J3.3 STRUCTURE OF TURBULENCE IN AN URBAN STREET CANYON

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1. INTRODUCTION

Urban areas usually consist of high concentrations of tall as well as wide buildings, e.g., in downtown areas. Arrangement of such buildings, separated by streets, form urban street canyons. This particular morphology results in modified flow and turbulence structure in the lowest few meters of the urban street canyon, in distinct contrast to flow over ideal and homogenous surfaces (Rotach 1993). There are only a limited number of field observations that deliver information on the mean flow and turbulence characteristics at the lower heights within an urban street canyon (e.g., Kastner-Klein and Rotach 2004; Cheng and Castro 2002). This paper attempts to address phenomena associated with the flow characteristics within the lower heights of a street canyon and the effects of the mean upwind angle on the flow within the canyon.

The present observations indicate that the mean wind direction inside a street canyon (at the measured locations) is under certain conditions highly sensitive to the mean incident wind direction. The direction of vertical transport of horizontal momentum (upward or downward) is also a function of the upwind direction. The heat fluxes are significant in all directions within the canyon (unlike flows in the inertial sublayer).

This study was conducted using data obtained from the Joint Urban 2003 field experiment conducted during July 2003 in Oklahoma City, OK, USA.

2. Experimental Setup

A multi-organization team conducted the Joint Urban 2003 experiment. These groups deployed wind and tracer sensing instrumentation (Brown et al. 2004) at various locations in Oklahoma City. A part of the experiment included a relatively high concentration of instrumentation deployed along Park Avenue, in downtown Oklahoma City.

Park Avenue forms an urban street canyon owing to the fact that it consists of a contiguous arrangement of tall buildings on both sides of the street. Figure 1 shows the placement and type of wind sensing instruments placed in Park Avenue. It also provides descriptive information related to the street canyon morphology in Park Avenue. The Park Avenue street canyon is aligned in the east-west direction.

For this paper, data from the 10 m University of Utah instrument tower was used extensively. This tower supported five 3-dimensional Campbell Scientific sonic anemometers placed at 3.19 m, 4.19 m, 5.04 m, 7.24 m and 9.84 m above ground level. The tower was located 15.61 m south and 118.05 m west of the northeast corner of Park Avenue. The sonic anemometers measured the three components of wind velocity i.e. u, v and w. As per standard meteorological convention:

- u is positive when the wind blows from west to east (along canyon)
- v is positive when the wind blows from south to north (across canyon)
- w is positive when the wind blows away from the ground

The sonic anemometers also measure temperature. An independent measurement of temperature was accomplished through the use of fine wire thermocouples. These were only employed, however, at specific heights and periods. The sampling frequency of the sonic anemometers was 10 Hz. Figure 2 shows photographs of some of the instruments used in the experiment. Figure 2a shows a photograph of 10 m University of Utah instrument tower.

Data from the Indiana University sonic anemometer tower (79.63 m), Pacific Northwest National Laboratory (PNNL) profiler/SODAR and University of Utah (UofU) profiler/SODAR were used to determine the mean direction and speed of the incident upstream wind. The Indiana University tower and the PNNL SODAR were located about 5 km and 2 km south of Park Avenue respectively. The University of Utah SODAR was placed on top of a parking structure located at the intersection of N. Broadway Avenue and Robert S. Kerr Avenue (about two blocks NE of Park Avenue).

Information relating to the detailed placement of other instruments and the groups that participated in the experiment can be obtained from Brown et al. (2004).

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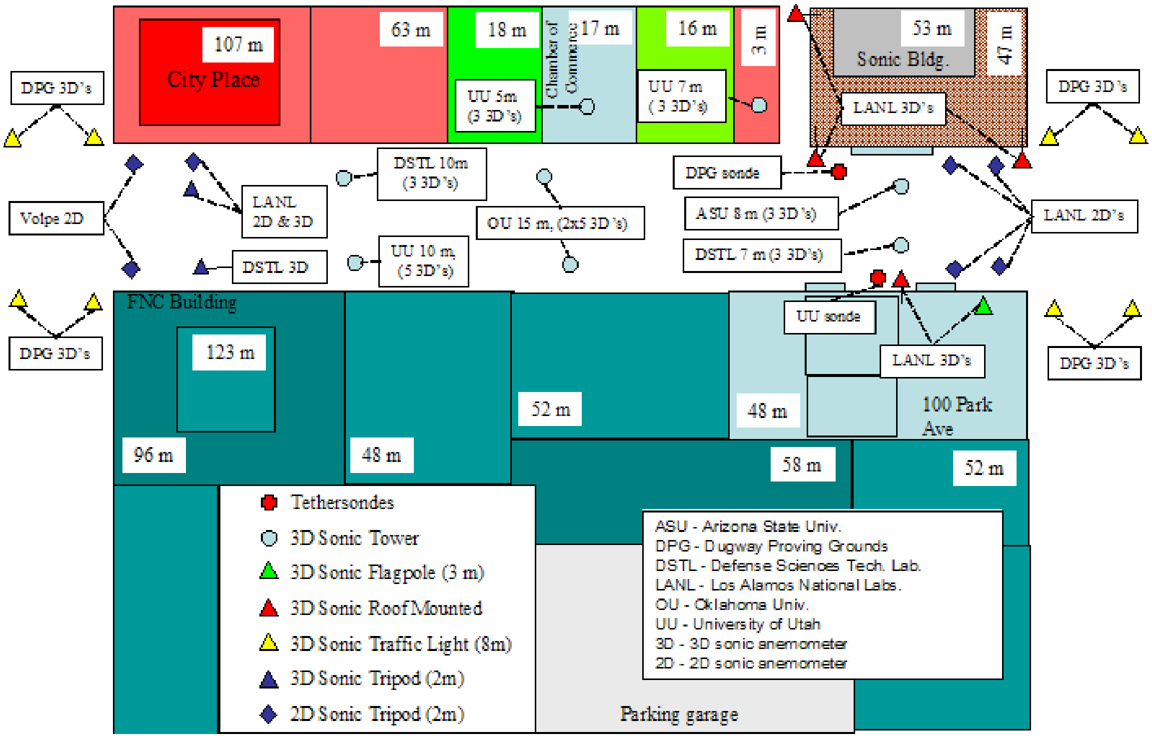


Figure 1: Sketch of the instrument layout in the Park Avenue street canyon. Note that the buildings and instrument locations are not to scale. (Brown et al. 2004).

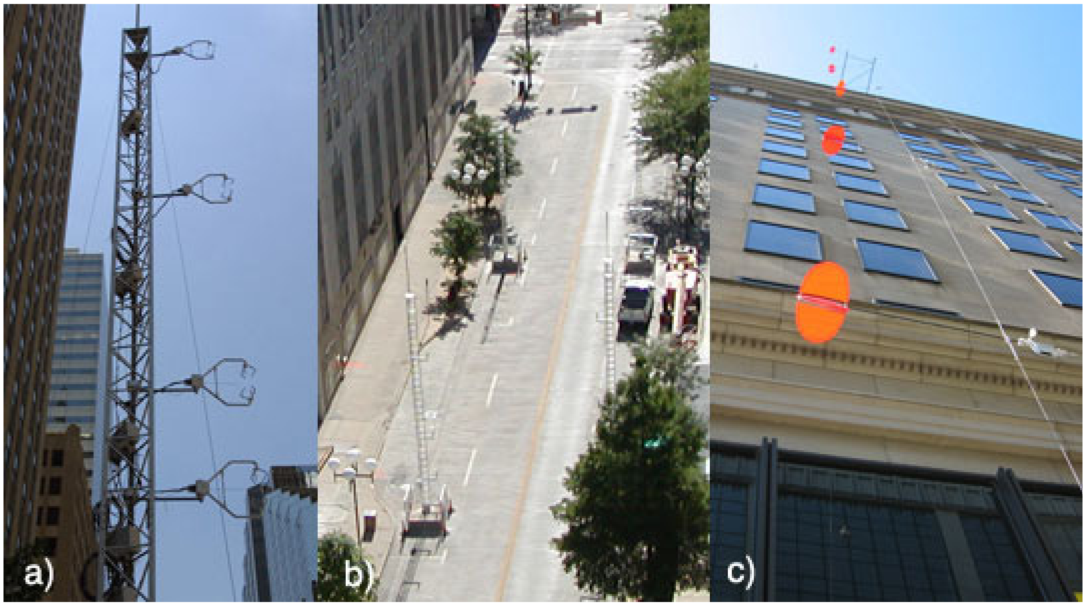


Figure 2: a) Campbell 3D sonics on the UU 10 m tower in Park Ave, b) Park Ave. viewed from the east with the two OU 15 m towers in the foreground and two UU/DSTL 10 m towers in the background, c) looking up at the UU tethersonde pulley system located at the southwest end of Park Ave. Photo a) courtesy of Aaron Kennedy. (Brown et al. 2004).

3. Approach and Concepts

Wind direction and turbulent fluxes within the street canyon were observed for a variety of mean incident wind directions. This was done to better understand the interaction/correlation between the various urban flow regimes. To describe the nature of turbulent fluxes, two types of statistical analyses were performed and are described below.

a. Joint Probability Distribution Function

The Joint probability distribution function *B(u, w)* is a function that measures the relative amount of time that two stationary variables, *u(t)* and w*(t),* are simultaneously in a small window between *u+du* and w+*dw* (Tennekes and Lumley 1994). Thus, integration over all possible *u*, *w* states yields,

$$B(u,w) \ge 0, \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} B(u,w)\,dudw = 1 \qquad (1).$$

When the joint probability density function is multiplied by the *u* and *w* values at each respective window, a weighted probability density function is obtained. The weighted probability density function gives the contribution from each of the quadrants to the total covariance. Thus,

$$\overline{uw} \equiv \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} uwB(u,w)\,dudw \qquad (2).$$

b. Quadrant Analysis

Eduction of flow physics is aided via an analysis that segregates the (*u*, *w*) space in to its four quadrants, i.e., (*u*>0, *w*>0), (*u*<0, *w*>0), (*u*>0, *w*<0) and (*u*<0, *w*<0) (Wallace et al. 1972; Willmarth and Lu 1972). The present *u, w* quadrant analysis employs a hyperbolic hole of size, *H*. This construct excludes from the analysis values of |*uw*| that are smaller than *H*|*uw*|, and thus yields a conditional sampling of *u* and w. Variation of *H* allows the investigation of the contributions from each of the quadrants to the total covariance of the signals *u* and *w*. Let [ ] represent conditional average. Then,

$$[uw]_{i,H} = \lim_{T_a\to\infty}\frac{1}{T_a}\int_0^{T_a} uwI_{i,H}(u,w)\,dt \qquad (3),$$

where T_a is the averaging time and $I_{i,H}$ the indicator function defined as

$I_{i,H}(u,w)=1$ if (*u*, w) is in quadrant *i* (1, 2, 3 or 4) and |*uw*|>H|*uw*|,

$I_{i,H}(u,w)=0$ otherwise (4).

The fractional contribution to each quadrant *i,* $S_{i,H}$, is then,

$$S_{i,H} = \frac{[uw]_{i,H}}{\overline{uw}} \qquad (5),$$

and the fraction of time spent in each quadrant, $\delta_{i,H}$ is

$$\delta_{i,H} = \overline{I_{i,H}(u,w)} \qquad (6).$$

(Note that the sum of $S_{i,H}$ for *i* = 1 to 4 at *H*=0 is unity.)

Further, the ratio *E* (Shaw et al. 1983) is defined as

$$E = \frac{S_{1,0}+S_{3,0}}{S_{2,0}+S_{4,0}} \qquad (7).$$

This ratio quantifies the relative positive to negative contributions to the total turbulent flux.

To decide upon an appropriate averaging time for various variables, the convergence of statistics of these variables was explored. Figure 3 shows the variation of standard deviation of along canyon velocity, *u,* with the averaging time for various heights on the UofU tower. These data are considered for the period between 1300-1330 on 20 July 2003.

The values of standard deviation converge to a nearly constant value for an averaging time about 300 seconds independent of sensor height. Thus, the averaging time or period of consideration for the analysis was chosen at 600 seconds (10 minutes) or greater.

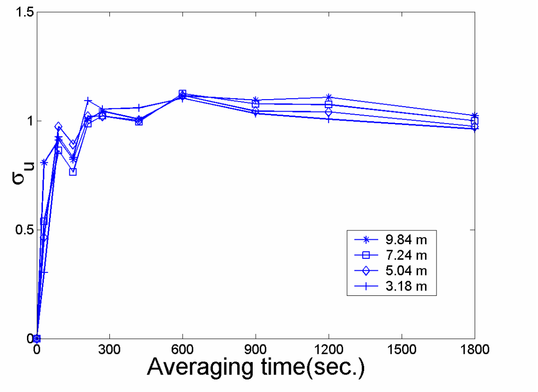


Figure 3: Convergence of σ_u on 20 July 2003 between 1300-1330. Mean upwind direction was about 180°.

4. Results and Analysis

a. Mean Wind Direction

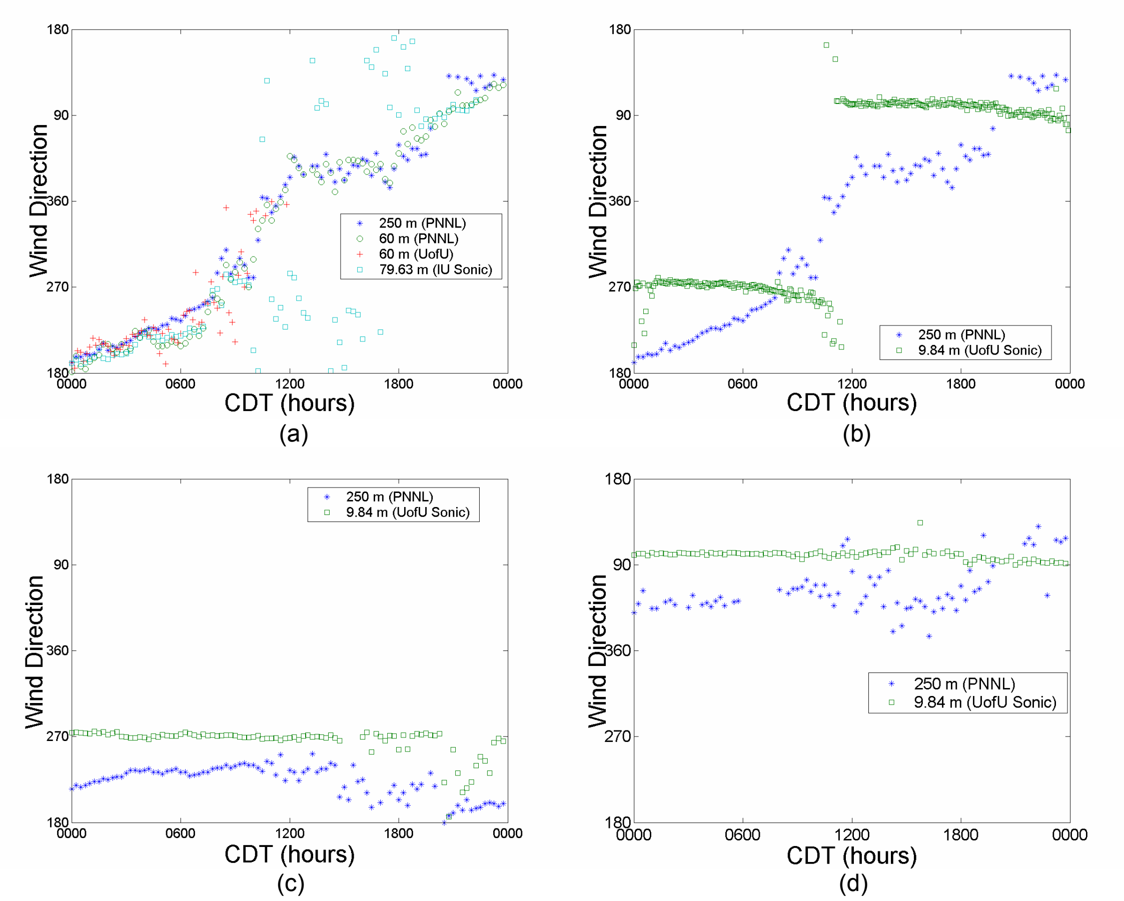
Figure 4 shows a comparison between the mean horizontal incident wind direction and the mean horizontal wind direction in the street canyon. It shows 15 minute averages of wind direction for three different days. Figure 4a shows the variation of the mean upwind direction through the day on 10 July 2003 as measured by the instruments discussed in Section 2. It is observed that all the instruments yielded self consistent results except for the Indiana University sonic anemometer at 79.63 m height for wind direction angles between 300°-70°. Therefore, the mean upwind direction values given by the PNNL SODAR at 250 m are considered in Figures 4b, 4c and 4d.

Figure 4b shows that the mean upwind direction gradually changes from 180° (southerly, across canyon) at 0000 to 360° (northerly, across canyon) at about 1200 and to 135° (south westerly) at 0000 on next day. The mean wind direction inside the street canyon remains around 270° (westerly, along canyon) up to 1200. After 1200 it makes a 180° shift and the mean wind direction inside the street canyon is about 90° (easterly, along canyon). Further from Figure 4b:

- Between 0000-0800 when the mean upwind direction is between 180°-270° (south westerly), the mean canyon wind direction is slightly greater than 270° (slightly north westerly, along the canyon).
- Between 0800-1200 when the mean upwind direction is between 270°-360° (north westerly), the mean canyon wind direction is slightly less than 270° (slightly south westerly, along the canyon).
- Between 1200-2000 when the mean upwind direction is between 360°-90° (north easterly), the mean canyon wind direction is slightly greater than 90° (slightly south easterly, along the canyon).
- Between 2000-0000 when the mean upwind direction is between 90°-135° (south easterly), the mean canyon wind direction is slightly less than 90° (slightly north easterly, along the canyon).

Similar observations are seen in Figure 4c and 4d indicating the above mentioned wind directions for 20 July 2003 and 23 July 2003 respectively.

Also from this it can be reasonably asserted that during this measurement period the mean wind direction in the street canyon is independent of diurnally varying factors such as stability etc., and thus is believed to be primarily dependent on the mean upwind direction.



(a) (b) (c) (d)

Figure 4: a) Mean upwind direction on 10 July 2003, b) Wind directions on 10 July 2003, c) Wind directions on 20 July 2003 d) Wind directions on 23 July 2003.

b. Across Canyon Wind Direction

Figure 4 indicates that when channeling takes place the mean wind direction inside the street canyon remains almost constant. But close observation of figure 4b reveals that the wind direction inside the street canyon fluctuates with considerable sensitivity between the two along canyon wind directions (270° & 90°) when the mean upwind direction is mostly across the canyon (360°).

Figure 5 shows the extent of fluctuation of mean canyon wind direction when the mean upwind direction is around 360° (northerly, across the canyon) on 29 July 2003. The mean canyon wind varies between 255°-113° when the mean upwind varies between 37°-348°.

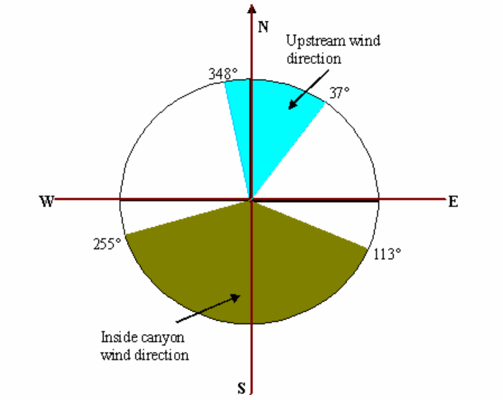


Figure 5: Correlation between the upstream cross canyon winds and the wind direction inside the canyon for 29 July 2003.

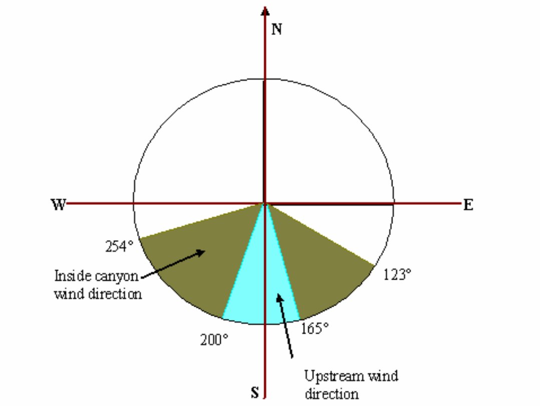


Figure 6: Correlation between the upstream cross canyon winds and the wind direction inside the canyon for 02 July 2003.

Figure 6 shows the extent of fluctuation of mean canyon wind direction when the mean upwind wind direction is around 180° (southerly, across the canyon) on 02 July 2003. The mean canyon wind varies between 254°-123° when the mean upwind varies between 165°-200°.

Thus, the mean wind direction inside the canyon is highly sensitive to the mean upwind direction when it is close to be flowing across the canyon. This is in contrast to the cases when channeling of canyon wind occurs.

c. Turbulent Fluxes

i. Momentum Flux

Figure 7 shows the vertical flux of horizontal momentum (normalized by the product of the standard deviations of the velocities considered) at the 10 m University of Utah tower for different days (various mean upwind directions). The velocity V considered here is the resultant horizontal velocity and w is the vertical velocity. For calculation of the momentum fluxes, velocity signals were linearly detrended and only the fluctuating component of each of the signals is considered.

Figure 7b shows the normalized momentum flux on 10 July 2003 between 0400-0450. The momentum flux at all positions on the tower (except during certain periods at 3.19 m) is downward. Although the magnitudes of the fluxes are low, the negative values are most likely indicative of a boundary layer formed within the canyon associated with channeling down the canyon (mean canyon wind direction=270°). Table 1 shows the values for E at various heights for different mean wind directions. For a 10 minute period under similar upwind conditions it is found that these values at 3.19 m are least and less than -1. This indicates upward transport of the horizontal momentum. At all other heights the value of E is greater than -1, indicating a downward transport of the horizontal momentum. All the values of E shown in Table 1 are significantly more negative than that commonly observed within the inertial sublayer over a smooth surface, where E is equal to -0.16 (Raupach 1981). This indicates the distinct nature of the contributions to the total transport of momentum within the urban street canyon, as compared to the transport within the inertial sublayer.

Similar observations have been made in the case where channeling in the street canyon takes place in the opposite direction. Figure 7a shows that the horizontal momentum is transported in the downward direction, likely indicating the presence of a boundary layer due to channeling. The values of E are similar to those of the previous case; indicating disorganization of the turbulence and hence the momentum transport.

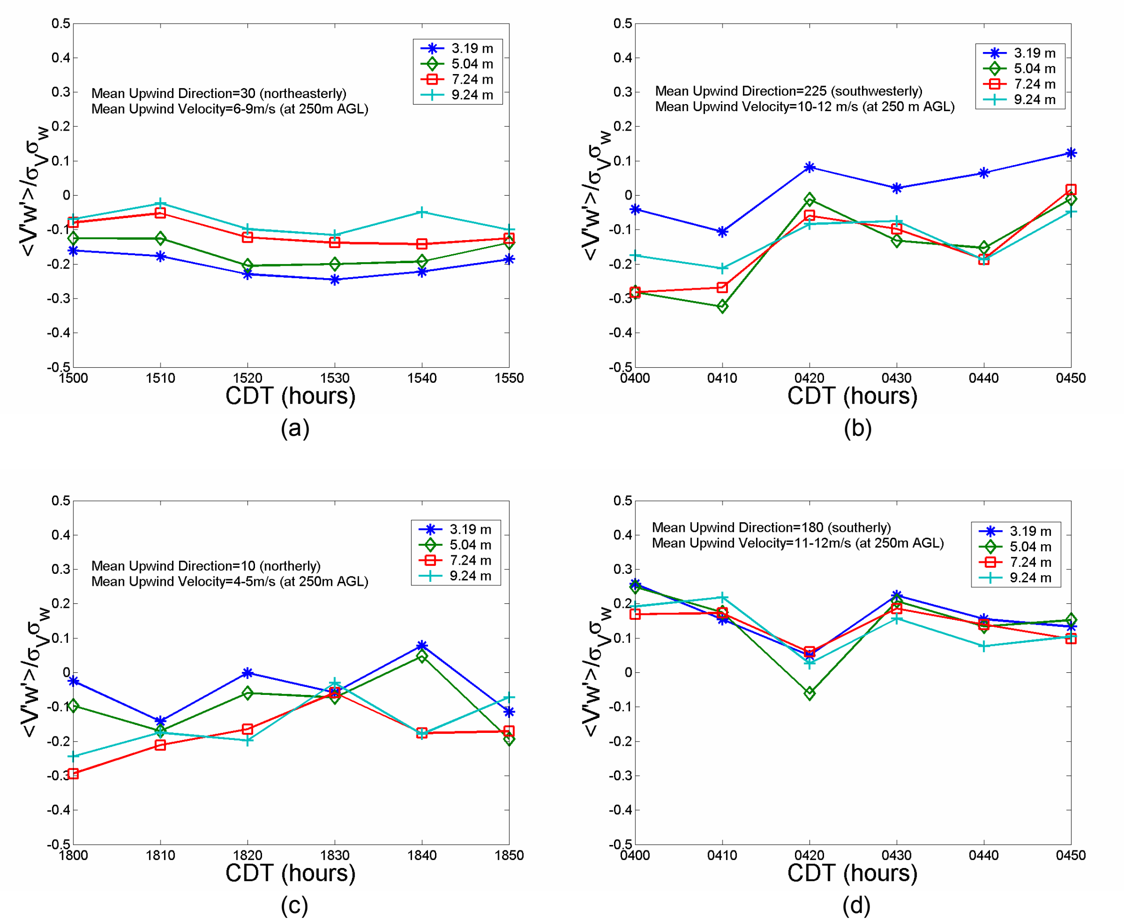


Figure 7: Ten minute averaged (< >) momentum flux at different heights for different mean incident upwind directions, (a) 10 July 2003 (1500-1550), (b) 10 July 2003 (0400-0450), (c) 29 July 2003 (1800-1850), (d) 09 July 2003 (0400-0450). Note that the value of $\sigma_V\sigma_w$ in all the cases is almost equal to unity.

Table 1: Values of the ratio *E* (Eq. 7), at different heights and mean upwind directions.

Mean Upwind Direction	Mean Canyon Wind Direction	Date	Time Period	*E*			
				3.19 m	5.04 m	7.24 m	9.84 m
30°	100°	10 July 2003	1510-1520	-0.578	-0.622	-0.739	-0.758
225°	280°	10 July 2003	0440-0420	-1.236	-0.607	-0.549	-0.543
10°	190°	29 July 2003	1850-1900	-0.681	-0.505	-0.553	-0.742
180°	220°	09 July 2003	0410-0420	-1.663	-1.766	-1.755	-2.125

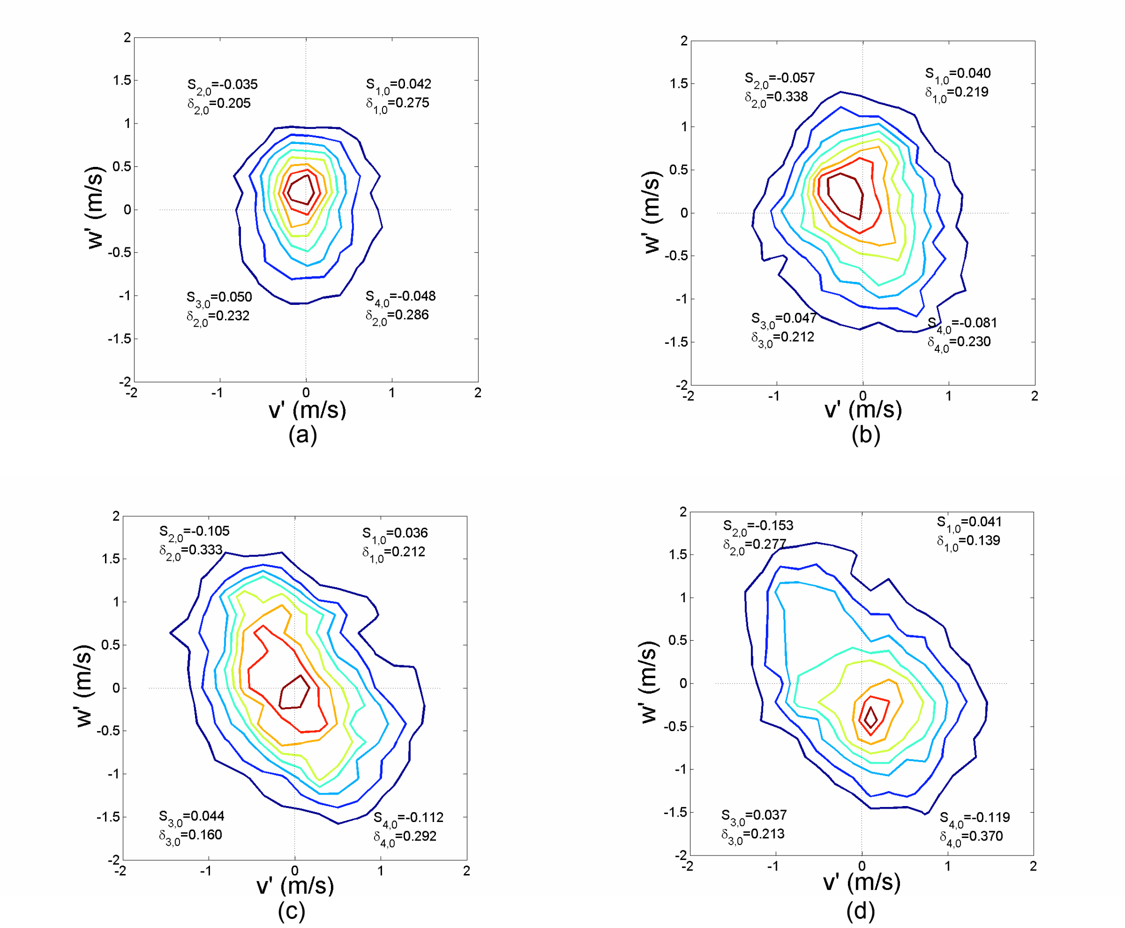


Figure 8: Joint Probability Distribution for *v'* and *w'* on 10 July 2003 (2045-2100) at different heights, (a) 3.19 m, (b) 5.04 m, (c) 7.24 m, (d) 9.84 m.

Figure 7d is a plot of the normalized momentum flux for 9 July 2003 between 0400-0450. The momentum flux at all positions on the tower is upward. This upward transport of momentum may be attributable to the existence of a vortex-like flow near the tower due to the cross canyon upwind condition (Vardoulakis et al. 2003; Jeong et al. 2002; Nakamura and Oke 1988) and the position of the tower on the leeward side of the street canyon. The same reason consistently explains the downward transport of the momentum on 29 July 2003 between 1800-1850. The position of the tower in this case was on the windward side of the street canyon.

Figure 8 shows the contour plots of the joint probability distribution of *v'* (across canyon velocity component) and *w'* for a 15 minute period between 2045-2100 on 10 July 2003 for different heights on the tower. The plot also displays the individual quadrant contributions by weighting the joint probability distribution with the instantaneous velocity values. The results in Figures 8a and 8b reveal that the individual quadrant contributions to the total momentum flux are almost equal and hence nearly cancel. The location of the peaks in probability shifts from the second quadrant to the fourth quadrant. This suggests a shift favoring the downward transport of high momentum fluid from above as opposed to the upward transport of low momentum fluid from below.

ii. Sensible Heat Flux

Figure 9 shows the 30 minute average of the sensible heat flux in various directions (along canyon <*u'Θ'*>, across canyon <*v'Θ'*> and upwards <*w'Θ'*> on 7 July 2003. The components of heat flux have comparable values and show a significant increase in magnitude at around 1100. This would seem to indicate heating of the street canyon surfaces at around this time period near the tower location. Also, there is an upward transport of heat flux even during early morning hours and late nights (except at 7.24 m), apparently indicating the heat retaining capacity of the street canyon.

Figure 10 shows the absolute values of the heat

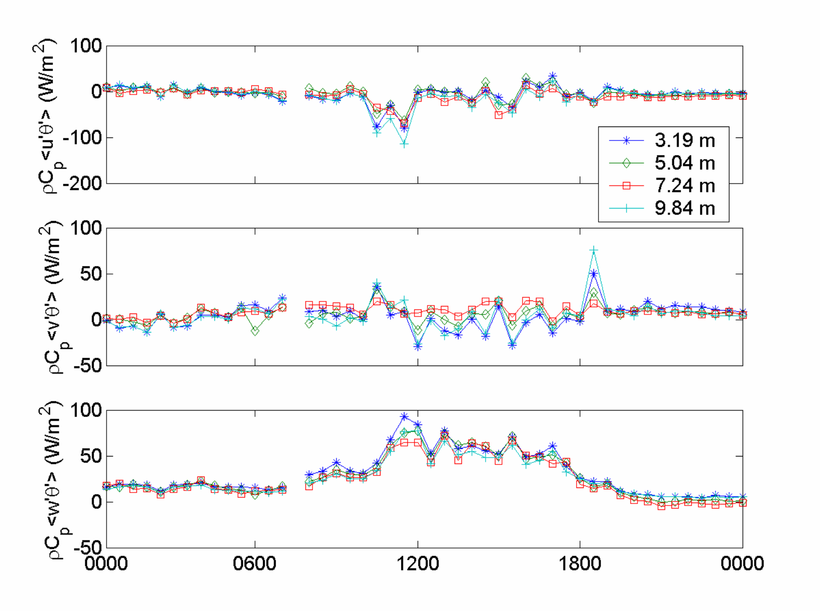


Figure 9: Thirty minute average (< >) of Heat Flux on 07 July 2003 at 10 m University of Utah tower.

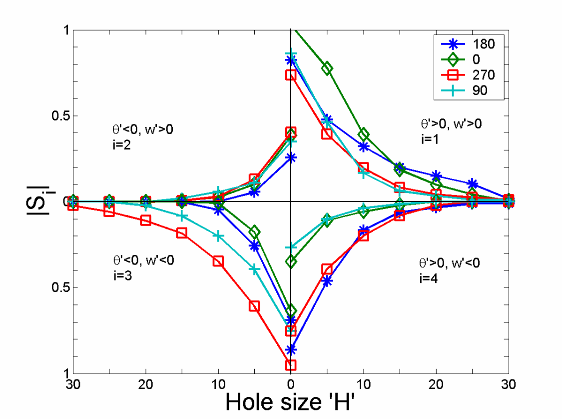


Figure 10: Heat Flux Fractions of ρCp<w'Θ'> for 10 minute periods under different mean upwind directions. The 10 minute periods considered are derived from different times and days, they are:

- 0400-0410 on 7 July 2003 for 180°
  Correlation coefficient=0.3379
- 0745-0755 on 29 July 2003 for 0°/360°
  Correlation coefficient=0.2416
- 1800-1810 on 21 July 2003 for 270°
  Correlation coefficient=0.2541
- 0400-0410 on 23 July 2003 for 90°
  Correlation coefficient=0.2950.

flux fractions for 0<*H*<30 and for different upwind conditions. The vertical component of the sensible heat flux has higher contributions from quadrants 1 and 3. This indicates the movement of cold fluid towards the surface and the movement of warm fluid away from the surface, hence explaining the net upward heat flux.

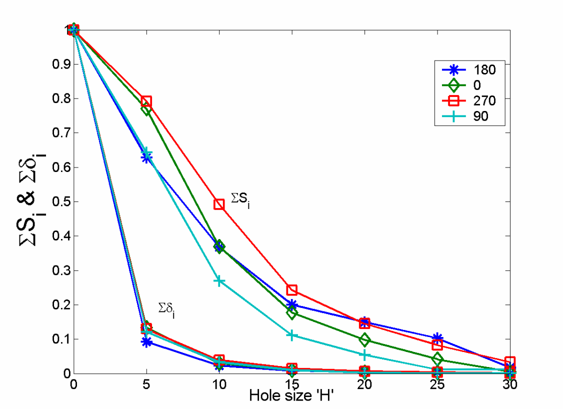


Figure 11: Summed Flux and Time Fractions for 10 minute periods under different mean upwind directions. The 10 minute periods considered are derived from different times and days, they are:

- 0400-0410 on 7 July 2003 for 180°
  Correlation coefficient=0.3379
- 0745-0755 on 29 July 2003 for 0°/360°
  Correlation coefficient=0.2416
- 1800-1810 on 21 July 2003 for 270°
  Correlation coefficient=0.2541
- 0400-0410 on 23 July 2003 for 90°
  Correlation coefficient=0.2950.

Figure 11 shows the summed flux and time fractions spent in each quadrant for the data of Figure 10. For *H*=5 about 80% of the turbulent transport of heat in the vertical direction occurs over about 10% of the time for the cases where the mean incident upwind is 270°(along canyon) and 0°/360°(across canyon from the north). That is a relatively low number of events contribute greatly to the total flux. For cases where the mean upwind direction is equal to 90° (along canyon) and 180° (across canyon form the south), however, 60% of the turbulent transport takes place in about the same amount of time. For these cases, a similar number of events contribute much less to the total flux. This indicates that the factors affecting the transport in the former case (270° and 0° upwind directions) have a higher rate of heat transfer as compared to the latter case (90° and 180° upwind directions) for *H*=5.

5. Conclusion

The above results show that the flow characteristics in the lowest few meters in an urban street canyon are strongly dependent on the mean incident upwind direction. At the location of the University of Utah instrument tower, channeling of the wind along the canyon takes place if the mean incident upwind direction is only slightly off the cross canyon wind direction (10°-20° from normal).

The magnitude of the momentum fluxes is low for the lowest few meters of an urban street canyon. This is due to almost equal contributions from all the quadrants. Turbulent transport of horizontal momentum is in the downward direction when channeling takes place in the canyon. During the cases when the upwind is in the cross canyon direction the turbulent transport of horizontal momentum is in the downward direction at the windward side of the canyon, and vice versa on the leeward side of the street canyon.

Unlike flows in the inertial sublayer, the heat fluxes are significant in all three directions. The magnitude of the vertical component is always positive at the lowest few meters of this urban street canyon.

6. Reference

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