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JOINT URBAN 2003 STREET CANYON EXPERIMENT

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1. INTRODUCTION

As part of the DOE-DTRA Joint URBAN 2003 field experiment in Oklahoma City, a multi-group team instrumented a downtown street canyon with a high density of wind sensor instrumentation. The goal was to garner flow field information in order to better understand the transport and dispersion of tracers released in the street canyon. In this paper, we briefly review prior field and laboratory experiments on street canyon flow, describe our experimental set-up and measurement apparatus, present some preliminary analyses of the measurements, and discuss their significance in relation to current understanding. Eventually this data set will be used to evaluate the next generation of urban dispersion models (e.g., Cox et al., 2000; DeCroix, 2002; Hall et al., 2000; Williams et al., 2002).

2. BACKGROUND

Much of the basic understanding of dispersion and flow patterns in the urban street canyon has been obtained from reduced-scale wind-tunnel experiments (e.g., Cermak et al., 1974; Hoydysh et al., 1974; Britter and Hunt, 1979). Early studies helped to determine that the nature of the flow between two buildings of equal height is determined by the ratio of the width between buildings (W) to the building height (H) (Hussain and Lee, 1980). They found that there is also a weak dependence on the cross-sectional length of the buildings. Hosker (1987) reported that several studies have shown that a helical vortex will form between two buildings if the wind is within 60 degrees of perpendicular to the building face, otherwise no vortex forms. As summarized by Oke (1987), in a street canyon a single vortex develops for skimming flow (H/W > 1), two counter-rotating vortices may develop for wake interference flow (H/W ~ 2/3), and for isolated roughness flow (H/W > 1/3) the flow field looks similar to the single building case. Recent water channel experiments by Baik et al. (2000) indicate that for deep canyons (H/W > 2) two vertically-stacked counter-rotating vortices exist.

Davidson et al. (1996) and Roth and Ueda (1998) measured vertical and lateral profiles of the mean wind and turbulent intensity along lines in staggered and unstaggered cubical arrays. Similar studies with a higher density of measurements were performed in wind tunnels and flumes that have fully captured the canyon vortex and rooftop recirculations (e.g., Lawson and Ohba, 1993; Kastner-Klein et al., 2001; Brown et al., 2002; MacDonald et al., 2002).

The effect of roof shape and relative building heights has also been studied in the wind tunnel.

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Based on smoke visualization studies, Meroney et al. (1996) found that rooftop recirculation zones do not form on a series of buildings of equal height, except for the building furthest upstream. Several wind-tunnel studies have demonstrated that building height differences can significantly change the urban canyon dispersion patterns and flow field (e.g., Wedding et al., 1977; Hoydysh and Dabberdt, 1988; Macdonald et al., 1998). In addition, peaked roofs and non-rectilinear buildings can alter urban canyon circulation (e.g., Rafailidis and Shatzmann, 1995; Kastner-Klein et al., 1997).

Recently, wind-tunnel experiments have been performed using detailed building models of Lower Manhattan (Perry, 2003) and downtown Oklahoma City (Kastner-Klein et al., 2003). Tracer dispersion has been studied for both cases, and velocity measurements within the street canyons have been or will be taken shortly.

Several informative reduced-scale outdoor field studies around building arrays have been performed that allow for the effects of real meteorology to be accounted for, e.g., stratification, large-scale wind meander. In general, these studies concentrated on dispersion measurements and contained few velocity measurements (e.g., MacDonald et al., 1997; Johnson and Hunter, 1999; Mavroidis and Griffiths, 2001). An exception was the Mock Urban Settings Test (MUST) held at Dugway Proving Ground in Utah (Biltoft, 2002). In addition to numerous dispersion trials, there were many sonic anemometers on towers and tripods (e.g., Nelson et al., 2003).

Although wind tunnel and reduced-scale field experiments have proven indispensable for understanding the basic physics of flows in street canyons and have been invaluable in model evaluations, the real-world is much more complex. Experiments in cities are required in order to evaluate our fundamental understanding of street canyon flow. Early field experiments by Johnson et al. (1973), Dabberdt et al. (1973), DePaul and Sheih (1985), Yamartino and Wiegand (1986), and Kitabayashi (1992) all confirmed the presence of a large vortex circulation within the urban canyon, although there was some disagreement under what conditions the vortex would form and what the controlling factors were for the vortex strength. These differences can probably be attributed to differences in the building configurations and meteorological conditions, and to uncertainties in the measurements. In all but one case, few meteorological measurements were made, as the emphasis was on tracer measurements. Depaul and Sheih (1986), however, measured the vortex circulation using tracer balloons and rapid sequence photography for a street canyon in Chicago. A few wind measurements were also obtained with a hot-wire anemometer.

Using a small number of sensors, a quality, long-term climatological dataset was obtained by Rotach (1995) in Zurich that included two vertical profiles in the street canyon and one profile at rooftop. Oikawa and Meng (1995) measured velocity statistics in suburban Sapporo, Japan near roof level and above in the urban roughness sublayer. These two studies provide useful information on the variation with height of mean and turbulence velocities in and above the street canyon.

Louka et al. (2000) measured wind velocities at a few positions in a street canyon between two farm house buildings with peaked roofs. They found the canyon vortex was highly intermittent and the mean field was dominated by turbulent fluctuations. Nielson (2000) reported on a street canyon experiment conducted in Copenhagen with two 3D sonic anemometers mounted on each of two towers on opposite sides of a street. Cross correlations of the tower measurements revealed that local velocity fluctuations dominated, also indicative that a steady mean vortex may not be evident.

Recently a new generation of street canyon experiments are providing more detailed wind measurements. The Basel Urban Boundary Layer Experiment (Rotach, 2002) includes numerous urban energy budget stations as well as 6 sonics on a tower located in a street canyon defined by 3-4 story buildings and extending to about twice building height. Gavze et al. (2002) describe a short-term experiment in an Israeli city in which several 6 m towers with 2 sonics each and thermocouples were sited on rooftops of 2-3 story buildings and one 10 m tower with 2 sonics was placed in the street canyon. The URBAN 2000 tracer field experiment in Salt Lake City included numerous 2D sonic measurements at street level and on building rooftops, as well as a few 3D sonics on towers in a building complex near the release point (Allwine et al., 2002). Recently, Eliasson (2003) has instrumented a 3-4 story street canyon in Goteborg, Sweden with several towers and several booms across the canyon that have been equipped with upwards of fifteen 3D sonics.

The impact of heating (and cooling) on street canyon flows is not well understood. Numerical simulations (e.g., Sini et al., 1996; Kim and Baik, 1998) and wind tunnel experiments (Uehara et al.,

2000) suggest that heating of canyon walls and street surfaces significantly impacts the flow fields. Field experiments (e.g., Nakamura and Oke, 1998; Santamouris et al., 1999) have yet to conclusively validate this, in part because of a lack of a sufficient number of simultaneous temperature and wind sensors.

3. EXPERIMENTAL SET-UP

The DOE-DTRA Joint URBAN 2003 field experiment was held in Oklahoma City in July 2003 and involved a large number of collaborating government, university, and commercial sector researchers. Its goal was to provide information useful for testing and evaluation of the next generation of urban transport and dispersion models. The experiment consisted of a large number of tracer releases, a network of concentration samplers, and fixed meteorological sensors placed in and around the city (JU 2003 Experimental Plan, 2003).

As part of the Joint URBAN 2003 experiment, a street canyon sub-experiment was performed. A large number of wind sensors were placed at street level, on towers, and at roof level within a one block section of a street canyon on Park Avenue. Park Avenue is located within the downtown core of Oklahoma City and was the site of several tracer releases during the latter stages of the Joint URBAN 2003 field experiment.

Figure 1 shows building footprints and heights for the area around the street canyon experiment site, which was performed on Park Avenue between Robinson and Main Streets. The buildings on Park Ave. are fairly uniform in height (~50 m) on the southern side of the street, except at the western end with one tall building (~120 m). The buildings along the northern side of the street mirror those on the south, except for a group of lower buildings (1-4 stories) and a narrow alley near the middle of Park Avenue on the eastern side. Using 50 m as the average building height, the height-to-width ratio is about 2. Although far from an ideal street canyon, for Oklahoma City this was actually one of the more idealized street canyons.

Figure 2 is a sketch showing instrument locations on Park Avenue. Three pairs of towers ranging in height from 7 to 15 meters and instrumented with a total of twenty-four 3D sonic anemometers were located on opposite sides of the street (Figs. 3a and b). A 7 and 5 m tower with a total of six 3D sonics were located on rooftops in the gap region on the northern side of the street. Fine-wire thermocouples were placed on several

Figure 1. Plan view of downtown OKC building footprints in the vicinity of the Park Avenue street canyon experiment site (data courtesy of May Yuan, OU Geography Dept.).

of the towers for obtaining relatively accurate vertical temperature profiles within the street canyon and on rooftop. Several IR sensors were also mounted on a few towers to evaluate local surface temperature. Four 3D sonics were mounted over the sides of the buildings on the eastern end of Park Avenue, hanging upside down just below roof level. In addition, one 3D sonic was placed on a flagpole on the roof of the building on the southern side of the street. During Intensive Operating Periods (IOP's), two tether-sondes were operated in ladder mode and hung over the sides of these two buildings, so that a vertical profile of wind, temperature, and relative humidity was obtained through the complete depth of the street canyon on each side of the street (Fig 3c). During IOP's seven 2D sonics and two 3D sonics were placed on 2 m tripods at street level in Park Avenue near the street intersections. In addition, there were four 3D sonics mounted on street and traffic lights in each of the Park-Robinson and Park-Broadway street intersections.

Table 1 provides a list of instrumentation that were used in the Park Avenue street canyon experiment, along with their locations and the heights at which they operated. The 3D sonics

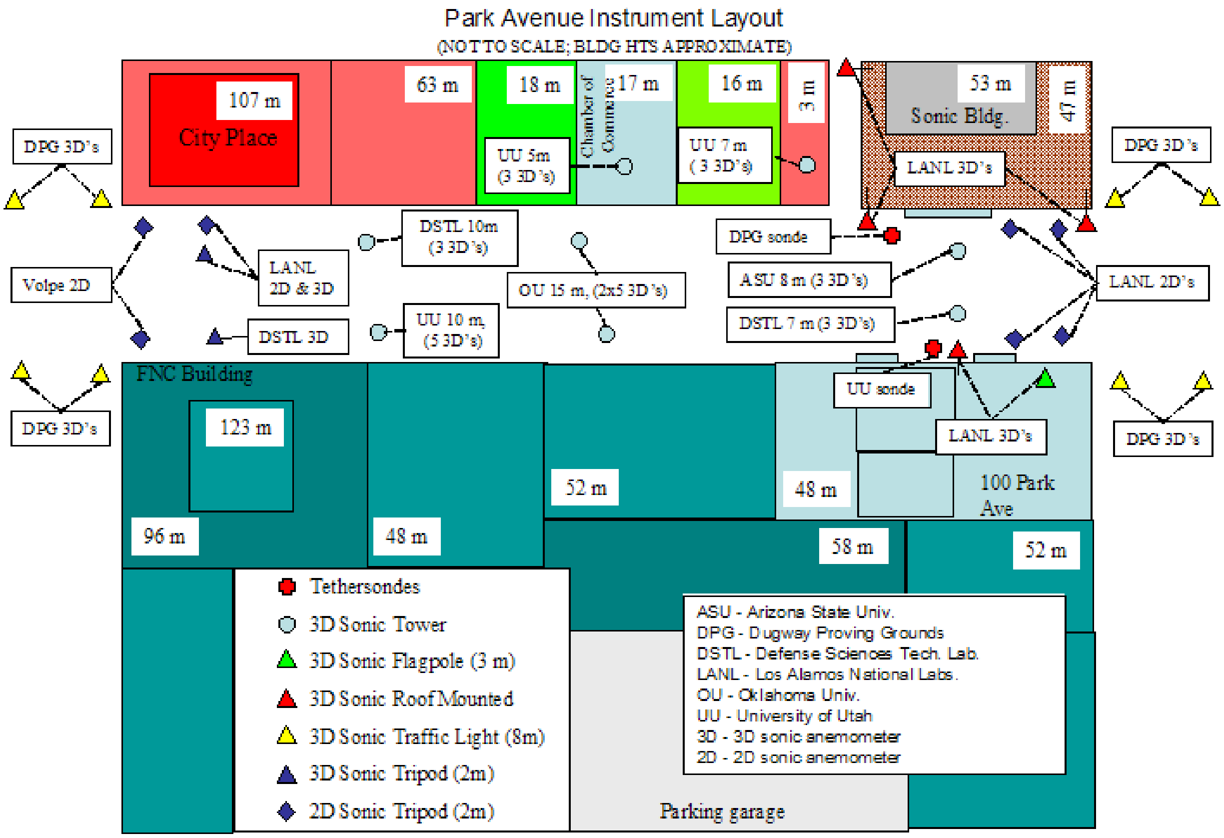

Figure 2. Sketch of the instrument layout in the Park Avenue street canyon. All instruments in place during the entire month of July, except the tripod-mounted sonics and tethersondes that operated only during the Intensive Operating Periods. Note: buildings and instrument locations not to scale.

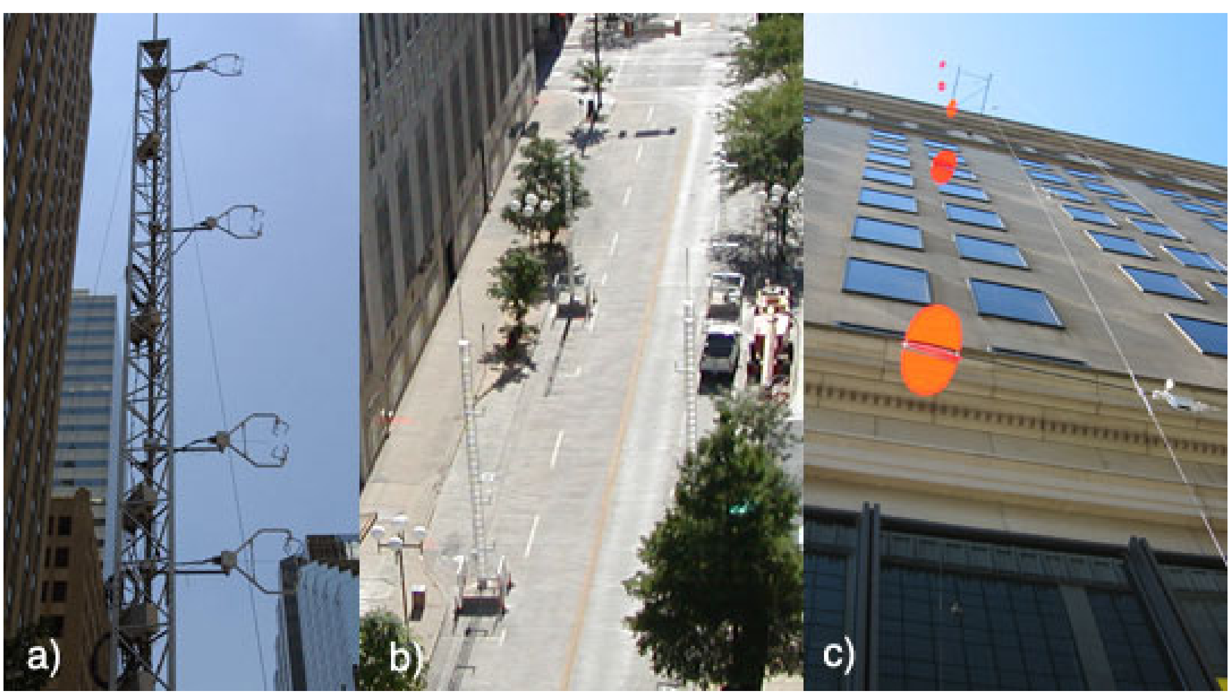

Figure 3. a) Campbell 3D sonics on the UU 10 m tower in Park Ave, b) Park Ave. viewed from the east with the two OU 15 m towers in the foreground and two UU/DSTL 10 m towers in the background, c) looking up at the UU tethersonde pulley system located at the southwest end of Park Ave. Photo a) courtesy of Aaron Kennedy.

Table 1. Meteorological Instrumentation in the Park Avenue Street Canyon

	Instrumentation	Location	Time of operation	Institution
2 – 15 m towers (street)	2 x 5 - 3D sonics 1.5, 3, 6, 10, 15 m	midpoint of Park Ave. both sides of street	Entire period	OU RM Young
10 m tower (street)	5 - 3D sonics 3.2, 4.2, 5, 7¼ , 10m 4 finewires 3.2, 4.2, 5, 10 m	western end of Park Ave. both sides of street	Entire period	UU RM Young
10 m tower (street)	3 - 3D sonics 3, 5, 10 m	western end of Park Ave. both sides of street	Entire period	DSTL Gill
1 – 8 m tower (street)	3 - 3D sonics 2.5, 5, 8.5 m	eastern end of Park Ave. north side of street	Entire period	ASU ATI, Metek
1 – 7 m tower (street)	3 - 3D sonics 3.5, 5, 6.5 m	eastern end of Park Ave. south side of street	Entire period	DSTL Gill
1 – 7 m tower (rooftop)	3 - 3D sonics 3, 5, 7 m 2 finewires 2, 3 m	4 story bldg on north side of Park Ave.	Entire period	UU Campbell
1 – 5 m tower (rooftop)	3 - 3D sonics 2, 3.5, 5 m 2 finewires 2, 5 m	1 story bldg on north side of Park Ave.	Entire period	UU Campbell
wall mounts (building tops)	3 - 3D sonics ¼ m below wall	11 story bldg on east end of Park on north side of street	Entire period	LANL Metek
wall mounts (building tops)	1 - 3D sonics ½ m below wall	11 story bldg on east end of Park on south side of street	Entire period	LANL Metek
flag pole – rooftop	1 - 3D sonic 3.7 m above roof	11 story bldg on east end of Park on south side of street	Entire period	LANL Metek
tripods - street	7 - 2D sonics, 2 - 3D sonics 2 m above street	4 at eastern end and 5 at western end of Park Ave.	Intensive Operating Periods	Volpe/UCF, DSTL & LANL Handar, Gill, Metek
2 Tethersondes -	6 cup & vane,T,rh 1,5,10,20,30,40 m	11 story bldgs on north and south side of street	Intensive Operating Periods	UU and DPG Vaisala
Vehicle counter	Road tube	Midpoint of Park Ave.	Entire period	OU
8 – Traffic & street light towers	8 - 3D sonics 8 m	Park-Robinson and Park-Broadway intersections	Entire period	DPG RM Young

and finewire thermocouples all recorded data at 10 Hz, except for those on the rooftop towers which recorded at 20 Hz. The 2D sonics operated at either 1 or ½ Hz. The tethersondes recorded information between 1/10 and 1/15 Hz. Instruments were all time synchronized to the nearest second at the start of each day.

4. RESULTS AND DISCUSSION

Data collected during the Joint URBAN 2003 field experiment are still being processed and checked, hence results at this time are preliminary. Nonetheless, several interesting features have been identified and are presented below. We begin with vertical profiles of wind speed and wind direction for IOP #5 on the two OU 15 m towers located half-way down Park Avenue (Fig. 4). What is of special interest here is the sudden 180 degree shift in wind direction at the midpoint of the tower height. Between 1500 and 1630 hrs, the winds are actually coming out of the east above 7.5 m and coming out of the west below. At the transition point, the

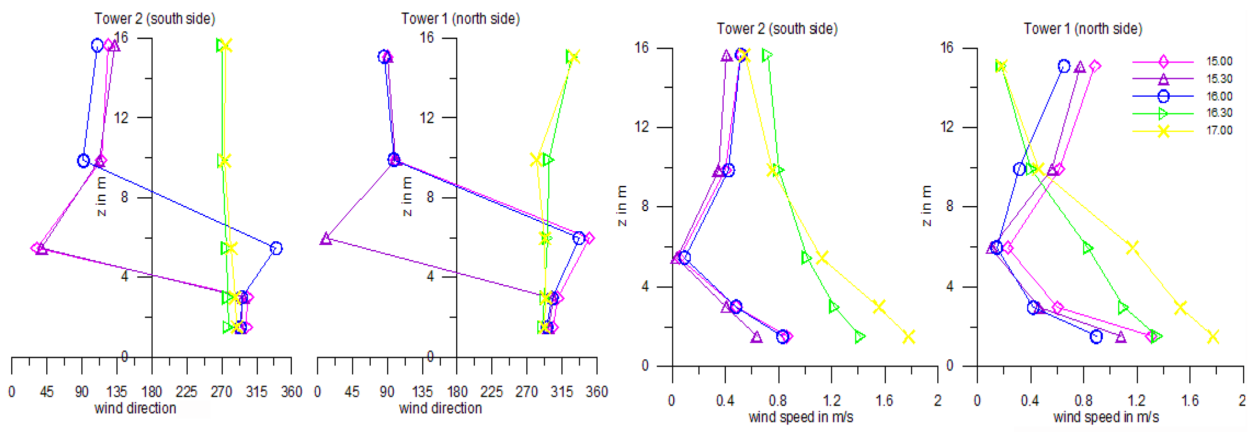

Figure 4. Vertical profile plots of wind direction and wind speed for the two OU 15 m towers located near the mid-point of Park Avenue. Prevailing winds are out of the south during this time period (July 13, IOP #5).

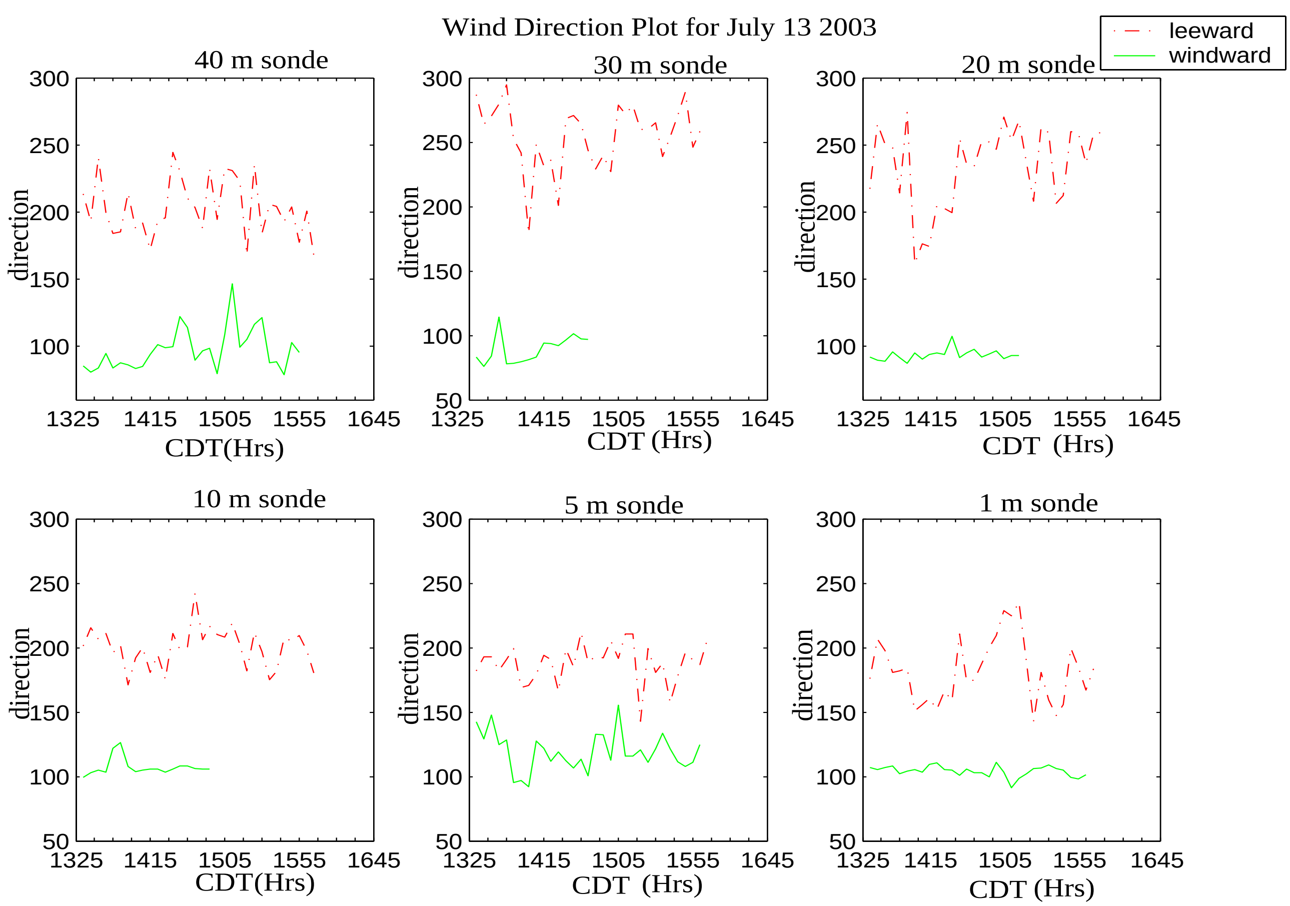

Figure 5. Vertical profile plots of wind direction at six heights as measured by the UU and DPG tethersonde systems located near the eastern end of Park Avenue. Winds on the windward (north) side of the street are predominately from the east, while those on the leeward (south) side vary with height from the south to the west. Prevailing winds are out of the south during this time period (July 13, IOP #5).

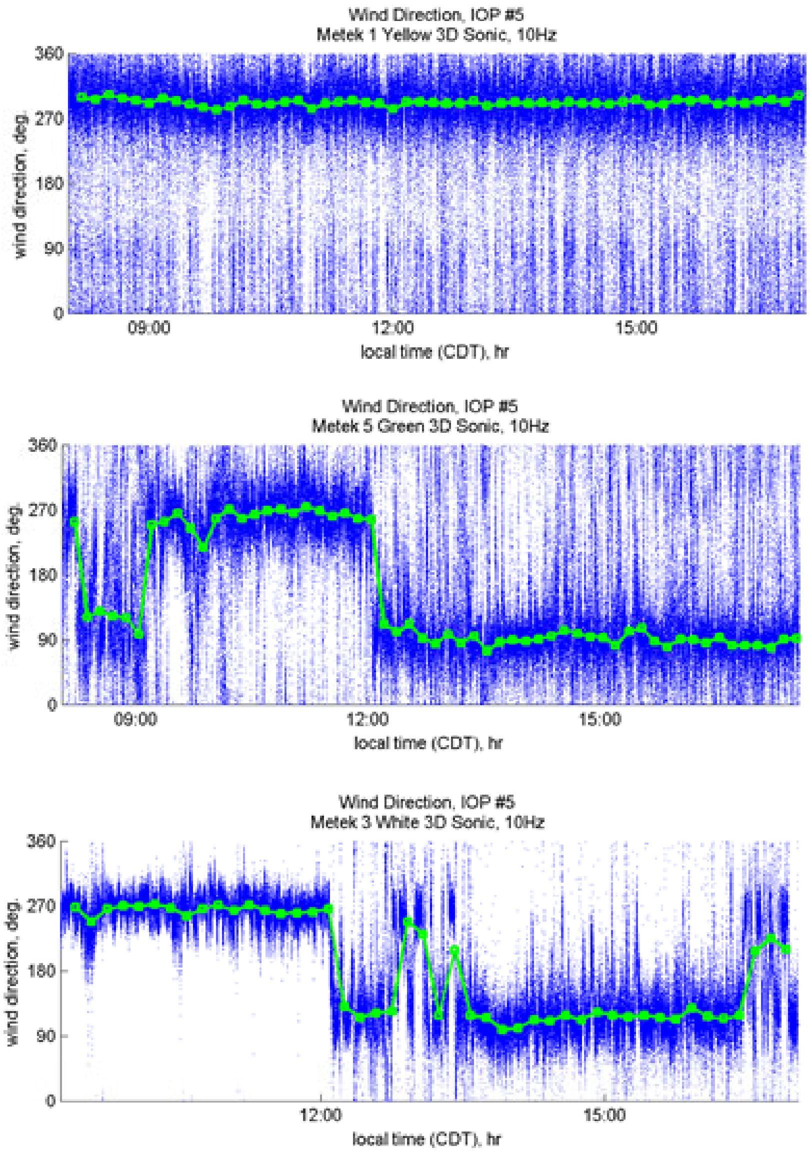

Fig. 6. Wind direction time series (blue - 10 Hz and green - 10 min. avg.) for the 3D sonics in the street canyon near roof-level on the southern side of the street (top), near roof-level on the northern side of the street (middle), and at street level on the northern side (bottom).

wind speeds drop to nearly zero. Later, the wind direction becomes constant with height (270 degrees) with wind speeds actually larger near the ground. During this time period, the winds on opposite sides of the street had similar behavior. Further analyses of other time periods will help to determine if this is common behavior.

Vertical profiles during the same time period to the east show different behavior. Whereas the OU towers at the street canyon midpoint showed similar behavior on both sides of the street, the wind directions measured by the tethersondes on opposite sides of the street are 90 degrees out of phase at the lowest three heights (Fig. 5). On the northern side, the winds are easterly and do not change with height. On the southern side the winds change gradually with height from southerly to westerly.

Wind direction time series from 3D sonics in the canyon just below roof-level at the eastern end show similar values to those measured at high elevations on the tethersonde (Figs. 6a & b, from 1300 to 1500 hours). An interesting feature occurs earlier in the day, with the flow on the north side of the street changing 180 deg. around mid-day (Figs. 6b & c). Apparently the flow pattern at the street ends changed from channelized (winds in the same direction on opposite sides of the street) to bi-directional. Also, note that the wind direction measure-ments near roof-level show large scatter, perhaps indicative of the strong shear layer and turbulence at building top level (Figs. 6a & b), while the measurements at street level show much less scatter (Fig. 6c).

The bi-directionality of winds on opposite sides of the street is very apparent at street level. Wind roses for the four street-level 2D sonics at the eastern end of Park Avenue show that an end vortex often develops in the horizontal plane (Fig. 7). The winds on the northern side of the street are easterly, while the winds on the southern side are westerly (note that prevailing winds are from the south). Six of the 10 IOP's showed this behavior. For two IOP's, channeling dominated, i.e., winds on both sides of the street blew in the same direction (Fig. 8), while the other two IOP's showed split behavior. Similar analyses will be performed in the future using the remainder of the wind sensors in order to get a better idea of the plan view flow behavior in the entire street canyon.

The east end of Park Avenue had mature broadleaf trees on both sides of the street. The 7 and 8 m towers on the east end had sonics above, below, and within the leaf canopy with

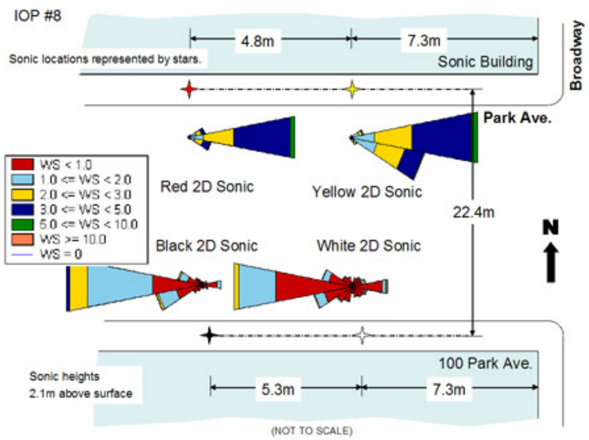

Figure 7. Wind roses for the 4 LANL street-level 2D sonics at the eastern end of the Park Ave. street canyon during IOP 8. The data suggests that there may be an end vortex, leading to easterly winds on the northern side of the street and westerly winds on the southerly side. Prevailing winds are out of the south –southeast during this time period.

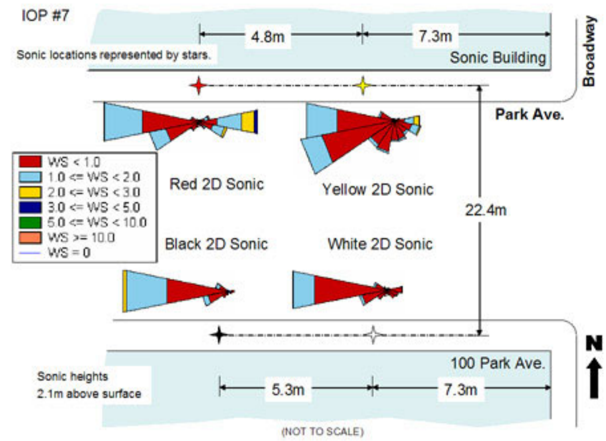

Figure 8. Wind roses for the 4 LANL street-level 2D sonics during IOP 7. For this day, the winds appear to be channeled, coming out of the west. Prevailing winds are out of the south-southwest during this time period.

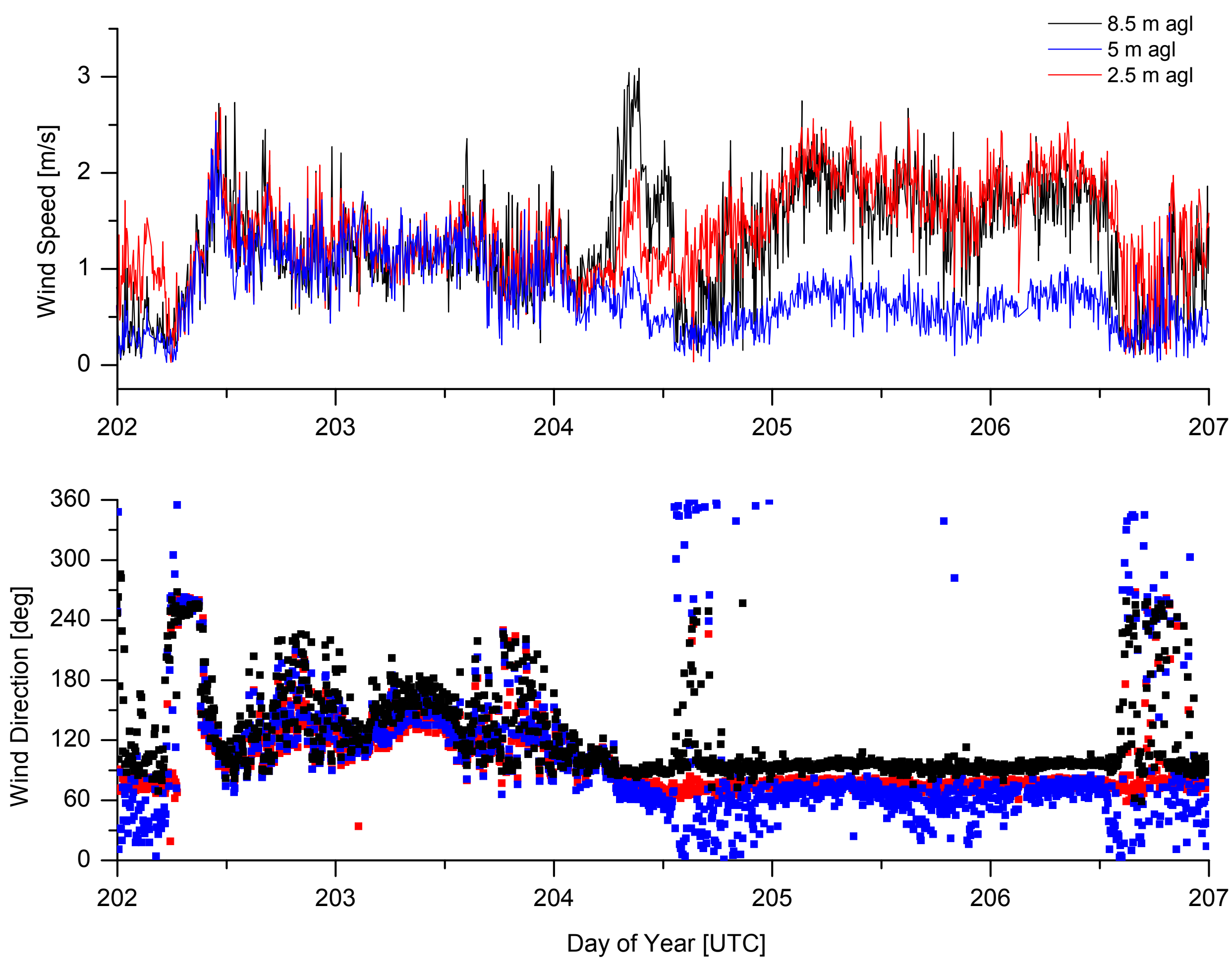

Figure 9. Time series of five minute averaged wind speed and wind direction at 3 heights from July 22 to 27. The ASU tower is located near the eastern end of the Park Ave. street canyon on the northern side of the street. The trees immediately to the east of the tower significantly reduce the wind speeds within the leaf canopy (~ 3 to 6 m agl) when the winds are out of the east (90 deg.).

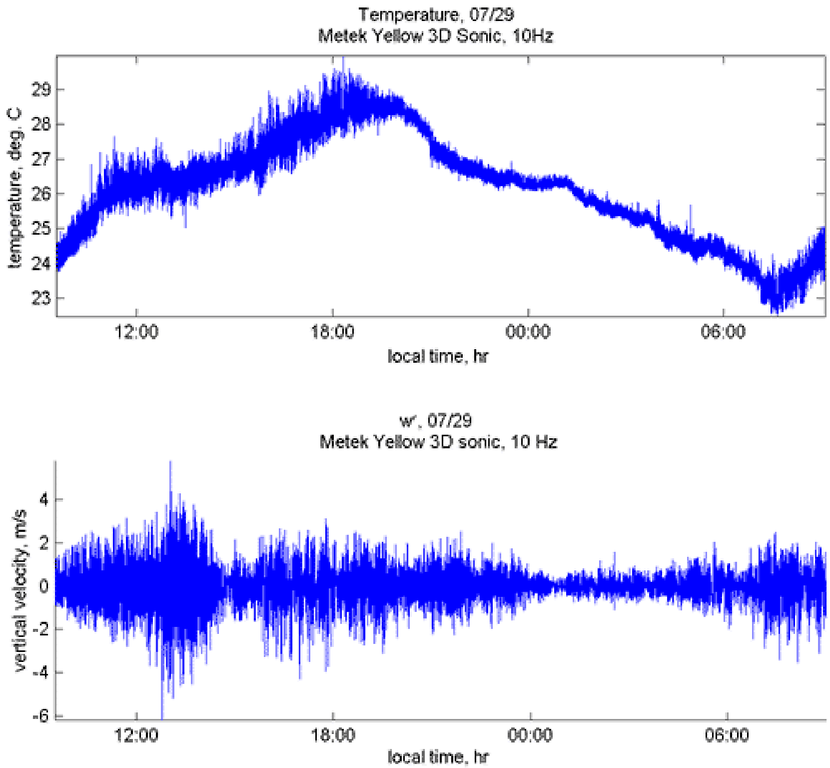

Figure 10. Time series of temperature and vertical velocity fluctuations over a diurnal cycle on July 29-30. The 3D sonic is on the southeast side of the street canyon mounted over the side of a building just below roof level.

trees directly to the east and west. Figure 9 shows that the middle sonic within the tree canopy has significantly reduced velocities when the winds are from the east or west. For other wind directions, the wind speeds for all three sensors are similar. What is not clear is whether they impact the entire canyon flow field or just locally.

Timeseries of temperature in Fig. 10 reveal that turbulent fluctuations within the urban core are stronger during the day compared to the night. Preliminary analyses suggest that this is common for sonics near the surface and those at rooftop. The vertical velocity fluctuations shown in Fig. 10 do show that turbulence is for the most part smaller during the night. However, more analyses need to be performed in order to account for the background wind and stability conditions. We have not analyzed enough temperature data to determine whether the air becomes stratified or remains near neutral. This area of research is of importance due to numerical modeling and wind tunnel experiment findings that indicate heating of wall surfaces significantly impacts the flow field.

5. **CONCLUSIONS**

As part of the Joint URBAN 2003 field experiment held in Oklahoma City in July of 2003, our team instrumented a street canyon on Park Avenue with a large number of meteorological sensors. During Intensive Operating Periods, there were 45 3D sonics and 5 2D sonics in the street canyon domain. The 3D sonics were placed on six towers located at street level, two towers at roof-level, and nearby street and traffic lights. Fine-wire thermocouples and IR sensors were attached to several of the towers. In addition, four 3D sonics were mounted over the side of building tops so that they were just below roof level. During Intensive Operating Periods seven tripods with 2D and 3D sonics were placed on sidewalks and two tethersonde pulley systems were suspended from two building tops so that vertical profiles of wind, temperature, and relative humidity could be obtained through the entire depth of the street canyon.

Data sets are now being processed and checked. In this paper we have presented some “first looks” at our data. We have found many interesting results, including

1. 180 wind direction shifts on the OU 15m towers located at canyon midpoint;
2. vertical profiles of wind direction that vary with height on one side of the street and not on the other (UU and DPG tethersonde profiles);
3. wind direction time series that show a rapid 180 degree shift in the mean horizontal flow on the northern side of the street;
4. a vortex in the horizontal plane near street level at the eastern end of the street canyon;
5. the strong influence of trees on sensors at leaf canopy height; and
6. differences in turbulence levels between day and night.

Our analysis work is just starting. In time, we hope to gain more insights on flows in street canyons. In the short term, the data will be used to better understand the transport and dispersion of tracer gases released in the street canyon during Intensive Operating Periods. In the longer term, this data set will be used for evaluation of the next generation of urban dispersion models.

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