Properties of the Wind Field within the Oklahoma City Park Avenue Street Canyon. Part I: Mean Flow and Turbulence Statistics

M. A. Nelson
Los Alamos National Laboratory, Los Alamos, New Mexico, and Department of Mechanical Engineering, University of Utah, Salt Lake City, Utah

E. R. Pardyjak
Department of Mechanical Engineering, University of Utah, Salt Lake City, Utah

J. C. Klewicki
Department of Mechanical Engineering, University of New Hampshire, Durham, New Hampshire

S. U. Pol and M. J. Brown
Los Alamos National Laboratory, Los Alamos, New Mexico

(Manuscript received 10 February 2006, in final form 10 July 2006)

Abstract

Velocity data were obtained from sonic anemometer measurements within an east–west-running street canyon located in the urban core of Oklahoma City, Oklahoma, during the Joint Urban 2003 field campaign. These data were used to explore the directional dependence of the mean flow and turbulence within a real-world street canyon. The along-canyon vortex that is a key characteristic of idealized street canyon studies was not evident in the mean wind data, although the sensor placement was not optimized for the detection of such structures. Instead, surface wind measurements imply that regions of horizontal convergence and divergence exist within the canopy, which are likely caused by taller buildings diverting the winds aloft down into the canopy. The details of these processes appear to be dependent on relatively small perturbations in the prevailing wind direction. Turbulence intensities within the canyon interior appeared to have more dependence on prevailing wind direction than they did in the intersections. Turbulence in the intersections tended to be higher than was observed in the canyon interior. This behavior implies that there are some fundamental differences between the flow structure found in North American–style cities where building heights are typically heterogeneous and that found in European-style cities, which generally have more homogeneous building heights. It is hypothesized that the greater three-dimensionality caused by the heterogeneous building heights increases the ventilation of the urban canopy through mean advective transport as well as enhanced turbulence.

1. Introduction

Urban areas affect the mean and turbulent flow characteristics of the atmospheric surface layer (ASL). This is realized through a variety of mechanisms such as enhanced form drag, heat storage, vortex shedding, etc. (Roth 2000). The urban boundary layer is defined as the region of the ASL where the effects of the urban landscape can be detected (Oke 1987). Understanding the mean flow structure and turbulence characteristics of ASL flow in and through urban areas is essential to predicting dispersion in cities, particularly in the regions near the source. Because of the difficulty in obtaining broadly representative measurements of the mean flow and turbulence in actual urban areas, simplified experiments (usually wind tunnel studies under neutral stability) are typically used to isolate the dominant flow mechanisms in and around buildings or groups of buildings (Bentham and Britter 2003; Chang and Meroney 2001, 2003; Cheng and Castro 2002;
MacDonald et al. 2002; Rafailidis 1997). Wind tunnel studies achieve partial similarity at best because it is nearly impossible to match the Reynolds number associated with true urban flows and difficult to match atmospheric stability conditions in the laboratory (Snyder 1981, 1985; Cermak 1996; Farell and Iyengar 1999; Uehara et al. 2003). Results from these simplified models are often used to validate computational models (Chang and Meroney 2001, 2003). These models are in turn used to predict the turbulence and flow characteristics in actual urban areas that have complex geometries and topography under nonneutral stability conditions based on a limited amount of data found in or around the urban area. Because of the complicated nature of ASL flow through urban areas, the study of it, referred to as urban fluid mechanics (UFM) by Fernando et al. (2001), incorporates a variety of disciplines such as fundamental fluid mechanics, meteorology, atmospheric chemistry, etc. The term UFM is used here rather than the terms urban climatology or urban micrometeorology because UFM implies a focus on flow kinematics and dynamics over the range of length and time scales that are the focus of this work. The challenges described above motivate the need for field campaigns performed in actual cities to, for example, discern the degree that the data obtained in the laboratory may be applied to real urban flows. Over the past few decades several field campaigns have been conducted in cities around the world that have explored the characteristics of the mean flow and turbulence in real-world cities (e.g., Nakamura and Oke 1988; Rotach 1993a,b; Roth and Oke 1993; Richards et al. 1997; Feigenwinter et al. 1999; Louka et al. 2000; Nielsen 2000; Rooney 2001; Allwine et al. 2002; Arnold et al. 2004; Longley et al. 2004; Rotach et al. 2005; Eliasson et al. 2006). Roth (2000) provides a good review of the results of a number of UFM field studies.

The complexity and extent to which the urban landscape affects the flow properties depends on the relative size and location of the flow scales in question. For large scales high above the buildings in the inertial sublayer, an urban area can typically be considered as distributed surface roughness, which retards the flow by increasing the skin friction and modifies the local energy budget. In this flow region well-known similarity relations (Monin and Obukhov 1954; Businger et al. 1971; Dyer 1974) for the ASL may still apply. [Roth (2000) provides a good review of several studies that demonstrate this.] This is because the underlying assumptions used to produce such relations (statistical stationarity, horizontal homogeneity, constant fluxes, zero-mean vertical and cross-wind components, etc.) may be approximately valid. For smaller scales of motion below a few average building heights, however [i.e., within the urban roughness sublayer (URSL) and urban canopy layer (UCL)], the buildings’ effects are much more pronounced, producing a flow that is highly heterogeneous, anisotropic, and three-dimensional (3D). To date no similarity theory exists for this type of flow.

Past urban street canyon research has often focused on numerical and wind tunnel studies of two-dimensional (2D) canyons with perpendicular winds and identical leeward and windward canyon wall heights (e.g., Kastner-Klein et al. 2001; Baik and Kim 2002; Jeong and Andrews 2002; Kim and Baik 2003; Dezso-Weidinger et al. 2003). These studies typically indicate that the transport and dispersion of pollutants into and out of the street canyon are principally associated with a standing along-canyon vortex. Clearly, however, no real-world urban canyon is truly 2D. The canyons are always finite, causing end effects; building heights are invariably heterogeneous to at least some degree; and perfectly perpendicular winds are very unusual. Hosker (1987) found that oblique upwind angles and taller buildings interspersed among smaller buildings tend to increase the ventilation (the transport of mass or scalar quantities between the canopy and the flow aloft) within the canopy, lowering the concentration of contaminants. The increased ventilation under these conditions may be a result of the addition of mean advective transport to the turbulent transport mechanisms from effects such as channeling and diversion of high-momentum air down into the UCL owing to greater three-dimensionality. Because the data presented in this work were obtained within a nonidealized street canyon, the comparison of this data with observations within an idealized canyon should provide insight into the similarities and differences between real and idealized street canyons.

In addition, most canopy flow studies concentrate on area-averaged profiles of velocity and turbulent fluxes averaged over multiple days, weeks, or even months (e.g., Rotach 1993a,b; Rotach et al. 2005). While this type of averaging is desirable for such applications as neighborhood or mesoscale models of flow through urban areas, it averages out the localized flow features that may have significant effects on, for example, near-source dispersion of a contaminant. In contrast to most UFM urban canopy studies, this work limits the averaging period to, at most, 3 h in order to focus on the complicated flow structures present within the urban canopy over these time scales. This work also takes advantage of what is to date one of the highest instrument densities in a single urban street canyon to explore the details of the mean flow characteristics and
turbulence statistics of the flow within a North American–style street canyon embedded in an urban core. The spectral characteristics of the flow in this street canyon over the same time periods are explored in Nelson et al. (2007, Part II of this paper).

2. Observation site and instrumentation

The Joint Urban 2003 (JU2003) field campaign was performed from 29 June through 30 July 2003 in Oklahoma City, Oklahoma (OKC; see Allwine et al. 2004; Brown et al. 2004; Nelson et al. 2004). OKC provided a relatively large urban area surrounded by terrain largely devoid of major topological features. In an effort to provide a more complete look at the flow within a real-world street canyon than has been done previously, a section of Park Avenue (PA) found in the urban core of OKC was selected to concentrate a large number of measurements. The average building height $H$ for the selected urban canyon was approximately 50 m (based on the buildings bounding the canyon) with a corresponding canyon width $S_1$ of approximately 25 m and canyon length $S_2$ of approximately 150 m, yielding a height to separation ratio $(HS_1^{-1})$ of approximately 2. An analysis of the building morphology data in the urban core of OKC performed by Burian et al. (2005) found the plan area fraction $\lambda_p$ to be 0.35 and the frontal area index $\lambda_f$ to range between 0.14 and 0.22 depending on wind direction. A $\lambda_f$ of 0.14 corresponded to winds out of the east and a value of 0.19 corresponded to winds out of the north. The largest value of 0.22 corresponded to winds that were oblique to the orientation of the streets in the urban core. These values characterize the flow through the urban core as being just above the transition from wake interference to skimming flow using the thresholds suggested by Grimmond and Oke (1999).

Several organizations participated in the PA street canyon subexperiment, including Arizona State University (ASU), the United Kingdom’s Defense Science and Technology Laboratory (DSTL), the U.S. Army’s Dugway Proving Ground (DPG), Los Alamos National Laboratory (LANL), the University of Oklahoma (OU), the University of Utah (UU), and the Volpe National Transportation Systems Center (VOLPE). Figure 1 shows the relative locations of the sonic anemometers deployed in and around the PA street canyon. Sonic locations are measured relative to the southeast corner of the northeast-most building in the canyon. The diagram is not to scale. Symbols are as in Figs. 4–6, and precise locations are as indicated in Tables 1–3. The exceptions to this are the DPG sonics for which the horizontal distances reported in Table 1 were estimated to within a few meters from photographs and a building database. For the sonics that were deployed on the roofs of buildings (see Table 2), both the height of the instrument AGL and the height above roof level (ARL) are reported. Most of the roof heights, with the observation periods (IOPs), when dispersion experiments were performed, an additional two 3D sonics and seven 2D sonics were deployed on tripods at the ends of the canyon (see Tables 1 and 3). An overall error of approximately ±0.25 m is attached to the horizontal position measurements in Tables 1–3. Error in the measurements of vertical position relative to the base of individual towers was smaller, approximately ±0.05 m. The exceptions to this are the DPG sonics for which the horizontal distances reported in Table 1 were estimated to within a few meters from photographs and a building database. For the sonics that were deployed on the roofs of buildings (see Table 2), both the height of the instrument AGL and the height above roof level (ARL) are reported. Most of the roof heights, with the
Table 1. Specifications of the street-level 3D sonic anemometers deployed in the PA street canyon. All instruments were nominally deployed continuously throughout the experiment with the exception of DSTL’s 2-m and LANL’s 2.2-m sonic anemometers. Distances are in the coordinate system defined in Fig. 1. Refer to Figs. 4–6 for the symbol that corresponds to each group label.

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<th>z (m)</th>
<th>OF (Hz)</th>
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* The actual output frequency of the DSTL instruments was 10 Hz; however, only 1-s averages of the original 10-Hz data were available for use in this study.

Table 2. Specifications of the 3D sonic anemometers deployed on the roofs of various buildings of the PA street canyon. All instruments were nominally deployed continuously throughout the experiment. Distances are in the coordinate system defined in Fig. 1. Refer to Figs. 4–6 for the symbol that corresponds to each group label.

<table>
<thead>
<tr>
<th>Make and model</th>
<th>Group label</th>
<th>x (m)</th>
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<th>z (m AGL)</th>
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exception of the smallest roof height, which was measured with a measuring tape, were determined using the building database with an accuracy of \( \pm 1 \) m.

For most instruments deployed in PA, the data output frequency (OF) listed in Tables 1–3 was identical to the internal sampling rate. It should be noted, however, that the DSTL sonics’ data presented here were produced from 1-s averages of the original 10-Hz data.

Velocities reported in this paper are in standard meteorological coordinates; that is, positive \( U \) velocities are from west to east, positive \( V \) velocities are from south to north, and positive \( W \) velocities are upward.

Because PA is perpendicular to true north within a few degrees (see Fig. 1), the standard meteorological velocity components have additional significance within the canyon, namely that \( U \) velocities are along-canyon winds and \( V \) velocities are cross-canyon winds. These components will be referred to in this context throughout the remainder of this work.

Figure 2 is a photograph that shows some of the locations of the instrument towers within the canyon interior. Various obstacles exist at the base of the canyon such as trees, statues, cars (both moving and stationary), etc. These further complicate the flow at street level. There are also significant deviations in the canyon geometry from the idealized urban canyon. The building heights shown in Fig. 1 indicate that the two buildings at the west end of the canyon are significantly taller than the rest of the buildings along the canyon walls. There was also a section of buildings along the middle of the north side of the canyon that were significantly shorter than the rest of the buildings composing the canyon. Both features will cause deviations from the ideal urban canyon to a greater or lesser extent depending on the prevailing wind direction.

3. Data selection and detrending

The inherent unsteadiness found in ASL flow makes obtaining meaningful statistical results difficult given the most ideal conditions. The interaction of unsteady prevailing flow with complicated morphology can further complicate the interpretation of statistical results in urban areas. To avoid confusion, time periods were selected where the upstream flow exhibited quasi-steady behavior. Typical winds during JU2003 were southeasterly to southwesterly. The upstream wind conditions were measured by the Indiana University (IU) 3D sonic tower and the Pacific Northwest National Laboratory (PNNL) sodar, which were both located in the suburban areas south of the urban core. Additional information on these instruments can be found in Ramamurthy et al. (2007).

For the analysis presented in this work, subsets of the IOP data were selected to ensure the highest density of measurements in the canyon and that the winds were nominally from the south (ensuring that the PNNL SODAR and IU 80-m sonic tower were nominally upstream of the urban core). The first two IOPs were omitted from this study because the 55-m level of the IU 80-m tower used to obtain upstream wind speed and friction velocity at building height (\( M_H \) and \( u^*_r \), respectively) was not operational during most of these two IOPs.

It was found that time periods with upstream wind
speed at building height greater than 6 m s\(^{-1}\) tended to exhibit less directional shear and that this occurred more often during the daytime hours. To focus on the directional dependence on the flow within PA rather than the effects of upstream thermal stability, this analysis has been limited to daytime hours. Thus, three time periods with thermally unstable conditions, \(M \geq 6 \text{ m s}^{-1}\), and little directional shear were selected to explore the directional dependence of the flow field statistics. The specific conditions broken into 1-h increments are presented in Table 4.

Fluctuating velocity time series were calculated using a simple 30-min running-block average (with one-sample steps) over the entire IOP. This was done to remove the effects of the diurnal cycle and mesoscale meteorological phenomena. The data were further subdivided into 1-h blocks for statistical analysis. The data points plotted in this work are averages of all the 1-h blocks of data available for a particular instrument for a prevailing wind direction (i.e., values can be a single 1-h block of data or an average of two or three 1-h blocks of data). For the southerly wind case the following data are missing: the second hour of the southwestern DPG sonic in the western intersection, all of the DSTL sonics for both hours, both hours of LANL3D-4, and both hours of OU tower 1. For southwesterly winds the following data were missing: all of the DSTL sonics for all three hours, the first two hours of LANL3D-6, and the first hour of both OU towers. For southeasterly case the following data were missing: all three hours of LANL3D-1 and the first hour of OU tower 2. In addition, the data plotted in this work have been separated into canyon interior and intersection sonics. Sonics that were located less than one canyon width from the intersections were categorized as intersection sonics and the remaining sonics were categorized as canyon interior sonics. This was done because the flow within the canyon and the flow within the intersections have very different characteristics (Kastner-Klein and Rotach 2004) and this approach has the added benefit of simplifying the visualization of this large amount of data.

The flow within the UCL tends to be highly heterogeneous and 3D. Recent studies have shown that these conditions can cause errors in sonic measurements because sonics are typically calibrated under conditions with little or no mean vertical velocity (Gash and Dolman 2003). The geometry of each make and model of sonic must be calibrated for a wide range of angles of attack and relative wind directions to properly account for the large vertical velocities possible within the UCL. The data presented here have not been corrected for these effects because the authors do not have the calibration algorithms for each of the various makes and models of sonics used in this work. Van der Mollen et al. (2004) found the error in the flux measurements introduced by the lack of calibration to be dependent on the angle of attack and that it generally produced an underestimation of the flux magnitudes between 5% and 15%.

### 4. Results and discussion

#### a. Mean velocities

Plan views of the velocity vectors within PA for all three upstream wind directions are presented in Fig. 3. The velocity vectors are colored by mean vertical velocity: light gray vectors are measurements where the mean vertical velocity is positive and has a magnitude greater than 2% of the horizontal scalar averaged wind speed (\(M\)), black vectors have negative mean vertical velocities with magnitudes greater than 2% of \(M\), and dark gray vectors are either 2D measurements or are 3D measurements with mean vertical velocities with magnitudes less than 2% of \(M\). These plots provide a holistic view of the directional dependence of the flow...
within a nonidealized urban canyon. Relatively small changes in the prevailing wind direction caused large changes in the mean flow structures within the canyon interior.

1) Southerly Upstream Winds

For PA, southerly winds are most similar to those typically studied in ideal street canyons because they are approximately perpendicular to the canyon axis. Vertical profiles of the mean wind components within PA normalized by $M_{HI}$ and measured under nominally southerly winds are presented in Fig. 4. A comparison of the along-canyon velocities with the relative positions of the various sonics (see Figs. 1 and 3a and Tables 1–3) shows that, with the exception of the recirculation zones at the extremes of the leeward side of the canyon, the winds at the western end and center of the canyon exhibited westerly channeling while the winds at the eastern end exhibited easterly channeling. The UU towers 2 and 3, which were located on the roofs of low buildings in the center of the north side of the canyon, had small along-canyon velocities. In general, for all of the towers within the street canyon, the cross-canyon

![Fig. 3. Mean velocity vectors within the PA street canyon for (a) southerly, (b) southwesterly, and (c) southeasterly winds. Rooftop sonics near $z = H$ at the east end of the canyon were excluded from these plots to avoid confusion with the measurements at street level. Black vectors are 3D measurements with positive mean vertical velocities, dark-gray vectors are either 2D measurements or 3D measurements with mean vertical velocities that are 2% or less of the mean horizontal wind speed, and light-gray vectors are 3D measurements with negative mean vertical velocities. Building and measurement locations are to scale.](image-url)
component was much weaker than was the along-canyon component. This is, however, not the case for the intersection sonics, which were all significantly influenced by the southerly channeling through the intersections. In addition, the data from the two UU rooftop towers show a dominance of the cross-canyon component, which is evidence of the flow being channeled through the low-level gap on the north side of PA. Because of the absence of the DSTL-2 and OU-1 data during this time period, it is impossible to verify the existence or nonexistence of the along-canyon vortex in the canyon interior for this time period. The sonics on the south side of the canyon interior measured small positive mean vertical velocities but it cannot be verified that the corresponding negative mean vertical velocities existed on the northern side of the canyon interior. Large magnitudes in the mean vertical velocities are found in some of the sonics near H (positive) and within the intersections at the ends of the canyon (both positive and negative).

2) SOUTHWESTERLY UPSTREAM WINDS

The mean velocities under southwesterly winds are presented in Fig. 5. The along-canyon velocity data indicate westerly channeling occurred throughout the canyon interior with the exception of some of the an-
emometers located in the end vortices near the intersections (Fig. 3b). It is noteworthy that the sonics at the tops of the OU towers measured stronger $M$ than was measured near $H$. It should, however, be remembered that the LANL 3D sonics were located within a couple of meters of the buildings, which may also have contributed to the observation of lower $M$ near $H$ than was observed lower in the canyon interior. While this local maximum of $M$ within the canopy contradicts the behavior implied by area averages of $M$ within the canopies of urban and urbanlike roughness (e.g., MacDonald 2000; MacDonald et al. 2002; Kastner-Klein and Rotach 2004; Rotach et al. 2005), it has been observed that groups of buildings can produce localized regions where the near-surface $M$ is higher than is found in flow around isolated buildings (Wise 1971; Britter and Hunt 1979). These effects are most pronounced in cases of heterogeneous building heights, such as is found in the urban core of North American–style cities. Wise (1971) hypothesized that this acceleration of the flow within the canopy was driven by a pressure gradient between the high pressure regions on the upwind faces of the taller buildings and the low pressure regions in the wakes of the smaller buildings, which redirected the higher-momentum fluid down into the canopy. If this is the cause of the local maxima of $M$ within PA, the positive mean vertical velocities at the OU towers suggest that the downdraft is occurring elsewhere through conservation of mass. Regions with strong downdrafts are observed in and near the inter-

**Fig. 5.** As in Fig. 4 but for the southwesterly wind case.
sections, which suggests that the local maximum in $M$ may be evidence of a wall jet radiating outward from the impinging of a downdraft of higher-momentum fluid on the street surface near the intersection.

Similar to what was found in the vertical velocities for southerly flow, the vertical velocities in the canyon interior have small positive mean values for southwesterly flow and larger magnitudes, both positive and negative, are found in the intersections. In a more idealized street canyon, one would typically expect a helical vortex (the superposition of along-canyon channeling with the along-canyon vortex) to form in the canyon as was observed by Eliasson et al. (2006). They found that, in a European-style city (where the building heights tend to be much more homogeneous), flow within 60° of perpendicular to the canyon axis produces a single helical vortex in the canyon. Observations on the two OU towers (see Figs. 3b and 5e) near the center of the canyon indicate that both the north and south sides of the canyon have positive mean vertical velocities and therefore indicate that a helical vortex is not formed in this region of the canyon. While the UU tower 1 and ASU tower sonics also show positive $W$ during this time period, the two DSTL towers were inoperable, making it impossible to definitively state whether or not a helical vortex formed in other regions of the canyon interior. The fact that there are regions where downdrafts existed in the mean flow field suggests by mass conservation arguments that corresponding regions of updrafts also existed in the mean flow.

Fig. 6. As in Fig. 4 but for the southeasterly wind case.
field, transporting fluid from the canopy up into the flow aloft. These regions of updrafts and downdrafts would also produce regions of horizontal convergence and divergence, respectively.

3) Southeasterly upstream winds

The mean velocity components under southeasterly winds are shown in Fig. 6. It is readily apparent that the flow within the canyon interior is much more complicated under winds from this direction. Instead of being mirror images of each other, as one might expect in the case of flow through a more idealized canyon, the southwesterly (Fig. 3b) and southeasterly (Fig. 3c) flows exhibited very different mean flow structures in the canyon interior. Similar to the results in idealized canyons, the southwesterly winds caused the flow to channel down the canyon. Under southeasterly winds, however, UU tower 1 and DSTL tower 2 appear to have been located in a region of horizontal divergence in the wind field (see Fig. 3c). As was the case with the southerly and southwesterly wind cases, most of the canyon interior measurements have a small positive vertical velocity. The exception to this observation is found for DSTL tower 2 where all three sonics measured a strongly negative vertical velocity. Under these wind conditions, the OU towers were in a region of strong directional shear where the lowest sonics observed relatively strong northwesterly winds and the upper sonics observed weak easterly winds. These observations are consistent with the hypothesis posed above regarding updrafts and downdrafts producing regions of horizontal convergence and divergence in North American–style urban areas. Figure 7 presents a hypothetical representation of the mean flow structures producing the observed flow in PA under southeasterly winds. The higher-momentum flow above H is transported down into PA after it impinges on the tall buildings at the western end of the canyon. The resulting downdraft causes a region of horizontal divergence and wall jets when it impinges on the street surface. The relatively high momentum wall jet interacts with the flow channeling into the canyon from the eastern intersection, producing the strong directional shear on the OU towers that forces flow out of PA through the gap in the north wall of the canyon.

The along-canyon vortex typical of idealized street canyon studies was not evident in the flow through PA, although it can be argued that the instruments deployed within PA during JU2003 were not placed to detect this feature. This is apparently because of the heterogeneous building heights producing more complicated mean flow structures within the canyon. Contrasting the results presented here with the fact that the along-canyon helical vortex has been observed in real-world European-style street canyons suggests that there may be a fundamental difference in the flow structures and transport mechanisms in the two styles of urban areas and calls into question the applicability of 2D idealized street canyon results in real-world North American–style urban cores where the building heights are typically highly heterogeneous.

b. Turbulence intensity

1) Southerly upstream winds

The local turbulence intensities, root-mean-squared (RMS) velocities normalized by $M$, in and around PA for the southerly wind case, are presented in Fig. 8. In general, the turbulence intensities were relatively large both within the canyon interior and in the intersections.
at the ends of the canyon. In fact, some regions near the surface actually had horizontal RMS velocities that were actually larger than $M$. The high turbulence intensities measured on the rooftop UU towers may indicate that small velocities measured at these sites (see Fig. 4c) were not caused by light winds in these regions but large fluctuations that reversed the flow from one moment to the next. For UU tower 2 for southerly flow the vector-averaged velocity magnitude is, on average, only 16% of $M$. For the most part, the turbulence intensities tended to grow with height AGL. This effect is most pronounced in the vertical turbulence intensity data where a sharp reduction in turbulence intensity occurred near the surface within the canyon interior, which may be evidence of the surface restricting the vertical turbulent motions. The restriction of turbulent motions from building morphology is most obvious in the data from UU tower 3, which was located in the narrow alley over the 4-m building where the cross-canyon turbulence intensity was about twice as large as the along-canyon component.

2) SOUTHWESTERLY UPSTREAM WINDS

The turbulence intensities in PA for southwesterly winds are presented in Fig. 9. Comparing the turbulence intensities on UU tower 1 and the OU towers

![Figure 8: Southerly wind case RMS along-canyon, cross-canyon, and vertical velocity components [respectively, (a), (c), (e) for canyon interior measurements and (b), (d), (f) for near-intersection measurements] normalized by the local mean horizontal wind speed. Horizontal positions are as indicated in Tables 1–3 and Fig. 1.]
under southwesterly and southerly winds shows that the velocity fluctuations in the canyon interior are much less intense under southwesterly winds than they are for southerly winds. An examination of the velocity vector plots for these two cases (Figs. 3a and 3b) reveals no obvious reason why this should be the case such as the complicated mean flow structures that were observed within the canyon under southeasterly winds (Fig. 3c). The fact that both cases have similar upwind conditions (see Table 4) and intersection velocity magnitudes might lead one to believe that they should have similar velocity magnitudes within the canyon interior. The southerly wind case, however, has significantly smaller velocities in the canyon, which are related to the enhanced turbulence intensity in this case. Because the data presented in Fig. 3 were produced from simple vector averages of the instantaneous velocity data over the entire time period, occasional flow reversals (similar to what was observed on the sonics in the gap) would reduce the apparent velocity magnitude. Such flow reversals seem likely in the southerly wind case because this flow regime is probably sensitive to atmospheric wind meander. In fact, a comparison of the vector-averaged along-canyon velocity component (the dominant velocity component in both cases) with $M\text{OU tower 2 during these time periods}$ reveals that the vector average was 13% lower than $M$ for the southerly case while it was only 4% lower for the southwesterly case. The slight westerly component to the southerly wind case (mean wind direction of 185° rather than
180°) made the westerly channeling more likely to occur than the easterly channeling, causing this effect in the canyon interior to be less pronounced than it was in the gap.

Similar to southerly flow, these towers also show a decrease in the vertical turbulence intensity near the surface under southwesterly winds. In contrast, the horizontal turbulence intensities slightly increase near the surface. The turbulence intensity data from LANL3D-4 and -5 are further evidence of the buildings restricting turbulent motions. The along-canyon turbulence intensity dominated over the cross-canyon intensity on LANL3D-5, while the opposite is true for LANL3D-4. The western face of the building redirected the flow to be southerly at LANL3D-4 (Figs. 1 and 5c) and the southern face of the building forced the flow channel westerly along the canyon at LANL3D-5 (Figs. 1 and 5a). The high turbulence intensity measured on the ASU tower could be due to one or both of two factors: first, this tower had large trees within a few meters of both the east and west sides of the tower, and second, this tower was several meters closer to the eastern intersection than the UU tower 1 and DSTL tower 2 were to the western intersection and it was therefore more likely to be influenced by the end vortex near the intersection. The LANL 2D sonics near the eastern intersection had exceptionally large turbulence intensities in the along-canyon direction, which were likely a result of the end vortex produced by the interaction of the westerly channeling flow within PA.

![Fig. 10](image-url) As in Fig. 8 but for the southeasterly wind case.
and the southerly channeling flow in the intersection (Fig. 3b).

3) Southeasterly Upstream Winds

The turbulence intensities for southeasterly flow are presented in Fig. 10. Similar trends were observed in the vertical turbulence intensities within the canyon interior under southeasterly winds as were observed under the other wind directions. In addition, similar to what was found for southerly flow, the turbulence intensities under southeasterly flow tended to have high turbulence intensities throughout the canyon interior as well as in the intersections. Although in contrast to the southerly wind case, the complicated mean flow structure shown in the vector plot for southeasterly winds (Fig. 3c) would lead one to expect the higher turbulence intensities in the canyon interior. Thus, the increased ventilation observed by Hosker (1987) may not only be due to the addition of mean advective processes but also appears to be enhanced by an increase of turbulence within the canopy owing to the more complex mean flow structures that are produced by the interaction of the flow with the heterogeneous building heights. Because the bulk of street canyon research has been performed on idealized canyons, and there are apparent fundamental differences in the behavior of idealized and nonidealized canyons, there is a lack of understanding of the physical processes that occur in the nonidealized canyons. Thus, the study of flow in nonidealized street canyons is an area of scientific interest that requires further study.

5. Conclusions

Three time periods were selected from the JU2003 PA subexperiment dataset to observe the directional dependence of the mean flow and turbulence within and around a North American–style urban street canyon. It was found that the complicated morphology of PA with heterogeneous building heights produced very different flow structures within the canyon interior for relatively small changes in the prevailing wind direction.

Much of the research studying detailed flow structure within the UCL has focused on flow over idealized street canyons with perpendicular winds. These studies show a dominant along-canyon vortex within the canyon. This key feature was not evident in the 1-h mean wind fields measured within PA presented in this work. It should be noted, however, that some of the data in the canyon interior were missing during the southerly and southwesterly time periods, making it impossible to verify if this structure was absent from the entire canyon interior during these periods. The most obvious departure from the along-canyon helical vortex was found under southeasterly winds. A region of horizontal divergence was observed on the UU and DSTL towers on the western side of the canyon. A rational conjecture is that these flow structures were generated by the heterogeneous building heights in the urban core. The taller buildings appear to have diverted the high-momentum air from the URSL down into the UCL, which produced the region of horizontal divergence as the resulting downdraft impinged on the surface of the street. Conservation of mass arguments indicate that these downdrafts that transport mass into the UCL and cause regions of horizontal divergence in the velocity vector field will produce regions of horizontal convergence where there is a flux of mass out of the UCL into the flow aloft. This behavior significantly deviates from the idealized urban canyon in which transport into and out of the UCL is principally identified with turbulence. Given these results, it appears that the research into the flow characteristics of idealized street canyons is more applicable to European-style cities (e.g., Eliasson et al. 2006), where buildings are often found to be the same height over large regions of the urbanized area because of building height limits. The study of idealized street canyon flow, however, appears to have little applicability to flow within the urban core of North American–style cities, where building heights are less restricted and are generally found to be heterogeneous.

Many regions within and around PA were found to have turbulence intensities well above the typical threshold of 0.5 used to determine the applicability of Taylor’s frozen turbulence hypothesis. In fact, there were a few instruments that measured turbulence intensities greater than one sustained over the 1-h averaging periods. Given the strong dependence of the mean flow structures within the canyon on the prevailing wind direction, it is not surprising that the turbulence intensities in this region were also found to be dependent on the prevailing wind direction. The relatively simple case of westerly channeling in the canyon under southwesterly winds produced much smaller turbulence intensities in the canyon interior than was observed under the southerly or southeasterly prevailing wind cases. The large turbulence intensities in the southerly case appeared to be due to sensitivities in the flow structure within the canyon to oscillations in the prevailing wind direction. The large turbulence intensities in the southeasterly wind case, however, appeared to likely be a result of the complicated mean flow structure within the canyon with regions of horizontal divergence and strong directional shear. These results sug-
gest that the ventilation of nonidealized street canyons is likely enhanced relative to their idealized counterparts through two processes: mean vertical advection, and increased turbulence produced by the complicated 3D flow structures within the canopy. While the PA subexperiment had one of the highest concentrations of measurements in a single real-world street canyon, it was still insufficient to capture all the details of even the major flow structures within the canopy. As such, further research is needed to explore and gain a better understanding of the physical processes governing the complicated flow structures within nonidealized street canyons, such as those that have been observed in the PA subexperiment of JU2003.

**Acknowledgments.** The work described in this paper was supported by the Defense Threat Reduction Agency and Dugway Proving Ground through a contract with the H. E. Cramer Company, Inc., as well as through the Biological Countermeasures Office in the Department of Homeland Security. The authors also acknowledge the hard work of the other Park Avenue Street canyon team workers and others that contributed to the datasets presented in this work, including the following: P. Ramamurthy, B. Hansen, B. Verhoef, Dr. P. Kastner-Klein, D. Storwold, Dr. F. Gallagher, Dr. H. J. S. Fernando, Dr. M. Princevac, Dr. J. Allwine, and Dr. S. Grimmond. In addition, the authors are very grateful to the local government workers, business owners and workers, and citizens of Oklahoma City who made the JU2003 field experiment possible.

**REFERENCES**


Longley, I. D., M. W. Gallagher, J. R. Dorsey, M. Flynn, and J. F. Barlow, 2004: Short-term measurements of airflow and tur-
bulence in two street canyons in Manchester. Atmos. Environ., 38, 69–79.


