN 2003

JU2003 was conducted during July 2003 in and around the central business district of Oklahoma City, Oklahoma. A large number of meteorological instruments were deployed, including: wind profiling radars, sodars, sonic anemometers, surface weather stations, temperature data loggers, and radiosondes. A network of tracer sensors was also deployed. The research presented here is based on measurements made using four Doppler sodars that were located along a north-south transect running through the central business district of Oklahoma City (Figure 1). A team from Pacific Northwest National Laboratory (PNNL) operated one of these sodars and a team from Argonne National Laboratory (ANL) operated the others.

2.1 PNNL AND ANL SODARS

PNNL deployed a Scintec MFAS sodar 2 km south of the central business district at a parking lot in the City Maintenance Yard (latitude 35.45° N; longitude 97.53° W) (Figure 1). This sodar was operated 24 hours a day for nearly all of the field campaign. The area immediately around the sodar site included a few low buildings, open space and trees. The area south of this sodar was covered with low-rise (less than three stories) buildings, houses, and trees. Low-rise industrial buildings and houses covered the area north of the City Maintenance Yard. Table 1 lists the likely displacement height (z_d) and aerodynamic roughness length (z_0) for all four sodar sites. Estimates of z_d and z_0, are based on the building height as suggested by Grimmond and Oke (1999). They suggest that z_d can be approximated using,

$$z_d = f_d z_{H,ave}, \qquad (1)$$

where f_d is an empirical constant of 0.5 and $z_{H,ave}$ is the average building height, and that z_0 can be estimated using,

$$z_0 = f_0 z_{H,ave}, \qquad (2)$$

where f_o is an empirical constant of 0.1. The building heights used here were obtained from the study of Burian et al. (2003). The roughness sub-layer is the layer where the flow is dominated by building wakes associated with specific buildings (Roth 2000). Garratt (1980) suggested a relationship between the depth of the roughness sub-layer (z_*), z_0, and z_d, such that, $z_*=150z_0+z_d$ during unstable conditions, and Garrett (1978) suggested that $z_*=4.5z_{H,ave}$ during neutral conditions.

Table 1. The values of z_0, z_d, $z_{H,ave}$, z_*. in meters at each sodar location. See text for a detailed description of each variable.

Location	z_0	z_d	$z_{H,ave}$	z_*. Unstable	z_*. Neutral
City Maintenance Yard	0.3	1.5	3	47	13
Botanical Garden	0.5	2.5	5	78	23
Minor Building	0.5	2.5	5	78	23
First Christian Church	0.3	1.5	3	47	14

ANL deployed three minisodars (Figure 1). One ANL minisodar was located near the southern edge of the central business district in the Oklahoma City Botanical Garden (latitude 35.46° N, longitude 97.52° W). The area south of this sodar was covered by low-rise industrial buildings. The central business district, which includes many high-rise buildings, was immediately north of this sodar. Another sodar was located approximately 1 km north of downtown near the Minor Building (latitude 35.48° N, longitude 97.52° W). The area immediately south of this was covered with business and apartment buildings one to two stories tall. The third ANL minisodar was located near the First Christian Church, approximately 5 km north of downtown (latitude 35.51° N, longitude 97.52° W). The area immediately around the sodar consisted of the large church building, parking lot and grassy areas. The generally vicinity of the First Christian Church site was dominated by one and two story houses and apartment buildings. The ANL minisodars were operated continuously, but the sodar at the Minor Building was not deployed until 12 July (DOY 193)

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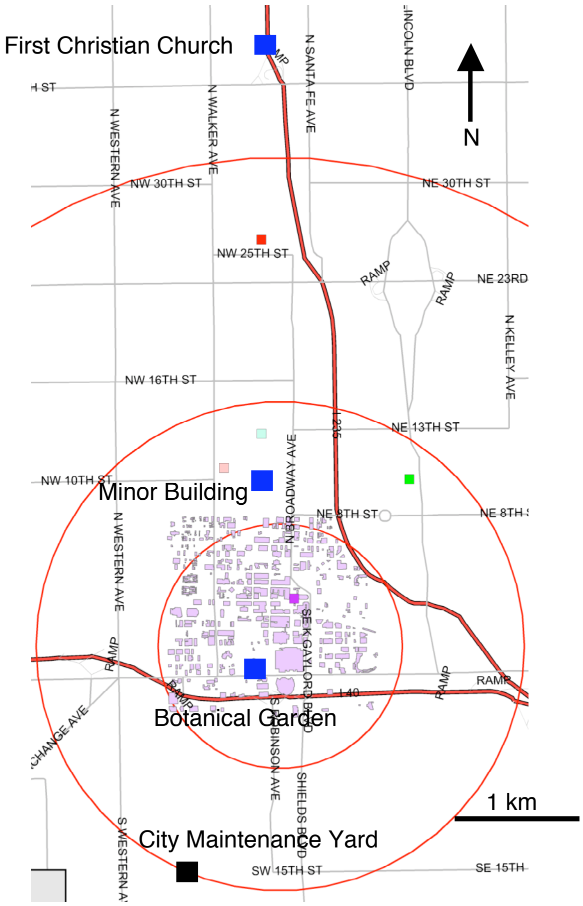

Figure 1. Relative locations of PNNL and ANL sodars during JU2003. Circles or arcs indicate a distance of 1, 2, or 4 km from the center of the central business district, respectively. Yellow symbol indicates the PNNL sodar site, blue symbols indicate ANL sodar sites. Other symbols indicate additional sodars that are not used in this preliminary analysis.

The PNNL sodar and the ANL minisodars were configured differently during JU2003 (Table 2). The ANL minisodars emitted higher frequency sound pulses than the PNNL sodar, which allowed the ANL sodar to use a lower first range gate and smaller range gates but limited the range of the instrument to 200 m or less. Before comparison of the data from the two types of sodars, the winds measured by the ANL sodars were averaged together to yield 10 m range gate spacing. All of the sodars used the same averaging time, so no time interpolation was required. Additional processing included removing cases in which the wind speed was less than 2 m s^{-1}, because there was a large amount of scatter in the measured wind direction at small wind speeds, and sorting all observations into 10° bins based on the wind direction.

Table 2. Operating characteristics of the PNNL sodar and ANL minisodars operated during JU2003. All ANL minisodars were configured identically.

Characteristic	PNNL	ANL
First range gate	30 m	5 m
Range gate spacing	10 m	5 m
Top range gate	500 m	200 m
Averaging time	15 min.	15 min.

3. RESULTS

A sample of data from Day of Year (DOY) 197 (16 July) is shown in Figures 2 and 3. There was a significant diurnal cycle to the observed winds at both 100 and 150 m above ground. Between DOY 197.0 and 197.3 [7 Local Standard Time (LST)], there was little scatter in the wind speed and direction measured 100 and 150 m above ground at the four sites. Near DOY 197.3, there were significant differences and increased scatter in the measured wind direction and wind speed. These observations are consistent with the onset of daytime convection, because increased surface heating leads to larger amounts of turbulence and increased scatter in the observed wind speed and direction. Later in the day, near DOY 197.8 (19 LST), the scatter at 100 and 150 m above ground shrinks again.

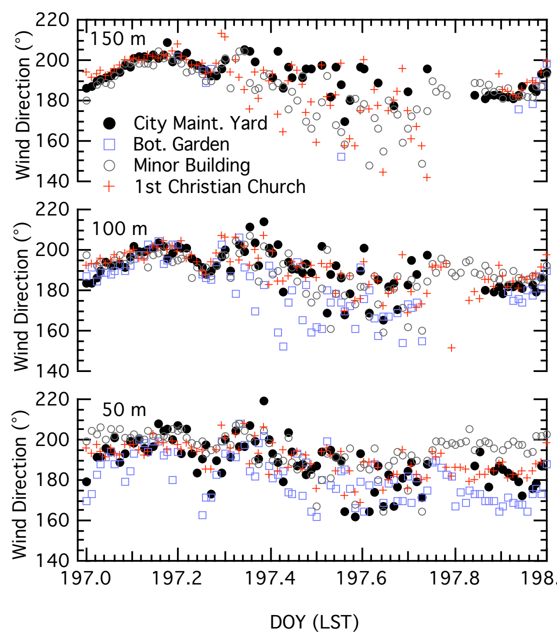

Figure 2. Wind direction measured 50, 100 and 150 m above ground at the City Maintenance Yard (black circles), Botanical Garden (blue squares), Minor Building (open circles), and First Christian Church (red crosses) sites during DOY 197.

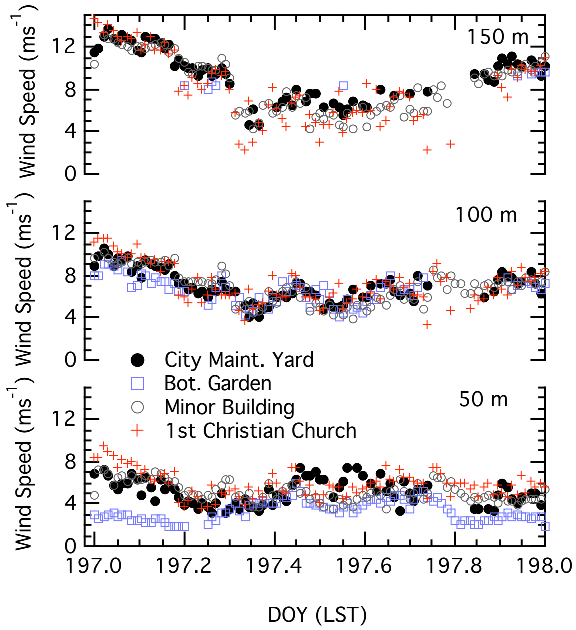

Figure 3. Wind direction measured 50, 100 and 150 m above ground at the City Maintenance Yard (black circles), Botanical Garden (blue squares), Minor Building (open circles), and First Christian Church (red crosses) sites during DOY 197.

In the following analysis of wind direction and wind speed differences, we will focus on southerly winds and assume that measurements at the PNNL sodar site at the City Maintenance Yard, which was located south of downtown, were representative of the large-scale undisturbed flow. All of the differences reported are defined as the wind direction or wind speed measured at the Botanical Garden, Minor Building, or First Christian Church minus the wind direction or wind speed measured at the City Maintenance Yard.

During the course of JU2003, when there were southerly winds from between 170 and 190° at the City Maintenance Yard winds measured 50 m above ground at the Botanical Gardens ranged from 160° to 180° (Figure 4, Table 3). The wind direction difference between these two locations decreases to near -2° 100 m above ground. There were differences between the wind direction difference measured at the Minor Building and at the First Christian Church ranging from -2° to 11° for cases in which the winds at the City Maintenance Yard were between 170° and 190° (Figure 4, Table 3). The differences are apparent at 50 m above ground and decrease with altitude.

There were also large wind direction differences measured between the Minor Building and the City Maintenance Yard when the winds measured at the City Maintenance Yard were easterly (Figure 4), albeit for a small number of observations. This finding was a surprise because we expect little difference in the wind direction observed at the sodar sites when the winds are easterly (because the winds should be unaffected by the central business district). On closer consideration, Figure 4 indicates that while the flow at the City Maintenance Yard is easterly, the flow north of downtown is northerly or northeasterly, and the winds do pass over the central business district.

Table 3. Wind direction difference measured between the City Maintenance Yard and the Botanical Garden, Minor Building and First Christian Church at altitudes of 50 and 100 m for cases with southerly winds (winds between 170° and 190°) at the City Maintenance Yard.

Height (m)	Botanical Garden	Minor Building	1st Christian Church
50	-10°	11°	6°
100	-2°	4°	6°

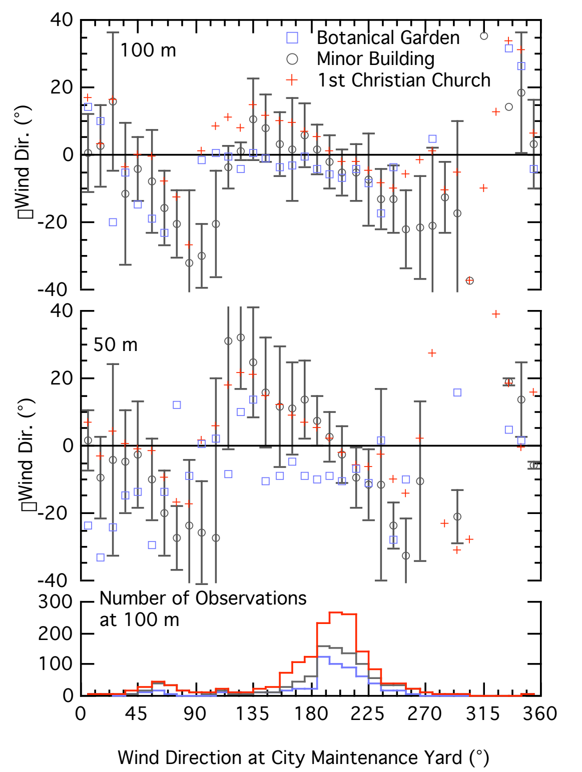

Figure 4. Average difference in wind direction measured at altitudes of 50 and 100 m during all of JU2003 at the Botanical Gardens (blue squares), Minor Building (circles), and First Christian Church (red +) for cases in which the observed wind speed was greater than 2 ms^{-1}, and the number of observations in each 10° bin for the Botanical Gardens (blue line), Minor Building (gray line), and First Christian Church (red line) at an altitude of 100 m. Error bars indicate standard deviation within each bin at the Minor Building site.

While there are significant differences in the wind directions observed at the various sites, the differences in observed wind speed are smaller (Figure 5, Table 4). We observed that when the winds at the City Maintenance yard are from the southwest, that the wind speed differences measured at the Minor Building and the First

Christian Church were small. One explanation is that the flow at these locations would not have passed over the central business district. The wind speed at the Minor Building is smaller than the wind speed observed at the City Maintenance Yard. This result is consistent with increased surface drag between the City Maintenance Yard and the Minor Building site. It is likely that z_* is higher than 50 m at the Minor Building site during unstable conditions (Table 1). The winds measured at 50 and 100 m above ground at the First Christian Church are generally faster than the winds at City Maintenance Yard.

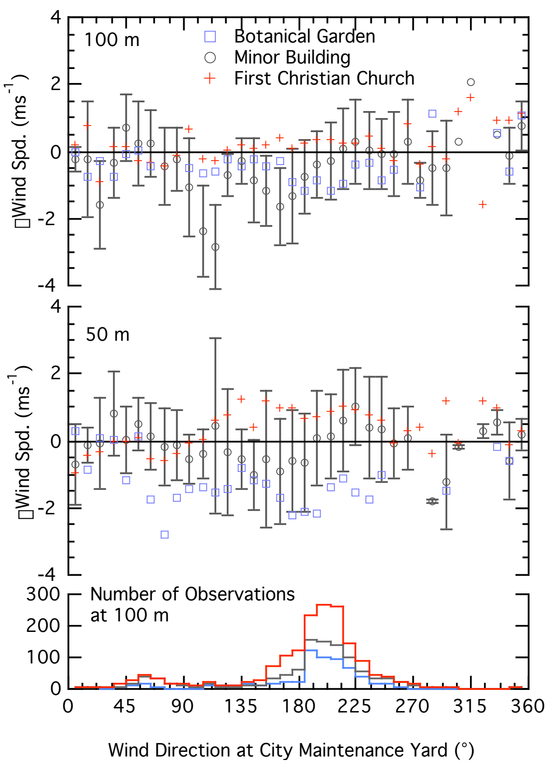

Figure 5. Average difference in wind speed measured at altitudes of 50 and 100 m during all of JU2003 at the Botanical Gardens (blue squares), Minor Building (circles), and First Christian Church (red +) for cases in which the observed wind speed was greater than 2 ms^{-1}, and the number of observations in each 10° bin for the Botanical Gardens (blue line), Minor Building (gray line), and First Christian Church (red line) at an altitude of 100 m. Error bars indicate standard deviation within each bin at the Minor Building site.

The wind speed at the Botanical Garden is consistently less than the wind speed at the City Maintenance Yard. This result is consistent with an increase in surface drag between the Botanical Garden and the City Maintenance Yard, but it is surprising to see that the wind speed measured at the Botanical Garden at 50 m above the ground is less than the wind speed measured at any of the other sites (Table 4). As shown in Figure 1, the Botanical Garden site is very close to the southern edge of the central business district. The value of z_*. is approximately 78 m during unstable conditions. Therefore, the 50 m range gate can be within the roughness sub-layer and measurements could be influenced by wakes from individual buildings.

Table 4. Average wind speed difference (ms^{-1}) measured between the City Maintenance Yard and the Botanical Garden, Minor Building and First Christian Church at altitudes of 50, 100, and 150 m for cases with southerly winds (winds between 170° and 190°) at the City Maintenance Yard.

Height (m)	Botanical Garden	Minor Building	1st Christian Church
50	-2.2	-0.6	0.8
100	-1.2	-1.1	0.2

4. DISCUSSION

A simple conceptual model would treat the city as an area of increased roughness. In such a model, the area of increased drag slows the winds as parcels pass over the city. As a result, the winds are expected to back with distance as the Coriolis force is reduced. Indeed, in a study over Oklahoma City using tetroons, Angell et al. (1974) found that the winds did back as the tetroon drifted over the city for a small set of case study days. But, our results indicate a backing or a veering of the wind depending on the wind direction measured at the City Maintenance Yard, as shown by the change in sign of the wind direction difference (Figure 4). Vukovich et al. (1976) found the response of a wind field to flow over a city to be a function of the wind direction, but they attributed this finding to local topography. Our observations suggest a relationship between the wind direction and the change in wind speed and direction due to the effects of an urban area in a region with very simple topography.

5. CONCLUSIONS AND FUTURE WORK

Two conclusions can be drawn from the preliminary work presented. First, our observations suggest that the presence of the central business district leads to measurable and consistent change in the wind patterns over the city. Second, a simple conceptual model, in which surface drag leads to a backing of the wind direction, does not appear to be applicable.

It has been only a short time since the field campaign, but already intriguing results are emerging. We have found a regular variation of the wind direction and wind speed differences measured upwind and downwind of the central business district. We will continue the analysis of the PNNL and ANL sodar data. Other sodars were deployed as well, and they will be included in future analysis. We will also conduct a modeling study to evaluate the effect of the Oklahoma City central business district on the regional flow patterns.

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