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Title:

STREET CANYON FLOW PATTERNS IN A HORIZONTAL PLANE: MEASUREMENTS FROM THE JOINT URBAN 2003 FIELD EXPERIMENT

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STREET CANYON FLOW PATTERNS IN A HORIZONTAL PLANE: MEASUREMENTS FROM THE JOINT URBAN 2003 FIELD EXPERIMENT

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1. INTRODUCTION

As part of the larger Joint URBAN 2003 tracer field experiment performed in Oklahoma City from June 29 to July 30, 2003, a collaborative team of government and university researchers instrumented a downtown street canyon with a high density of wind sensor instrumentation (Brown et al., 2003). The goal of the Park Avenue street canyon experiment was to garner flow field information in order to better understand the transport and dispersion of tracers released in the street canyon and to test and improve the next generation of urban dispersion models. In this paper, we focus on describing the mean flow patterns that developed in the street canyon in a horizontal plane near the surface. We look at the patterns that develop over entire Intensive Operating Periods (IOP's) lasting from 6-9 hours in length, and as a function of inflow wind direction. Most prior street canyon experiments have generally focused on the vertical structure of the flow; this work contributes to the understanding of the horizontal nature of the flow.

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; Hussain and Lee, 1980; Lawson and Ohba, 1993; Meroney et al., 1996; Davidson et al., 1996; Roth and Ueda, 1998; Kastner-Klein et al., 2001; Brown et al., 2002; MacDonald et al., 2002), dispersion field experiments (e.g., Georgi et al., 1967; Johnson et al., 1973; Dabberdt et al., 1973; DePaul and Sheih, 1985; Yamartino and Wiegand, 1986; Kitabayashi, 1992), and outdoor wind measurements (e.g., Depaul and Sheih, 1986; Oikawa and Meng, 1995; Rotach, 1995; Louka et al., 2000; Nielson, 2000; Rotach, 2002; Gavze et al., 2002). As summarized by Oke (1987) the nature of the flow between two buildings of equal height is determined by the ratio of the spacing between buildings (S) to the building height (H). In a narrow street canyon (H/S > 1) a single vertically rotating horizontally-aligned in-canyon vortex develops, while a smaller counter-rotating vortex may develop next to the larger in-canyon vortex in a wider canyon (H/S ~ 2/3).

Recent experiments (e.g., water channel experiments by Baik et al., 2000 and outdoor experiments by Eliasson et al., 2004) have tried to elucidate the vertical structure for deeper canyons (H/S > 2). Other studies have looked at the effect of roof shape and relative building heights on vertical transport and dispersion (e.g., Wedding et al., 1977; Hoydysh and Dabberdt, 1988; Rafailidis and Shatzmann, 1995; Kastner-Klein et al., 1997; Macdonald et al., 1998). A number of wind tunnel tracer experiments have shown that concentrations for releases in the street canyon are particularly sensitive to inflow wind direction (e.g., Wedding et. al., 1977; Hoydysh and Dabberdt, 1988; Kastner-Klein and Plate, 1999). Dabberdt and Hoydysh (1991) also found that concentrations within the street canyon vary significantly with block shape (rectangular vs. square) and with the relative width of street vs. avenues.

Most flow studies have focused on the vertical structure of the flow in the street canyon rather than the horizontal. Many questions remain regarding the horizontal nature of the flow, how it influences the vertical flow structure, and how it impacts transport and dispersion. For example, when does channeling occur, for oblique angle flows does a spiral vortex develop down the length of the street canyon, for approach flow perpendicular to the street canyon do horizontally-rotating eddies exist at each end of the canyon, and if so how far into the canyon do they extend?

Wind-tunnel smoke visualization experiments of Hoydysh et al. (1974) for a street intersection were among the first to show horizontally-rotating vertically-aligned eddies at the end of the street canyon near the intersection. Their sketches show these "corner" vortices extending up the entire side of the building in a spiral vortex and interacting with the in-canyon vortex in the interior

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of the street canyon. Wind-tunnel experiments of line source releases in a street canyon by Cermak et al. (1974) showed that these corner vortices lead to elevated concentrations on the leeward side of the canyon at each end of the street. Strangely, for similar experiments, Hoydysh and Dabberdt (1988) and Hayden et al. (2002) explain reduced concentrations on the leeward wall at each end of the street as being a result of the corner vortices. Wind-tunnel velocity measurements by Kastner-Klein et al. (2004) directly confirmed these end vortex motions for a street canyon of cross-stream length-to-height (L/H) ratio of 5, but when the length of the canyon was increased (L/H=10) the corner vortex disappeared or was not resolved.

For a street canyon experiment in Kyoto with H/S = 1, Nakamura and Oke (1998) indicated that inflow perpendicular to the street canyon resulted in a roof vortex with winds at street level in the opposite direction to the prevailing wind, inflow parallel to the street canyon resulted in winds at street level in the same direction, and they suggested that inflow winds at oblique angles resulted in a corkscrew spiral vortex along the length of the street canyon.

Using two storage units to create a reduced-scale street canyon, Johnson and Hunter (1999) found that along canyon flow must be taken into account since it modified the simple 2D picture of roof vortex flow. With a sensor at the ground in the center of the street canyon and one at rooftop, they found that for non-perpendicular approach flows, the measured winds were not mirror images of each other, but rather appeared to be a combination of roof vortex flow and down canyon flow.

Bächlin and Plate (1988) performed wind tunnel experiments of an industrial site. Twenty or so mean wind vectors are mapped at street level showing channeling under oblique angle ambient wind conditions. Although the channeling is fairly strong, vertical profiles show a simultaneous horizontally-aligned, vertically-rotating in-canyon vortex in the cross-stream direction.

During a street intersection CO experiment held in San Jose, California, winds were measured in street canyons (Johnson et al., 1971). The data report shows the average wind directions at street level at six locations in three street canyons meeting at an intersection. The average wind measurements are stratified by inflow wind direction. The resultant street-level winds are very complex, but evidence of channeling, corner vortices, and reverse flow due to the in-canyon vortex are apparent.

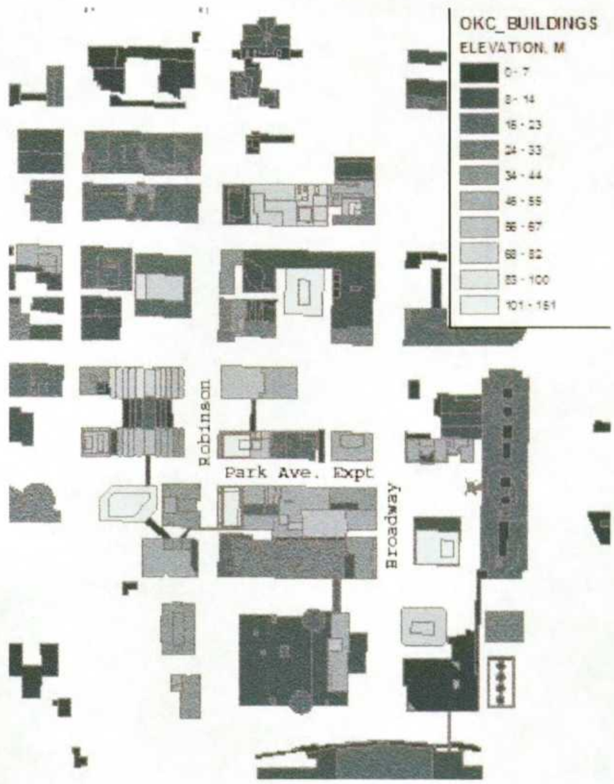

Figure 1. Plan view of downtown OKC building footprints in the vicinity of the Park Avenue street canyon experiment site (data courtesy of May Yuan, OU Geography Dept.).

3. EXPERIMENTAL SET-UP

As described in Allwine et al. (2004), the Joint URBAN 2003 field experiment was held in Oklahoma City and consisted of a large number of tracer releases, a network of concentration samplers, and fixed meteorological sensors placed in and around the city. The goal of the study was to collect meteorological and concentration data useful for testing and evaluation of the next generation of urban transport and dispersion models.

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. The width of Park Avenue is about 24 m and it's east-west length from building corner to building corner is about 157 m. Using 50 m as the average building height, the height-to-width ratio is about 2.

Tall buildings upstream and downstream of Park Avenue may influence the flow fields within the street canyon. One block to the southeast is the Bank One building, a 100+ m high structure. Two blocks to the north is the 115 m high Kerr-McGee building. The 117 meter Oklahoma Tower sits one block to the east-southeast. Additionally, the east end of Park Avenue had mature broadleaf trees on both sides of the street. During the IOP's, cars were allowed to travel through the avenue, though traffic was generally light. Although one of the more idealized street canyons in Oklahoma City, it is far from ideal and should be considered when interpreting wind measurements.

Figure 2 is a sketch showing instrument locations on Park Avenue and 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. Below we describe the wind sensors used to study the mean flow patterns in a horizontal plane near surface level. During Intensive Operating Periods (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. The heights of the sonics were between 2.0 and 2.5 m above ground level (agl). 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 within the central part of the street canyon (Figs. 3a and b). For this study, we have used the lowest sonics (or 2nd lowest for the OU towers) which are between 2.5 and 3.5 m agl. In each of the Park-

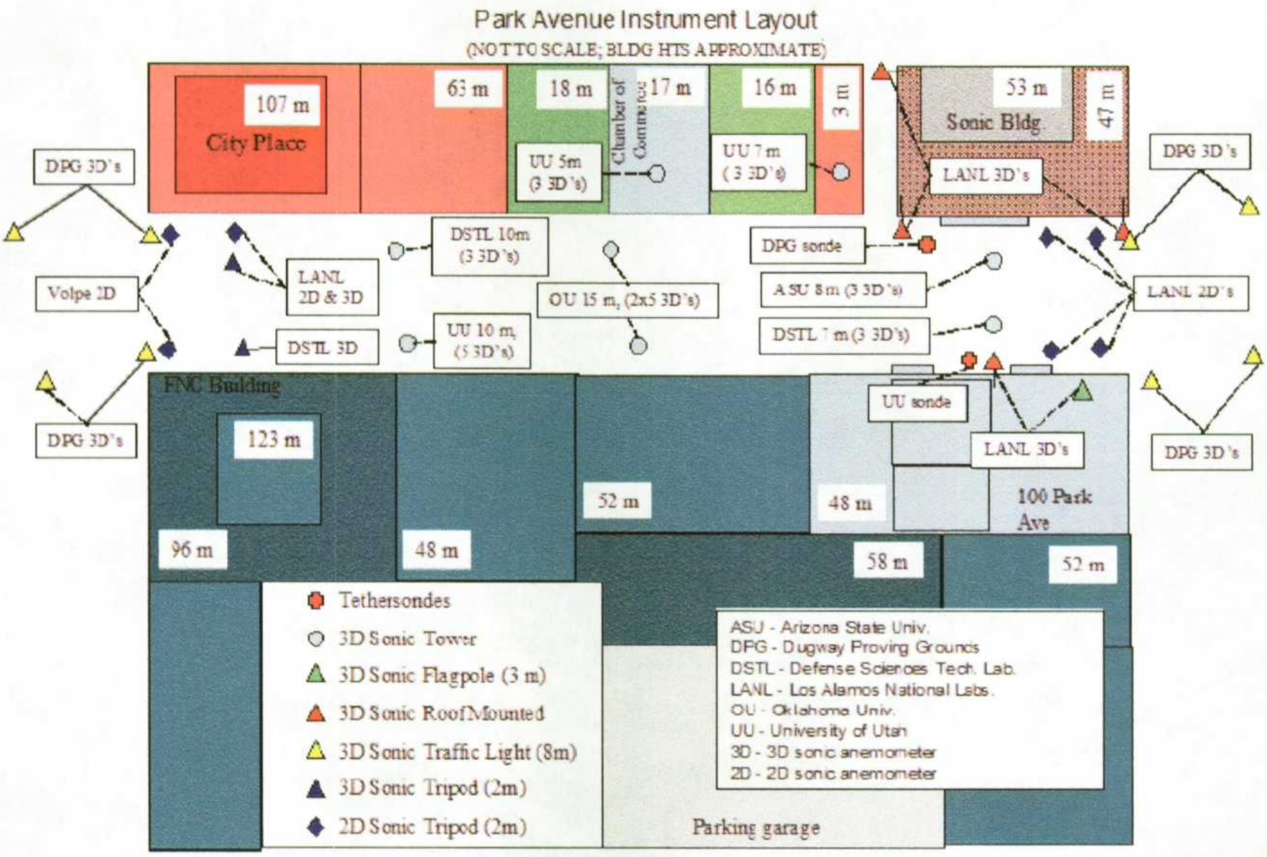

Figure 2. Sketch of the instrument layout in the Park Avenue street canyon. All instruments in place during the entire month of July, except the tripod-mounted sonics and tethersondes that operated only during the Intensive Operating Periods. Note: buildings and instrument locations not to scale.

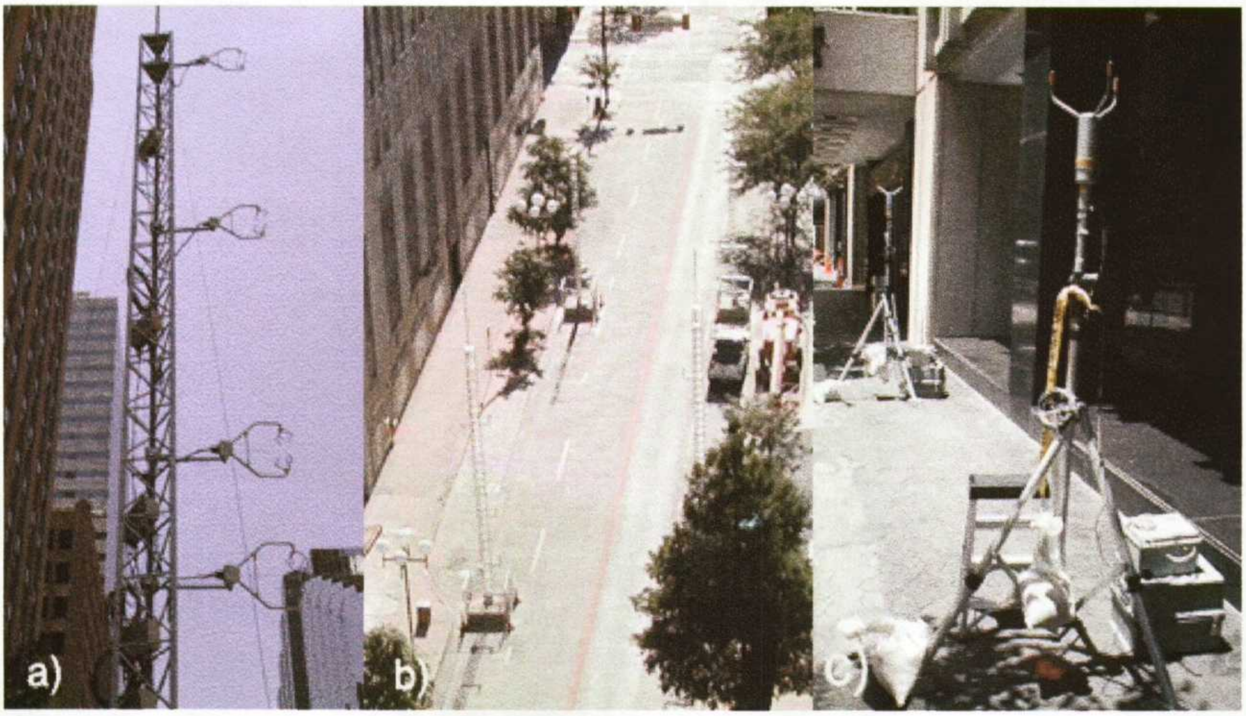

Figure 3. a) Campbell 3D sonics on the UU 10 m tower in Park Ave, b) Park Ave. viewed from the east with the two OU 15 m towers in the foreground and two UU/DSTL 10 m towers in the background, and c) 2D sonics on the northeast end of Park Avenue at the base of the Sonic Building. Photo a) courtesy of Aaron Kennedy.

Table 1. Wind Sensor 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, 7_, 10m	western end of Park Ave. south side of street	Entire period	UU RM Young
10 m tower (street)	3 - 3D sonics 3, 5, 10 m	western end of Park Ave. north side 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	4 story bldg on north side of Park Ave.	Entire period	UU Campbell
8 – Traffic & street light towers	8 - 3D sonics 8 m	Park-Robinson and Park-Broadway intersections	Entire period	DPG RM Young
tripods – street	7 - 2D sonics, 2 - 3D sonics 2-2.5 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

Robinson and Park-Broadway street intersections, there were four 3D sonics mounted on street and traffic lights. These sonics were at 8 m agl.

The 3D sonics all recorded data at 10 Hz, while the 2D sonics operated at either 1 or _ Hz. A more complete description of the instrumentation used in the street canyon experiment can be found in Brown et al. (2003). Ambient wind conditions were obtained from the 250 m level of the PNNL sodar located 2 km south-southwest of downtown Oklahoma City.

4. RESULTS AND DISCUSSION

Winds during the IOP's were predominately from the south. The east-west running street canyon was often found to contain light surface-level winds, except near the intersections at each end of the street. In order to obtain a picture of the average behavior of the horizontal flow within the canyon we have plotted wind roses for each of the near-surface wind sensors for each IOP.

Figure 4a shows the wind roses for a "typical" case, IOP 6, with the ambient winds (as measured by the PNNL sodar at 250 m agl) being primarily southerly $\pm 30^{\circ}$. For a majority of the IOP's, the wind sensors at each end of the street near the intersection show winds on average flowing in opposite directions on the north and south sides of the street, perhaps indicative of a horizontally-rotating corner vortex as postulated by Hoydysh et al. (1974). As shown in Fig. 4, these horizontal eddies have opposite rotation at each end of the street with stronger winds on the north side and lighter, more variable winds on the south side. Note that the greater variability in wind direction on the south side of Park Avenue at the western end (the Volpe 2 and DSTL 7 sonics) as compared to the eastern end of the street (the LANL black and white sonics) is more likely due to poor wind sensor resolution by the latter (0.1 vs. 0.01 m/s), than actual wind fluctuation differences. Looking at the western half of Park Avenue, the measurements show that the winds on the southern side of the street (the UU and OU tower 2 sonics) switch direction with distance into the canyon and quasi-unidirectional flow develops similar to the idealized street canyon wind-tunnel measurements of Kastner-Klein et al. (2004) shown in Fig. 4b.

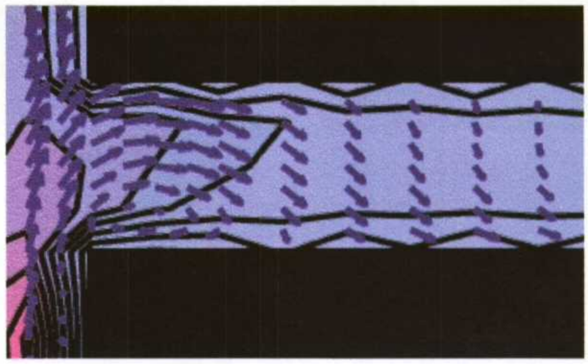

Figure 4b. Wind measurements in horizontal plane obtained in meteorological wind tunnel street canyon experiments by Kastner-Klein et al. (2004).

The end vortex may be induced by the lateral fluctuations of the strong southerly winds channeled in the north-south running streets of Broadway and Robinson, such that momentum is intermittently injected into the canyon as the mean wind hits the north wall and is deflected laterally. The wind roses obtained from the four sonics in the intersection (Fig. 5) suggest that the mean wind deflects towards the Park Avenue street canyon opening. This may result naturally from the expansion of the channeled flow as the wind travels north confined at first on both sides by buildings and then as the air reaches the street intersection it deflects outwards as the volume expands.

For several IOP's, east-west channeling appeared. Our thought was that channeling would occur down the entire length of the canyon when prevailing winds aloft became more southeasterly or southwesterly. As seen in our data, however, channeling did not occur along the complete length of the street canyon, rather channeling occurred on one end of the street and a corner vortex on the other end. IOP 8 illustrates this phenomenon for a southeasterly flow aloft (WD = 150 – 175) with a corner vortex on the eastern end of Park Avenue and channeling on the western end (Fig. 6). What is very interesting and markedly different during this IOP is the behavior of the flow in the interior of the canyon on the western end with north and north-westerly flow components at the UU and OU sonic locations. The vertical variation of the mean flow on these towers for this IOP needs to be examined. IOP 7 displays the opposite flow behavior at the street ends, with an end vortex developing on the western end of Park Avenue and channeling occurring on the eastern end (Fig. 7). The ambient winds for this case have a

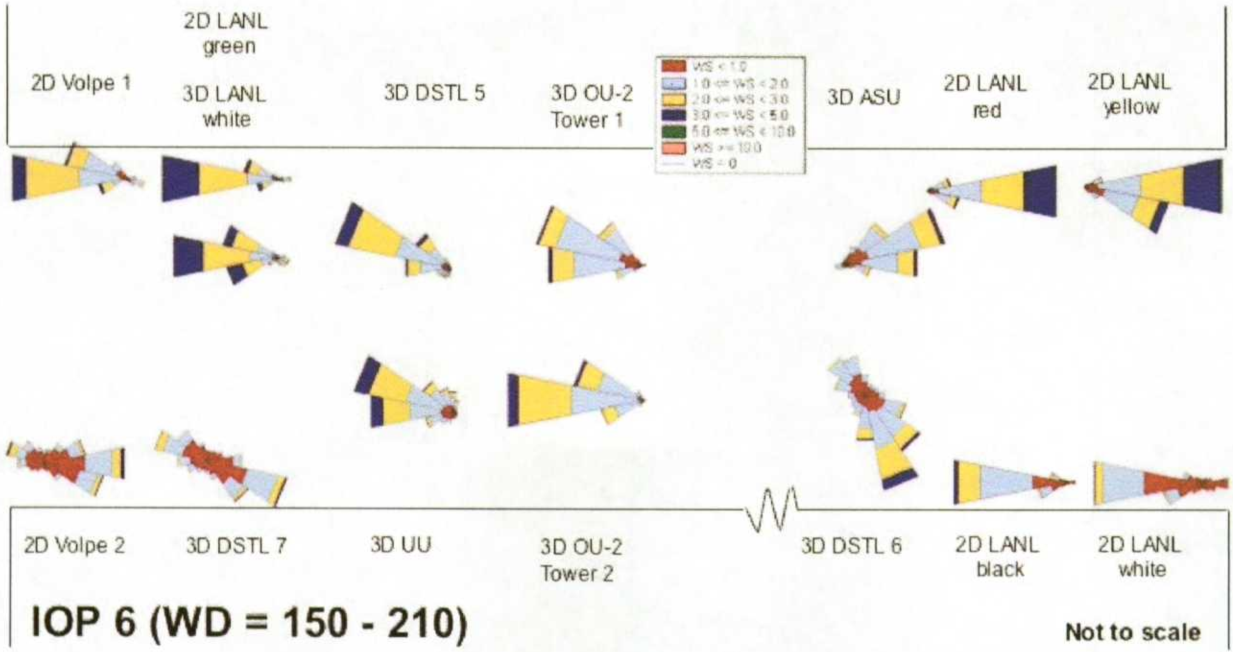

Figure 4a. Wind roses for the near-surface sonic anemometers in Park Avenue for IOP 6 (July 16, 8 am – 6 pm CDT). The winds aloft as measured at 250 m agl by the PNNL sodar are southerly between 150 and 210 degrees.

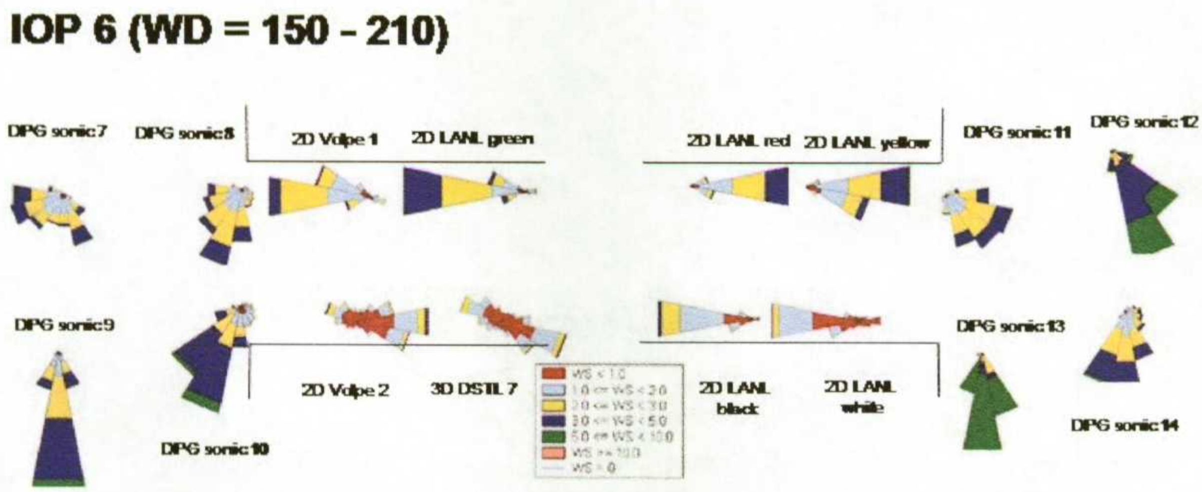

Figure 5. Wind roses for the near-surface sonic anemometers at the Park Avenue-Robinson intersection (left) and the Park Avenue-Broadway intersection (right) for IOP 6 (July 16, 8 am – 6 pm CDT). The winds aloft as measured at 250 m agl by the PNNL sodar are southerly between 150 and 210 degrees.

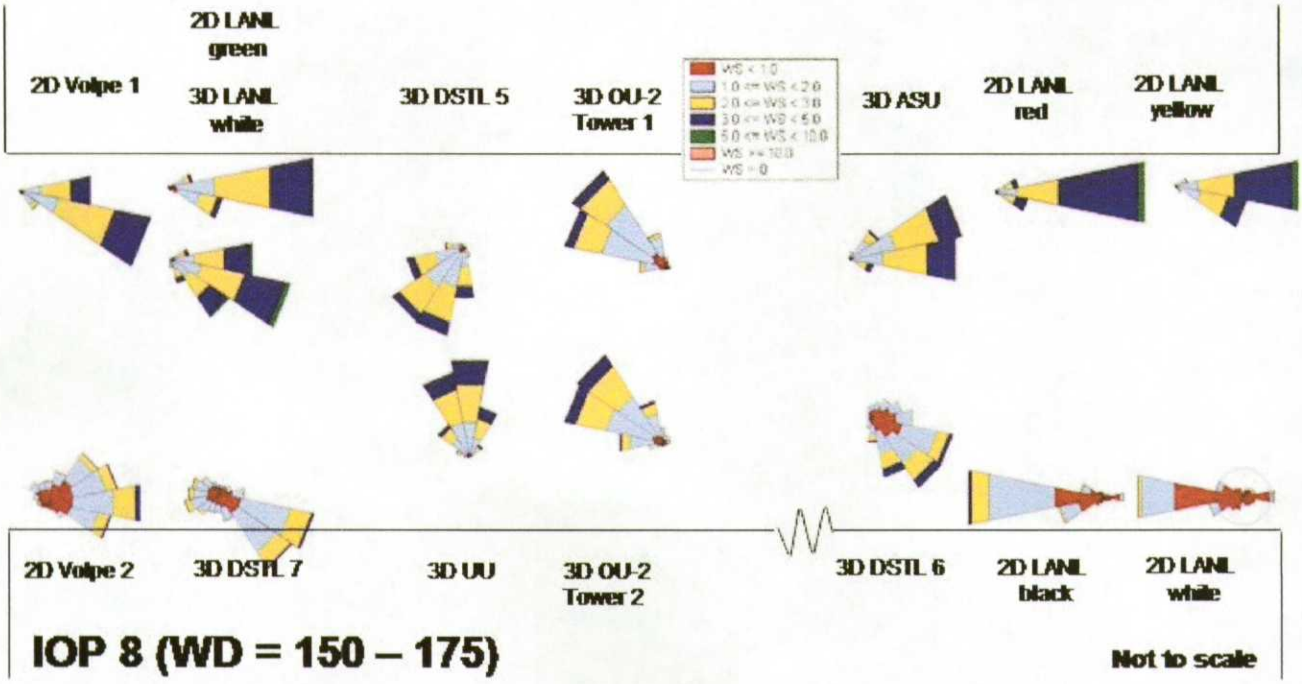

Figure 6. Wind roses for the near-surface sonic anemometers in Park Avenue for IOP 8 (July 24, 8 pm – July 25, 8 am). The winds aloft as measured at 250 m agl by the PNNL sodar are south-southeasterly between 150 and 175 degrees.

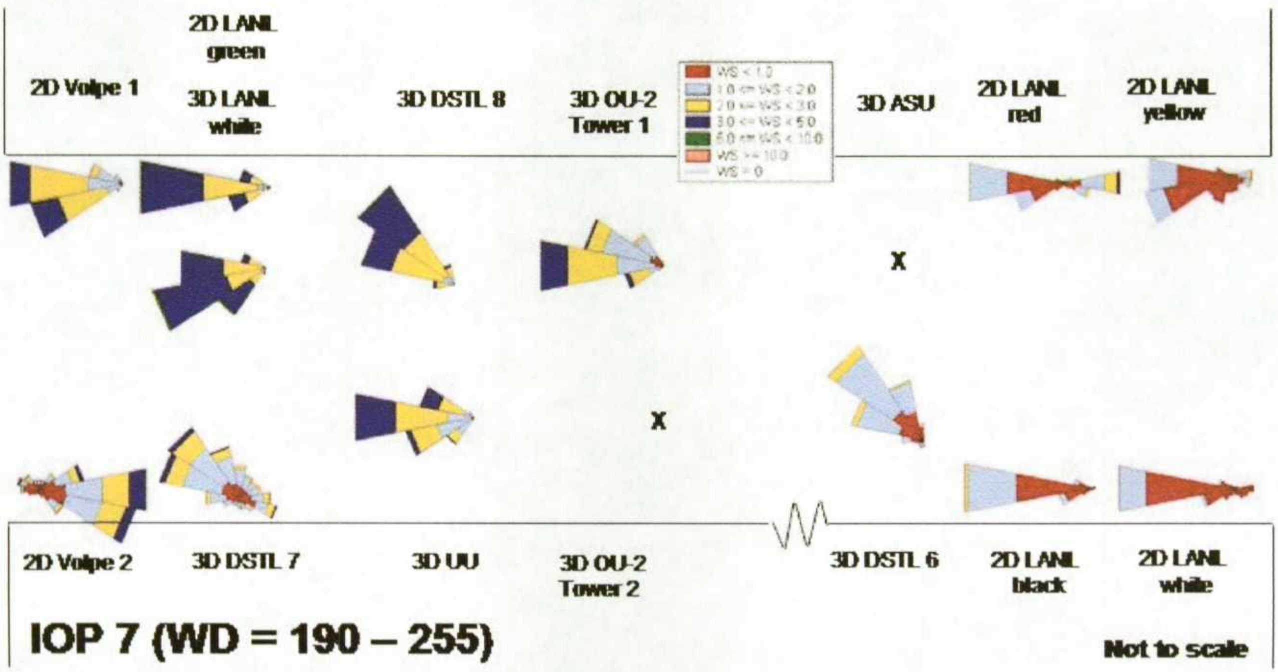

Figure 7. Wind roses for the near-surface sonic anemometers in Park Avenue for IOP 7 (July 18, 10 pm – July 19, 8 am). The winds aloft as measured at 250 m agl by the PNNL sodar are south-southwesterly between 190 and 255 degrees.

more southwesterly component (190-255). Although the ASU sonic does show a northerly component and hints that the behavior in the interior on the eastern half of Park Avenue may mirror that on the western half as seen in IOP 7, this cannot be confirmed as there are no wind sensors there (note that the positions of sensors in the drawings are not to scale). However, it should be pointed out that the flow behavior should not necessarily be symmetric with respect to a variation about a southerly inflow because the street canyon is non-ideal (e.g., tall and short buildings define the street canyon, there is an alley way on the northern side of the street at the eastern end, more trees at the eastern end of Park Avenue, an upwind tall building and downwind tall building that might deflect the flow).

The remainder of the IOP's show similar features as in the "typical" IOP 6 case. As shown in Table 2, what we are surmising to be a corner vortex occurred a majority of the time. At the east end of Park Avenue a corner vortex occurred seven of the ten IOP's, while it appears to have occurred on the western end eight of the ten IOP's. For two IOP's, channeling occurred at one end of the street, i.e., winds on both sides of the street blew in the same direction (as shown in Figs. 6 and 7), while the other two IOP's showed split behavior. However, there are particular sonic wind roses that exhibit a peculiar behavior and are hard to immediately explain.

Table 2. Flow features by IOP and WD

IOP	West End	East End	Ambient WD
1	Mixed?	Mixed	N/A
2	End Vortex?	End Vortex?	180-240
3	End Vortex	End Vortex	180-210
4	End Vortex	End Vortex	180-220
5	Mixed	End Vortex	130-300
6	End Vortex	End Vortex	150-210
7	End Vortex?	Westerly Channeling	190-255
8	Easterly Channeling	End Vortex	150-175
9	End Vortex	End Vortex	170-215
10	End Vortex	Mixed	160-360

Similar analyses will be performed in the future using the remainder of the wind sensors on the towers and on building rooftops in order to get a better idea of the plan view flow behavior in the entire street canyon. Further analyses will include conditional sampling, where flow patterns are investigated as a function of the inflow wind direction. There also may be dependence on wind speed and stability. Figures 8 and 9 illustrate preliminary results from conditional sampling. For IOP 5, we sampled sonic data only when the ambient wind direction as measured by the PNNL sodar was between 130 and 180 (Fig. 8) and between 180 and 270 (Fig. 9). For the former case, we obtain channeling at the western end of the street, while in the latter case and end vortex is found. Continued analyses of this type will help to meet our longer-term goal of determining when different street canyon flow conditions occur as a function of the ambient winds aloft.

5. CONCLUSIONS

A large number of wind sensors were placed in the east-west-running Park Avenue street canyon during the Joint URBAN 2003 field experiment in Oklahoma City. In order to study the horizontal flow patterns, a subset of the 2D and 3D sonic anemometers were placed near ground level in the canyon.

Wind roses were created to visualize the horizontal wind flow during intensive operating periods. During the IOP's, winds were primarily from the south. The data show that horizontally-rotating corner vortices are likely to occur at the street ends when the wind has a strong southerly component. In addition, channeling was found for several cases, but channeling across the entire canyon was found to be rare.

Future work will include conditionally sampling the wind data in order to help determine under what conditions corner vortices and channeling are most likely to occur. This dataset provides a unique opportunity for better understanding horizontal flow patterns in a real street canyon.

Acknowledgements. The street canyon experiment was a collaborative effort involving the University of Utah, Oklahoma University, Arizona State University, University of Central Florida, Volpe, Dugway Proving Ground, UK Defence Sciences Technology Laboratory, and Los Alamos National Laboratory. We are especially indebted to street canyon co-planners Eric Pardyjak and Petra Kastner-Klein, and Joint Urban project leader Jerry Allwine. This work was supported under the Department of Homeland Security's Biological Counter-measures program.

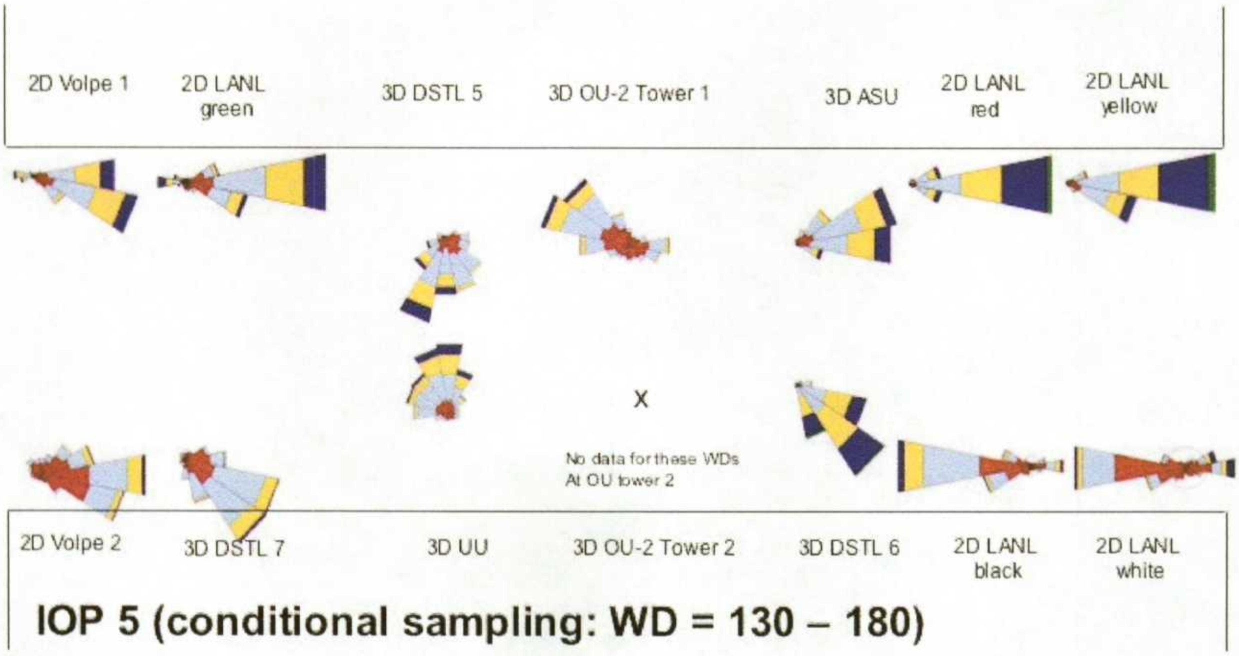

Figure 8. Wind roses after conditional sampling for the near-surface sonic anemometers in Park Avenue for IOP 5 (July 13, 7 am – 6 pm). The winds aloft as measured at 250 m agl by the PNNL sodar varied from 130 to 300 degrees during this experiment, but only the data is being plotted for when the upper-level winds are between 130 and 180 degrees.

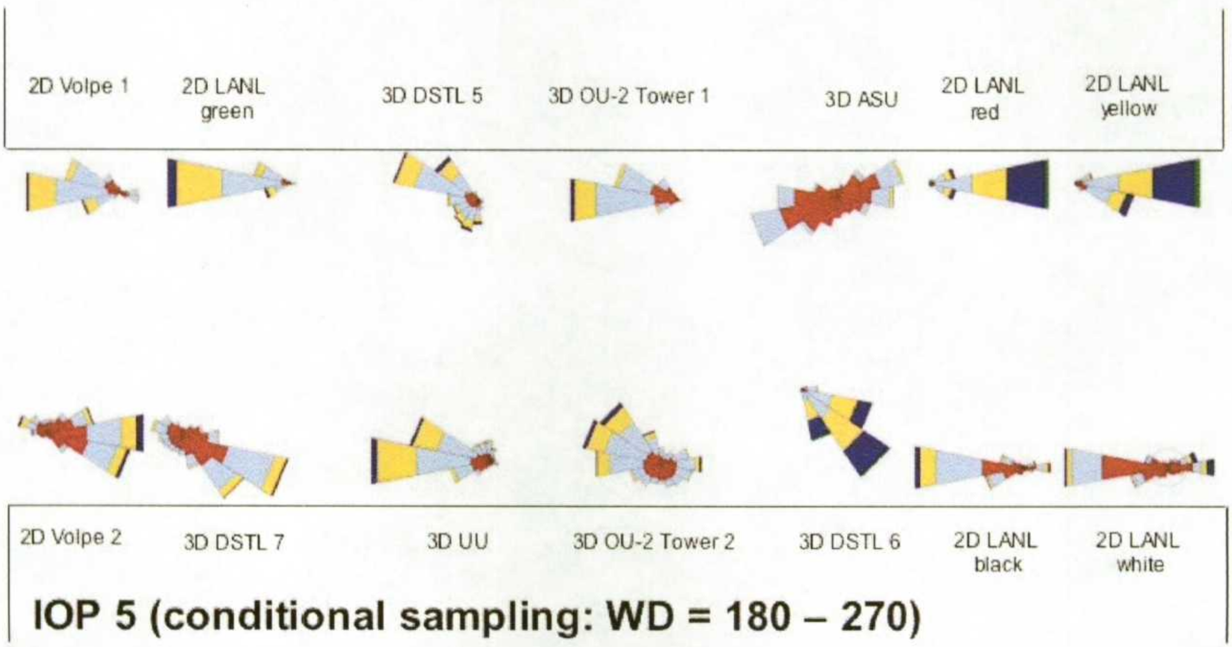

Figure 9. Wind roses after conditional sampling for the near-surface sonic anemometers in Park Avenue for IOP 5 (July 13, 7 am – 6 pm). The winds aloft as measured at 250 m agl by the PNNL sodar varied from 130 to 300 degrees during this experiment, but only the data is being plotted for when the upper-level winds are between 180 and 270 degrees.

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