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Flow Patterns at the Ends of a Street Canyon: Measurements from the Joint Urban 2003 Field Experiment

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1. Introduction

As part of the Joint Urban 2003 tracer experiment conducted in Oklahoma City in July of 2003, a relatively high concentration of wind sensor equipment was deployed within a one block of Park Avenue street canyon during intensive operation periods (IOP's). These included sonic anemometers placed near ground level, on towers, and just below roof-level, and tethersonde systems operated in ladder mode adjacent to building walls in the street canyon. The wind sensors at each end of the street near the intersection often showed winds on average flowing in opposite directions on the north and south sides of the street, perhaps indicative of a horizontally-rotating corner vortex (Brown et. al. 2004). This study focuses on understanding the relationship between the upper-level wind direction and the presence of end vortices in the Park Avenue street canyon. Further, the study of the vertical extent of the end vortices through the whole depth of the street canyon is also explored. We begin by providing a short background on street canyon circulations and end vortices, followed by a brief description of the Joint Urban 2003 field experiment, and ending with the experimental results.

2. Background

When the wind is nearly perpendicular to the street between two rows of buildings, it is well known that a vertically-rotating cylindrical vortex with its central axis horizontally-aligned to the street often forms in the street canyon (DePaul and Sheih, 1986). The presence of the street canyon vortex can significantly alter the ventilation and the local pollution patterns within the street (e.g., Yamartino et al., 1989). 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.

Street intersection smoke visualization wind-tunnel experiments by Hoydysh et al. (1974) revealed horizontally-rotating vertically-aligned eddies at the end of the street canyon near the intersection. These "corner" or "end" vortices were shown extending up the entire side of the building in a spiral and interacting with the in-canyon vortex in the interior of the street canyon. Recently, Kastner-Klein et al. (2004) directly measured these end vortex motions in wind-tunnel experiments 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. End vortices may have also been identified in full-scale outdoor experiments by Brown et al. (2004). They found winds at street level on the opposite side of the street blowing in opposite directions, revealing what appears to be a horizontally-rotating eddy (Fig. 1). The details of the experiment and this particular street are given later in this paper.

Wind-tunnel dispersion experiments by Cermak et al. (1974), Hoydysh and Dabberdt (1988), and Hayden et al. (2002) have all implicated corner vortices as significantly impacting the concentration levels on the leeward side of the canyon at each end of the street. Presence of such lateral recirculation zones may result in modified ventilation of the street canyon causing changes in pollutant levels within (Kastner-Klein P. et al., 2004). Since the street canyon forms a basic geometric unit which can be used to construct larger urban structures (Terjung and Louie, 1973; Nunez and Oke, 1977), the study of such flow characteristics in an urban street canyon becomes highly relevant.

3. Experimental Description

With the goal of gathering high resolution wind field and dispersion data in a city, the Defense Threat Reduction Agency (DTRA) and the Department of Homeland Security (DHS) joined in an effort to conduct the Joint Urban 2003 atmospheric dispersion experiment in Oklahoma City in July 2003. Meteorological and tracer measurements were made in and around downtown of Oklahoma City at around 200 locations (Alwine et. al., 2004). As a part of the Joint Urban 2003 experiment, a street canyon sub-experiment was performed with relatively high concentration of sensor equipment deployed within a one block section of an east-west

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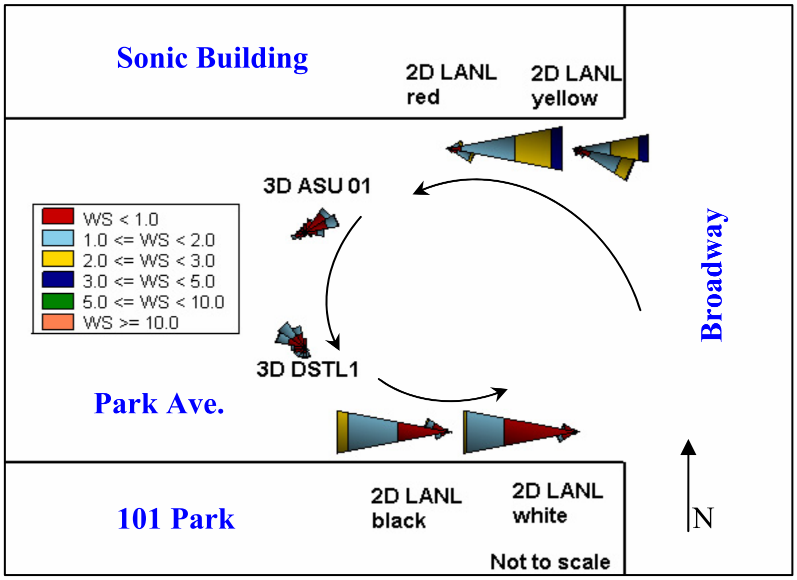

Figure 1: Wind rose plots indicating the presence of an end vortex at one of the street ends for a half hour period on IOP 06 (July 16, 2003, 09:00-09:30 hrs. CDT). Measurements obtained during the Joint Urban 2003 field experiment.

running two lane street called the Park Avenue street canyon (Brown et al., 2003). This sub-experiment included participants from the University of Utah (UU), Arizona State University, Oklahoma University, Volpe, the U.K. Defense Sciences Technology Laboratory (DSTL), the US Army's Dugway Proving Ground (DPG), and Los Alamos National Laboratory (LANL).

Fig. 2 is a sketch of the Park Avenue street canyon showing approximate building heights and the instrument locations used to identify the end vortices. The approximately 150 m long and 24 m wide Park Avenue street canyon consisted of tall buildings on the western end of the street, a low section of buildings in the middle of the canyon on the northern side, a 3m wide alley lane opening on the north side at the eastern end, and a few trees at the east end. It was therefore not an idealized street canyon, but nevertheless a "typical" US city urban street canyon. Vehicular traffic was allowed during the whole period of the experiment; however, at most times the traffic was light and at low speeds.

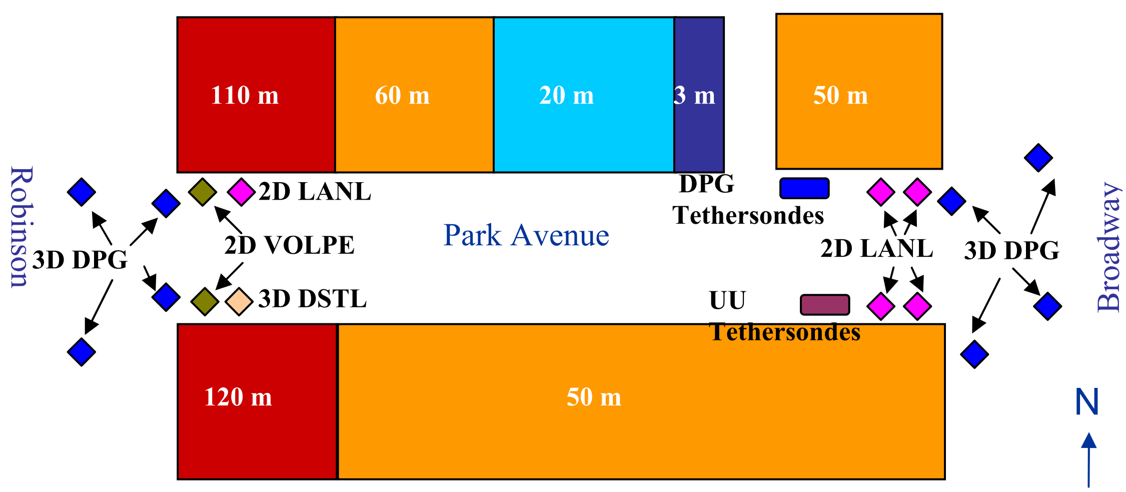

Figure 2: Plan view of the Park Avenue street canyon showing approximate building heights and sonic anemometer and tethersonde locations used to identify the end vortices (figure not to scale).

At the east end of the street canyon, four 2D sonic anemometers were mounted on tripods at a height of about 2m above ground level (agl) and four 3D sonic anemometers were attached to traffic lights at the Park Avenue-Broadway Street intersection at about 8m above ground level. Tethersondes were draped over the sides of the buildings on either side of the street at the east end of the street canyon and operated in ladder mode. Velocity measurements were made using the tethersondes at 1, 5, 10, 20, 30 and 40 m above ground level using cup anemometers. Fig. 3 shows the relative distances between the instruments and the building walls at the eastern side of the street canyon.

At the west end of the street canyon, one 3D and three 2D sonic anemometers were mounted on tripods at a height of about 2m above ground level and four 3D sonic anemometers were attached to traffic lights at the Park Avenue-Robinson Street intersection at about 8m above ground level. Fig. 4 shows the relative distances between the instruments and the building walls at the western side of the street canyon.

Table 1 lists the characteristics of the instruments (e.g., make of instrument, sampling rate and height agl). The sonic anemometers and tethersondes were operated only during the IOP's. These IOP's occurred during the day and night (see Table 2).

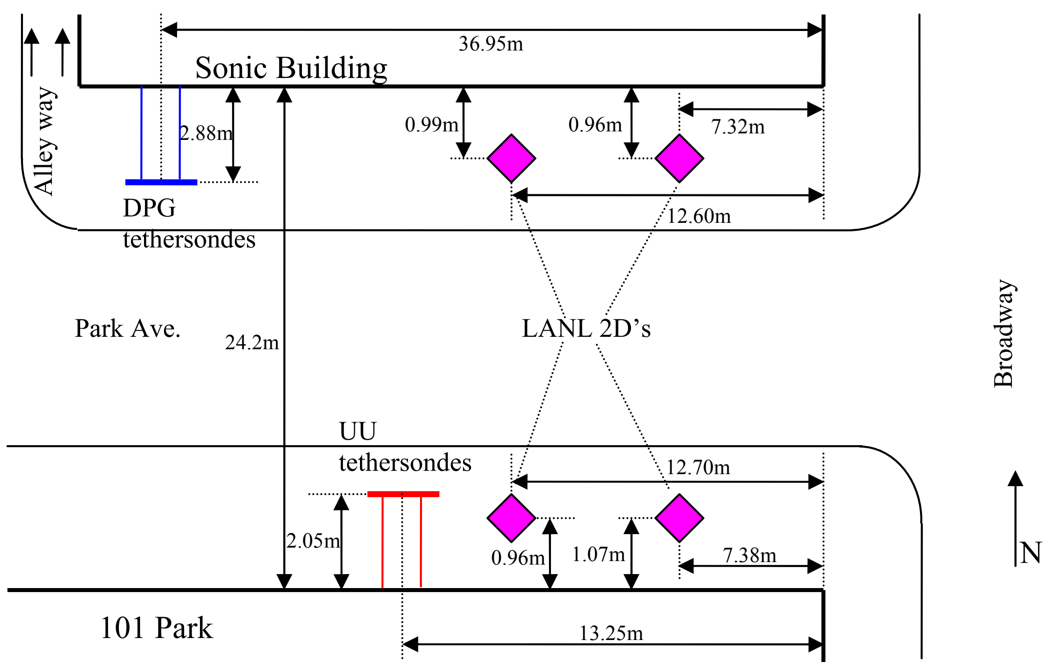

Figure 3: Instrument locations relative to building walls at the eastern side of the Park Avenue street canyon. Sonic were places on tripod stands about 2m above ground level. Tethersondes were placed on each side of the street at heights about 1, 5, 10, 20, 30 and 40m. Figure not to scale.

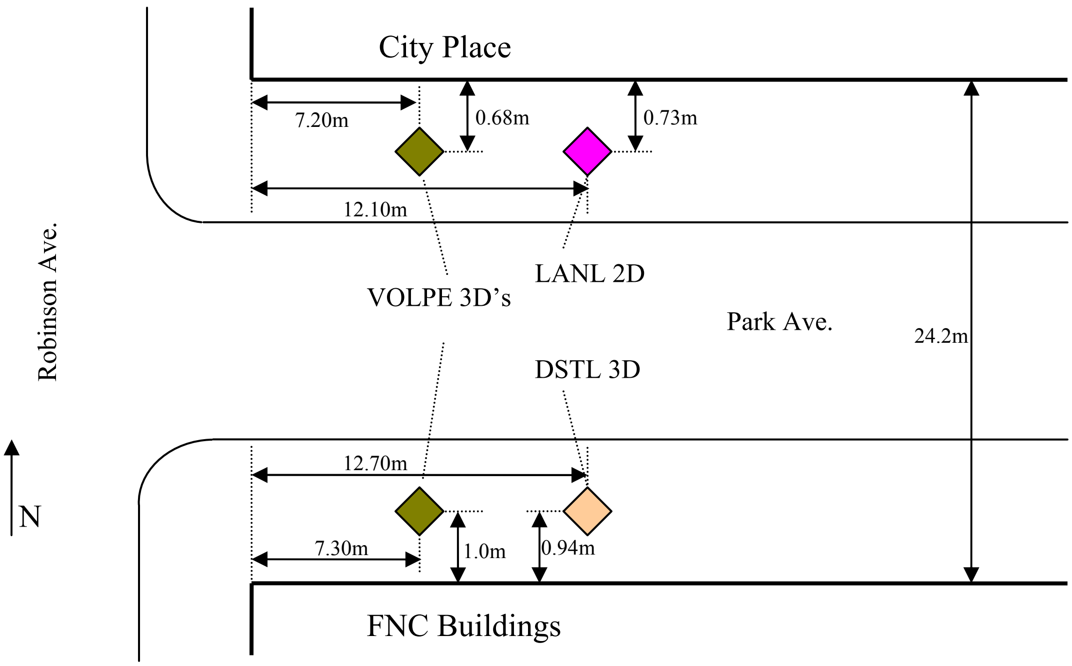

Figure 4: Instrument locations relative to building walls at the western side of the Park Avenue street canyon. Sonic were places on tripod stands about 2m above ground level. Figure not to scale.

Table 1: Instrument Characteristics.

Instrument	Height (m agl)	Manufacturer	Sampling rate
LANL 2D's	2	HANDAR 425 A ultrasonic anemometer	0.5 Hz.
VOLPE 3D's	2	METEK ultrasonic anemometer	1.0 Hz
DSTL 3D	2	Gill ultrasonic anemometer	1.0 Hz.
DPG tethersondes	1, 5, 10, 20, 30 and 40	Vaisala cup anemometers	0.05-0.1 Hz.
UU tethersondes	1, 5, 10, 20, 30 and 40	Vaisala cup anemometers	0.05-0.1 Hz.

Table 2: Joint Urban 2003 Intensive Operating Periods.

IOP	Start Time (CDT)	End Time (CDT)
IOP 03	July 07 09:00	July 07 17:00
IOP 04	July 09 09:00	July 09 17:00
IOP 05	July 13 09:00	July 13 17:00
IOP 06	July 16 09:00	July 16 17:00
IOP 07	July 18 22:00	July 19 06:00
IOP 08	July 24 22:00	July 25 06:00
IOP 09	July 26 22:00	July 26 06:00
IOP10	July 28 22:00	July 29 06:00

4. Analysis and Discussion

In order to ascertain the predominant flow patterns at the street canyon ends, the time series velocity data from all the Intensive Operating Periods were used without any time averaging to obtain wind roses for each wind sensor. Flow patterns were determined under different ambient flow conditions through conditional sampling, i.e., wind roses were computed when upper-level winds fall within specific wind direction intervals. The Pacific Northwest National Laboratory (PNNL) SODAR located about 2 km south of the Park Avenue street canyon was used to specify the upper-level wind direction. The fifteen minute time-averaged winds measured at 250 m were chosen for our analyses since they should provide information about the undisturbed flow conditions. Even for northerly wind directions, for which the SODAR is located downwind of the downtown core, the urban influence on the wind direction measurements at 250 m height can be assumed to be small (Kastner-Klein and Clark, 2004).

a. East End of Park Avenue Street Canyon:

Fig. 5 shows the wind roses for the near-surface sonic anemometers near the Park Avenue-Broadway intersection for upper-level winds between 150° and 215°. The wind roses were obtained using 42.5 hours of data from all the IOP's. One can clearly see that the wind direction on the northern side of the street is opposite to that on the southern side and also stronger, perhaps indicating the presence of a horizontal counter-clockwise-rotating vortex at the east end of the street for these upper-level wind directions. The DPG sonic #13 shows that fairly strong south-to-north channeling is present along Broadway. At the Park Avenue intersection the wind has a significant easterly component (DPG #11) resulting in a fraction of the channeled wind hitting the northern wall and by mass conservation perhaps driving the end vortex.

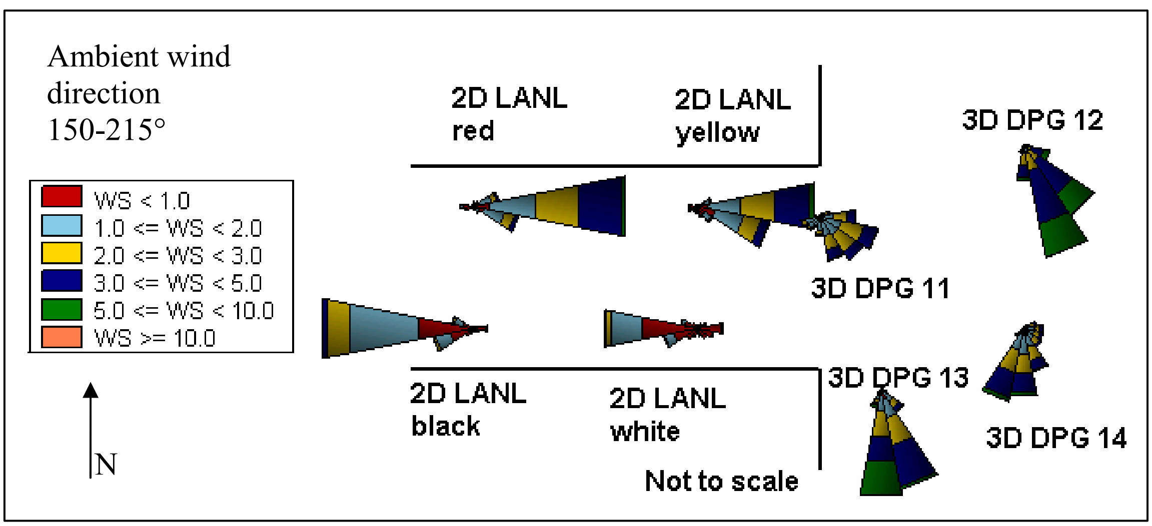

Figure 5: Wind roses for the near-surface sonic anemometers at the Park Avenue-Broadway intersection possibly revealing an end vortex at the east end of the Park Avenue street canyon. The winds aloft measured at 250 m above ground level by the PNNL SODAR are southerly between 150° and 215°.

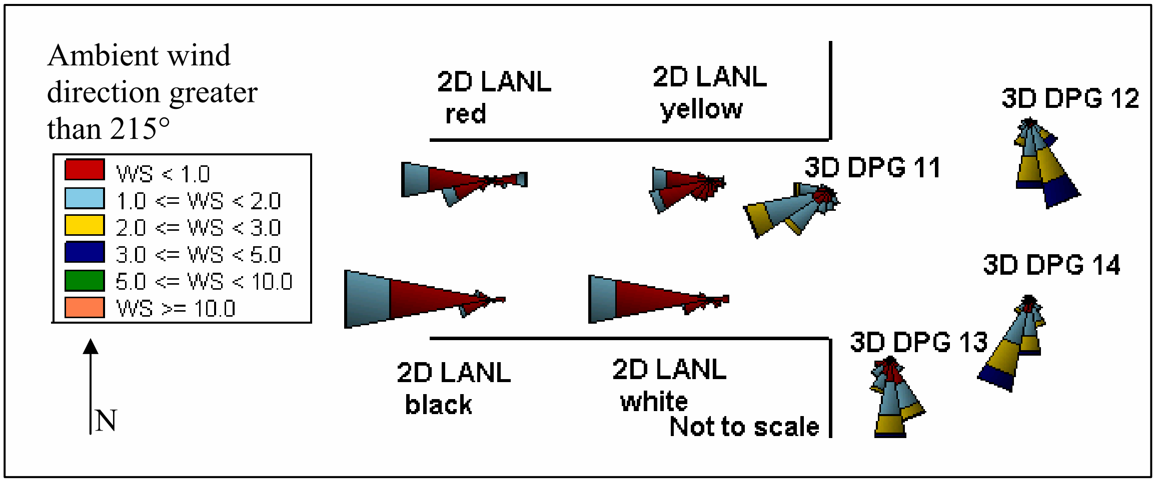

Figure 6: Wind roses for the near-surface sonic anemometers at the Park Avenue-Broadway intersection at the east end of the Park Avenue street canyon. The winds aloft are measured at 250 m above ground level by the PNNL SODAR are southwesterly and above 215°. For these ambient wind conditions, no end vortex is found.

Fig. 6 shows the wind roses for the near-surface sonic anemometers near the Park Avenue-Broadway intersection for upper-level winds greater than 215° (outside the range between 150° and 215°). The wind roses were obtained using 8.25 hours of data from all the IOP's. The wind direction on both sides of the street is westerly indicating that the end vortex does not exist for these ambient wind conditions. The wind rose at the intersection (DPG #11) indicates that the wind flows from the street canyon towards the intersection, opposite to that found when the end vortex exists. During the IOP's, prevailing winds aloft were seldom less than 150°, thus a definite range of upper-level wind direction could not be established for when the end vortices form at the east end of the Park Avenue street canyon.

b. West End of Park Avenue Street Canyon:

Fig. 7 shows the wind roses for the near-surface sonic anemometers near the Park Avenue-Robinson intersection for upper-level winds between 180° and 240°. The wind roses were obtained using 39.5 hours of data from all the IOP's. One can clearly see that the wind direction on the northern side of the street is opposite to that on the southern side, perhaps indicating the presence of a horizontal clockwise-rotating vortex at the west end of the street for these upper-level wind directions. The DPG sonic #09 shows that fairly strong south-to-north channeling is present along Robinson. At the Park Avenue intersection the wind has a significant westerly component (DPG #07, 08, and 10) resulting in a fraction of the channeled wind hitting the northern wall and by mass conservation perhaps driving the end vortex. These observations are similar to those at the east end of the street canyon.

Fig. 8 shows the wind roses for the near-surface sonic anemometers near the Park Avenue-Robinson intersection for upper-level winds between 150° and 180° (outside the range between 180° and 240°). The wind roses were obtained using 8.25 hours of data from all the IOP's. The wind direction on both sides of the street is most often easterly indicating that the end vortex does not exist for these ambient wind conditions. The wind rose observed at the northwestern edge of the street canyon (Volpe #1) shows that there is mixed flow regime or significant intermittency for this upper-level wind direction range. The wind rose plots in the street intersection (DPG #07, 08, and 10) show that the winds in the intersection have more of an easterly component, opposite to the case when the end vortex forms. During the IOP's, prevailing winds aloft were seldom less than 150°, thus a definite range of upper-level wind direction could not be established for when the end vortices form at the west end of the Park Avenue street canyon.

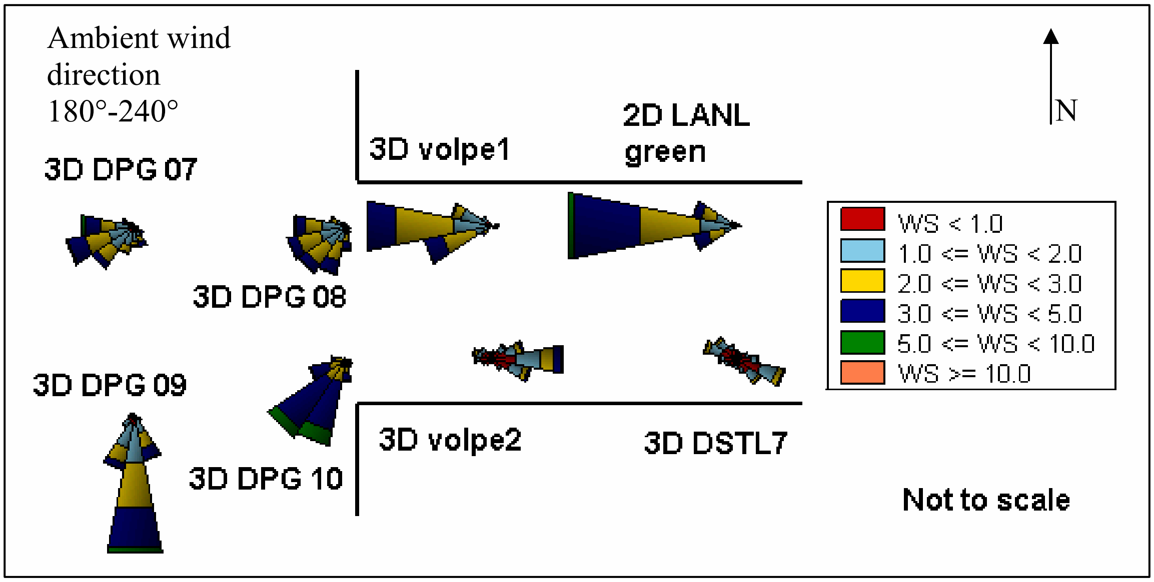

Figure 7: Wind roses for the near-surface sonic anemometers at the Park Avenue-Robinson intersection possibly revealing an end vortex at the east end of the Park Avenue street canyon. The winds aloft are measured at 250 m above ground level by the PNNL SODAR are southerly between 180° and 240°.

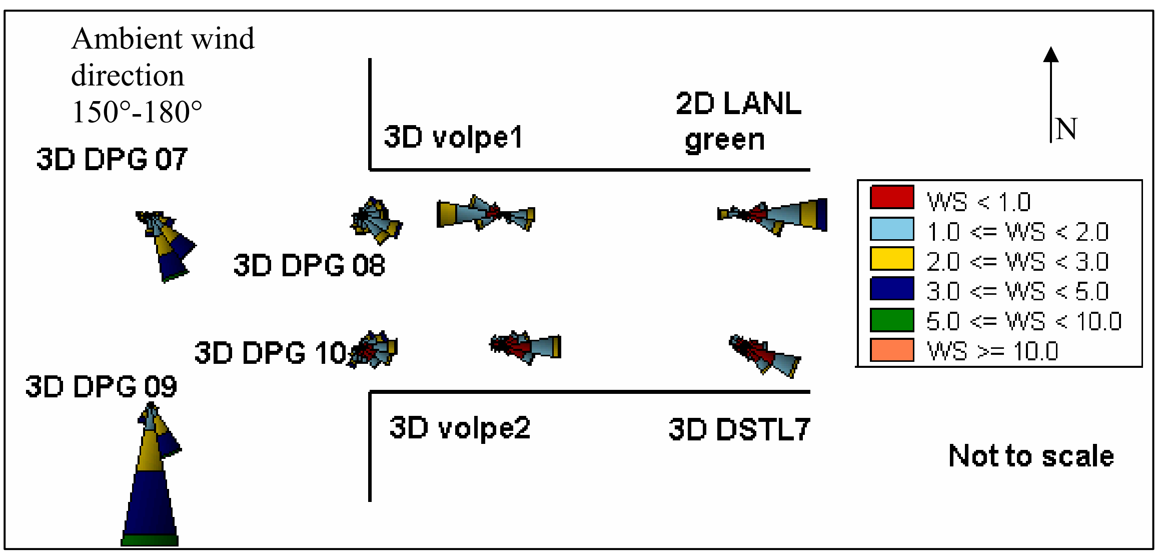

Figure 8: Wind roses for the near-surface sonic anemometers at the Park Avenue-Robinson intersection s at the east end of the Park Avenue street canyon. The winds aloft are measured at 250 m above ground level by the PNNL SODAR are southeasterly between 150° and 180° . For these ambient wind conditions, no end vortex is found.

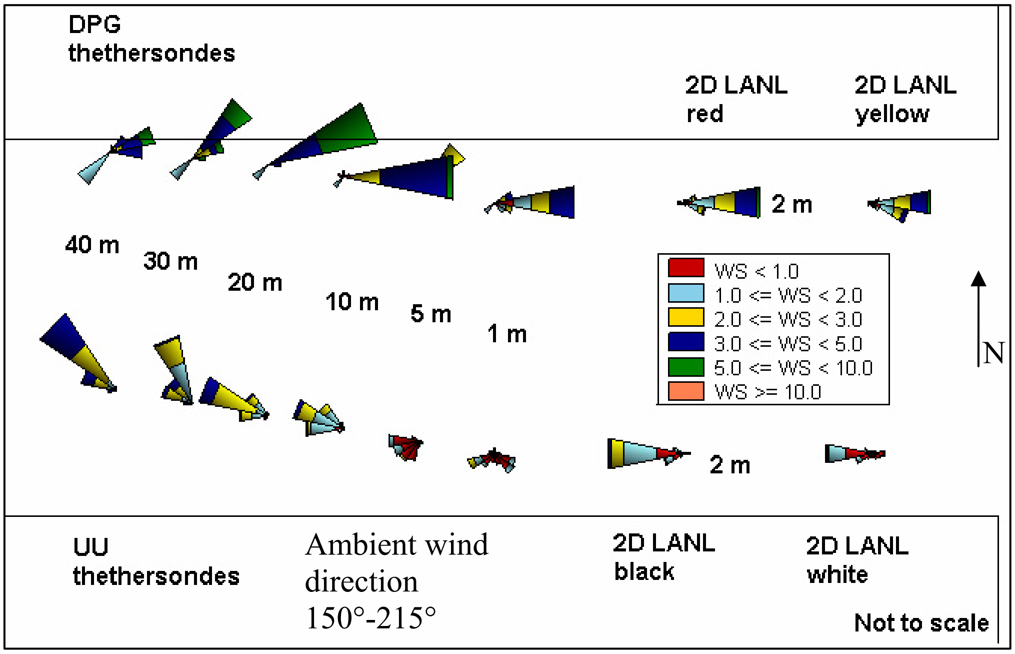

Figure 9: Wind roses for the near surface sonic anemometers and ladder-mode tethersondes at the Park Avenue-Broadway intersection possibly revealing an end vortex through the depth of the street canyon. The winds aloft are measured at 250m above ground level by the PNNL sodar and are southeasterly between 150°-215°.

c. Vertical Extent of End Vortex

Does the end vortex extend through the depth of the street canyon? The tethersonde wind measurements located at the eastern end of Park Avenue can be used to help determine the vertical extent of the end vortex. Fig. 9 shows the wind roses for the near-surface sonic anemometers and building-side tethersondes at the eastern end of Park Avenue for upper-level winds between 150° and 215°. The wind roses were obtained using 42.5 hours of data from all the IOP's. The wind roses show that the winds are easterly on the northern side of the street and westerly on the southern side throughout the entire depth of the street canyon, indicating the existence of an end vortex for almost the whole height of the street canyon. Tethersonde measurements on the northern side of the street show an increasing northerly component of wind direction above 20 m with increasing height, while tethersonde measurements on the southern side show an increasing southerly component above 20 m with the increase in height. These observations possibly indicate that the horizontal penetration of the end vortex into the street canyon is reduced with increasing height. Similar analysis could not be performed for other prevailing wind directions due to lack of data.

5. Conclusions

As part of the Joint Urban 2003 Park Avenue Street Canyon sub-experiment, we have identified what appears to be a horizontally-rotating end vortex. The end-vortex was observed at street-level at the western end of the street canyon for upper-level wind directions between 180° and 250°. Uni-directional flow from east to west was apparent at this location for upper-level wind directions between 150° and 170°. At the eastern end of the street canyon, the horizontally rotating vortex like flow pattern was observed for upper-level wind directions between 150° and 215°. For upper-level wind directions greater than 215°, uni-directional flow from west to east was found at the street ends instead of the horizontally-rotating vortex. The wind measurements in the intersections show strong southerly channel flow, but the wind has a component into the street canyon for the cases where the end vortex is formed at the street ends. It is thought that the wind coming into the canyon hits the north wall and drives the end vortex (a clockwise rotating eddy on the western end of the canyon and counter-clockwise on the eastern end). The wind measurements in the intersections show that the southerly channel flow has component out of the street canyon into the street intersection when the end vortex is not formed. Tethersonde measurements on both sides of the street at the eastern end of the street canyon show that the end vortex may exist through the whole depth of the street canyon. However, the horizontal extent of the end vortex may vary with height above the ground level.

6. References

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