Observations of the Effects of Atmospheric Stability on Turbulence Statistics Deep within an Urban Street Canyon

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ABSTRACT

Data obtained in downtown Oklahoma City, Oklahoma, during the Joint Urban 2003 atmospheric dispersion study have been analyzed to investigate the effects of upstream atmospheric stability on turbulence statistics in an urban core. The data presented include turbulent heat and momentum fluxes at various vertical and horizontal locations in the lower 30% of the street canyon. These data have been segregated into three broad stability classification regimes: stable \((z/L > 0.2)\), neutral \((-0.2 < z/L < 0.2)\), and unstable \((z/L < -0.2)\) based on upstream measurements of the Monin–Obukhov length scale \(L\). Most of the momentum-related turbulence statistics were insensitive to upstream atmospheric stability, while the energy-related statistics (potential temperatures and kinematic heat fluxes) were more sensitive. In particular, the local turbulence intensity inside the street canyon varied little with atmospheric stability but always had large magnitudes. Measurements of turbulent momentum fluxes indicate the existence of regions of upward transport of high horizontal momentum fluid near the ground that is associated with low-level jet structures for all stabilities. The turbulent kinetic energy normalized by a local shear stress velocity collapses the data well and shows a clear repeatable pattern that appears to be stability invariant. The magnitude of the normalized turbulent kinetic energy increases rapidly as the ground is approached. This behavior is a result of a much more rapid drop in the correlation between the horizontal and vertical velocities than in the velocity variances. This lack of correlation in the turbulent momentum fluxes is consistent with previous work in the literature. It was also observed that the mean potential temperatures almost always decrease with increasing height in the street canyon and that the vertical heat fluxes are always positive regardless of upstream atmospheric stability. In addition, mean potential temperature profiles are slightly more unstable during the unstable periods than during the neutral or stable periods. The magnitudes of all three components of the heat flux and the variability of the heat fluxes decrease with increasing atmospheric stability. In addition, the cross-canyon and along-canyon heat fluxes are as large as the vertical component of the heat fluxes in the lower portion of the canyon.

1. Introduction

A large body of experimental field data exists in the literature describing turbulence statistics for atmospheric surface layer (ASL) flow over uniform surfaces with variable atmospheric stabilities (e.g., Businger et al. 1971; Kaimal et al. 1976; Nieuwstadt 1984; Poulos et al. 2002). Far fewer comprehensive datasets exist for ASLs that interact with urban roughness elements. This is especially the case for real cities and is largely a result of the difficulties associated with making high quality measurements within an urban area. As a result, some very basic questions exist that have yet to be answered both in the areas of the dispersion of tracers and basic turbulence characteristics. This paper attempts to utilize observations made deep within an urban street canyon during the Joint Urban 2003 field experiment in Oklahoma City, Oklahoma, to add insight into some of these questions including the following: What is the effect of upstream atmospheric stability on turbulence statistics deep within a real city? What are typical val-
ues of turbulence statistics within real urban canopies? How do turbulence statistics vary spatially within an urban street canyon? While these questions are not fully answered in the present work, new insight has been added toward answering each of the questions.

Recently, Roth (2000), Britter and Hanna (2003), and Kastner-Klein and Rotach (2004) have all reviewed much of the existing literature related to flow in urban areas. The urban studies that have been conducted in the past fall into the broad categories of scale-model wind tunnel experiments, scale-model field experiments, full-scale field experiments, and computational studies. Here, important findings associated with some of the experimental results are discussed.

The wind tunnel studies of Kastner-Klein and Rotach (2004) identified the existence of a sharp peak in the Reynolds stresses and turbulent kinetic energy located just above the average building height in scale-model cities immersed in a neutral stability flow. For neutral conditions over a large range of building frontal and plan areas, Macdonald et al. (2002) have identified the basic shapes for mean and turbulence profiles within and above regular, idealized arrays of buildings.

During stable conditions, many questions still exist regarding the effect of upstream stability on flow within cities. This is likely a result of the high variability of urban morphologies, land uses, and land fabrics that make developing a unified theory quite difficult. For example, in wind-tunnel studies of a uniform cubic array \( (\lambda_f = \lambda_p = 0.33, \text{where } \lambda_f \text{ is the frontal area index and } \lambda_p \text{ is the plan area fraction}) \) Uehara et al. (2000) found that for a wide range of bulk Richardson numbers, the turbulence statistics within the canopy \( (Z < H, \text{where } H \text{ is the height of the canopy}) \) were highly influenced by atmospheric stratification. A Rafailidis (2001) wind-tunnel study investigated the influence of stable stratification on flow over various street canyons with flat and peaked roofs. He studied street canyons with aspect ratios of \( H/W = 3, 2, 1, \text{and } 2/3 \) (where \( W \) is the width of the street canyon). He noted a capping effect owing to the stable stratification; however, it was also found that for narrower streets the local influence of buildings reduced the effects of stratification.

For the near-full-scale Mock Urban Setting Test (MUST) experiment with \( \lambda_p = 0.096 \) and \( \lambda_f = 0.10 \) and 0.03 (Nelson et al. 2004), the data of Pardyjak et al. (2002) indicated that the vertical location of the peak in the turbulent stress may fall below the average building height with increasing stability. In contrast, for a narrow street canyon \( (H/W \sim 1) \) on the Kyoto University campus, Nakamura and Oke (1988) found that during all times of the day the street canyon was unstable, with the canyon being more unstable during the day and less unstable at night. Similarly, Santamouris et al. (1999) found that temperatures decreased with height during both the day and night in a real street canyon \( (H/W \sim 2.4) \) in Athens, Greece. Kanda et al. (2005) investigated seasonal variations of temperatures in a suburban area of Tokyo with a building plan area fraction of \( \lambda_p = 0.326 \) and a vegetative plan area fraction of \( \lambda_p = 0.252 \). They found that the daily maximum temperature occurs at the base of the buildings during the summer, approximately at building height during the winter, and at approximately one-half of building height during the spring and fall. They also observed that the flow above the urban canopy was always unstable; however, below building height the flow was typically unstable during the summer and stable during the winter. They attributed their findings to variations in seasonal absorbed solar radiation.

Recently, three intensive full-scale field campaigns—the Basel Urban Boundary Layer Experiment (BBB; Rotach et al. 2004), the Marseille Experiment (Mestayer et al. 2005), and a street canyon study in Göteborg, Sweden (Eliasson et al. 2006)—have been undertaken in Europe. These experiments have added tremendous insight into the appropriate use of measuring techniques in urban areas while also improving the general understanding of basic urban transport physics.

The Joint Urban 2003 (JU2003) atmospheric dispersion study is the most recent dispersion experiment in a series of cooperative multiagency–multiuniversity full- and near-full-scale experiments. JU2003 built on the experiences and knowledge gained during the Urban 2000 field campaign (Allwine et al. 2002) conducted in Salt Lake City, Utah, and the MUST experiment (Yee and Biltoft 2004) conducted at the U.S. Army Dugway Proving Grounds (DPG) in Utah’s west desert. Oklahoma City (OKC) was selected as a site because of the limited terrain influence on the winds, excellent upstream homogeneity, regular winds out of a narrow directional range, and community willingness to support the type of disruption associated with a large urban field campaign. As part of JU2003, a detailed subexperiment was conducted in the east–west-running Park Avenue street canyon located near the center of OKC’s central business district (CBD). The results presented in this work include observations focusing on the effects of the upstream atmospheric stability on the mean and turbulence quantities deep within OKC’s Park Avenue street canyon. To simplify the analysis, only winds from the south with similar upstream wind speeds at the average building height of the street canyon have been considered.
2. Observation site and instrumentation

The JU2003 field campaign was conducted during July 2003 in and around the urban metropolitan area of Oklahoma City, Oklahoma. A large number of instruments were deployed during the JU2003 field campaign. Details of the locations and types of the full suite of sonic anemometers that were deployed during JU2003 are presented in Nelson et al. (2007a). The locations of the instruments used for the Park Avenue street canyon analysis in this paper are shown in Figs. 1 and 2. The instrument location measurements shown in Fig. 2 were made with a standard metric tape measure that was accurate to ±0.005 m; however, other human error introduced in making the measurements increased the error to approximately ±0.25 m. Error in the measurements of the vertical locations was far smaller: approximately ±0.05 m. The analysis done in this paper focuses on measurements made on three towers within the Park Avenue street canyon. The tower marked UU3 was operated by the University of Utah, the towers marked OU1 and OU2 were operated by the University of Oklahoma (Klein and Clark 2007), and the tower marked ASU was operated by Arizona State University. Instrument models, manufacturers, sampling frequency, sensor heights, and street canyon locations are given in Table 1. The x, y locations are given in meters referenced to a coordinate system centered at the southeast corner of the building labeled the “sonic building” in Fig. 2. The universal transverse Mercator (UTM) coordinates of this coordinate system origin are 634 768.8 m east and 3 926 053.4 m north [for
zone 14 of the North American Datum of 1983 (NAD83). As described in detail by Nelson et al. (2007a), the average building height for the Park Avenue street canyon was $H \sim 50$ m, while the canyon length and width were $L \sim 157$ m and $W \sim 25$ m, respectively (see Fig. 2), yielding an $H/L \sim 2$. In addition, $\lambda_f = 0.35$ and the frontal area index $\lambda_f = 0.19$ (northerly flow), 0.22 (northeasterly flow), 0.14 (easterly flow), and 0.22 (southeasterly flow).

The Park Avenue street canyon is located at the core of OKC’s CBD. This street canyon has very little parking located on the street, and, as a result, during the day there was usually light to moderate vehicular traffic (often including large delivery vehicles) accompanied by significant pedestrian traffic. At night, there was very little traffic, with the dominant activity resulting from researchers involved in the JU2003 experiment.

As shown in Fig. 2, in addition to the sonic anemometers, a tethersonde “tower” (labeled UUT) was deployed in the street canyon to investigate the mean static stability. This tower also provided vertical profiles of humidity, wind speed, and wind direction throughout the entire depth of the canyon. The tethersonde system was deployed by the University of Utah team in the southeastern portion of the street canyon. The tethersonde tower was a modified version of the standard DigiCORA tethered balloon system made by Vaisala, Inc. (Boulder, Colorado) and typically used to make atmospheric boundary layer measurements. As indicated in Table 1, six Vaisala TS111 tethersondes were located approximately 1 m away from the southeastern-most building in the canyon at heights of 1, 5, 10, 20, 30, and 40 m above the ground. Each tethersonde was affixed to premeasured and marked sections of the tether line and then raised into position by the pulley system shown in Fig. 3. The tethersondes transmitted data approximately once every 2 s per sonde to a Vaisala SPS220T sounding processor operated in the 400-MHz frequency range. Since the sounding processor is not capable of simultaneously sampling all sondes at once, the effective sampling frequency for each sonde was approximately 1/12 Hz. Quite surprisingly, even in the urban street canyon the transmission signals were quite strong. Each tethersonde measured temperature, pressure, relative humidity, wind speed, and wind direction at the six vertical locations. Vaisala reports uncertainties of $0.5^\circ$C, 1.5 hPa, 5%, and 0.5 m s$^{-1}$ for the temperature, pressure, relative humidity, and wind speed, respectively. Unfortunately, additional uncertainty owing to interference between the tethersonde’s compass and the urban magnetic field was introduced into the wind direction measurements. Tests were run near the ground indicating that the wind direction reported by the sensor was accurate to approximately $\pm 10^\circ$. However, since the magnetic field in the urban area is expected to be highly spatially variable, once the sondes were raised into their final measuring location, it was impossible to determine the devices’ accuracy with great precision. Fortunately, visual inspection of the direction of the tethersondes and the repeatability of the results indicated that the measurements were at least accurate to $\pm 22.5^\circ$.

As indicated in Fig. 1, a Pacific Northwest National Laboratory (PNL)-operated sodar, a U.S. Army Dugway Proving Ground–operated Portable Weather In-

![Fig. 3. Photo of the tethersonde tower system (UUT) looking at the 101 Park Avenue building located at the southeastern end of the Park Avenue street canyon indicating winds coming from the west. (Photo courtesy of A. Kennedy.)](image)

<table>
<thead>
<tr>
<th>Tower</th>
<th>$x$ (m)</th>
<th>$y$ (m)</th>
<th>Sensor heights (m)</th>
<th>Sonic anemometer model</th>
<th>Sampling frequency (Hz)</th>
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<td>UU3</td>
<td>-118.1</td>
<td>-15.6</td>
<td>3.1, 4.16, 5.04, 7.24, 9.84</td>
<td>Campbell Scientific CSTAT3</td>
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<td>OU1</td>
<td>-85.3</td>
<td>-15.9</td>
<td>1.5, 3.0, 5.46, 9.86, 15.65</td>
<td>R. M. Young 8100</td>
<td>10</td>
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<tr>
<td>OU2</td>
<td>-90.0</td>
<td>-8.3</td>
<td>1.5, 2.96, 5.97, 9.91, 15.08</td>
<td>R. M. Young 8100</td>
<td>10</td>
</tr>
<tr>
<td>ASU</td>
<td>-22.8</td>
<td>-8.6</td>
<td>5.0</td>
<td>R. M. Young 8100</td>
<td>10</td>
</tr>
<tr>
<td>UUT</td>
<td>-13.3</td>
<td>-23.2</td>
<td>1, 5, 10, 20, 30, 40</td>
<td>Vaisala TS111</td>
<td>$\sim 1/12$</td>
</tr>
</tbody>
</table>

Table 1. Summary of the towers, instruments, and locations of the equipment used in the present work. Note that the $x$–$y$ locations are relative to the southeast corner of the building labeled “sonic building” in Fig. 2.
formation Display System (PWID), and an Indiana University (IU)-operated sonic anemometer were utilized to define the upstream mean wind speed, wind direction, and atmospheric stability. The PNNL sodar was a Scintec Flat Array sodar Model MFAS located less than 2 km south of the CBD near Wheeler Park (35.45°N, 97.53°W). The Dugway PWID consisted of an R. M. Young model 05103 wind monitor, datalogger, power regulator, Campbell Scientific CS500 temperature–humidity probe, a tripod, and an enclosure. Data were sampled every second and averaged over a 10-s interval. The 10-s averages were sent back to a computer via telemetry. The PWID that was used for this study was mounted approximately 50 m above ground on a 25-m tower located on a five-story local post office building (320 SW 5th Street; 35.46°N, 97.52°W) directly upwind of the CBD. The wind speed and direction information from this tower were used to define the upstream reference velocity at the average building height. The data from the sodar were used to provide a secondary estimate of the upwind conditions. In general, during the periods considered, the agreement between the two instruments was quite good.

The IU tower used in this work was the Tyler Media A tower located approximately 6 km south of the OKC CBD (35.42°N, 97.51°W) in a relatively homogeneous residential area with surrounding buildings that were approximately two stories high. The IU sonic anemometer used for the upstream stability measurements was a Campbell Scientific CSAT3 model that acquired data at 10 Hz and was located at the 79.6-m level of the tower.

3. Data processing

The results presented in section 5 below represent a subset of a total of approximately 48 h of data that were acquired from 29 June through 29 July 2003 from each of the sonic anemometers mounted to the UU3, OU1, OU2, and ASU towers. The 48 h of data were broken up into three datasets representing the three stability regimes considered as follows: 20 h, stable; 16 h, unstable; and 12 h, neutral. The fluctuating components of velocity and temperature were calculated by first linearly detrending the raw dataset using 5-min windows. The detrended data were then used to calculate 15-min averages of various turbulence statistics (i.e., momentum fluxes, heat fluxes, turbulent kinetic energy, and variances). Fifteen-minute averaging periods were chosen because tests of the computed variances and fluxes showed convergence to a steady value in approximately 15 min regardless of the upstream stability or wind direction. The above process was applied to all blocks of data gathered on different days and from different sonic anemometers. An ensemble average for each anemometer and stability category was then computed from the mean of all 15-min-averaged quantities. The error bars presented in the plots represent the standard deviation associated with the ensemble averaging process. Table 2 provides information regarding the mean wind speed and wind direction upstream of the urban core at 50 m above ground as obtained from the Dugway PWID. Times during which data were acquired are given in local time beneath each stability category.

<table>
<thead>
<tr>
<th>Local times of datasets</th>
<th>0500–1000</th>
<th>0100–0300</th>
<th>1400–2000</th>
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<td>Yeardays of datasets (2003)</td>
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<td>190</td>
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<td>200</td>
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</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Stabilty</th>
<th>$z/L &gt; 0.2$</th>
<th>$-0.2 &lt; z/L &lt; 0.2$</th>
<th>$z/L &lt; -0.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind direction (°)</td>
<td>190.2</td>
<td>183.3</td>
<td>186.4</td>
</tr>
<tr>
<td>Mean wind speed (m s⁻¹)</td>
<td>8.3</td>
<td>6.4</td>
<td>6.9</td>
</tr>
<tr>
<td>Standard deviation of mean wind direction (°)</td>
<td>8.2</td>
<td>14.6</td>
<td>12.6</td>
</tr>
<tr>
<td>Standard deviation of mean wind speed (m s⁻¹)</td>
<td>1.5</td>
<td>1.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>
All of these data were processed into 15-min averages and ensembles of these 15-min averages were calculated. As indicated in Table 2, the upstream winds during the periods considered were southerly to southwesterly (170°–190°) based on the 50-m Dugway PWID measurements.

The notation utilized for averaging is as follows: for time averages the standard Reynolds averaging notations is used (e.g., \( u = \bar{u} + u' \)) and for ensemble averages brackets (i.e., \( \langle \rangle \)) are used. Hence, the ensemble average of the vertical transport of the along-canyon momentum would be written as \( \langle \overline{u'w'} \rangle \).

It should be noted that the authors recognize that within an urban street canyon, the presence of relatively large vertical velocities can introduce “angle of attack” errors associated with the factory sonic anemometer calibrations that do not account for significant vertical velocities such as those described by van der Molen et al. (2004) and Gash and Dolman (2003).

In this work, the standard manufacturer-provided calibrations were used. Figure 4 shows the mean vertical and horizontal velocities measured within the canyon. An estimate of the mean wind angle between the horizontal and vertical components using the top Campbell Scientific CSAT3 anemometer on the UU3 tower yields an angle of attack of approximately 11°. According to Pahlow and Parlange (2005), the CSAT3 has a (co)sine error (Gash and Dolman 2003) of ±3% for angles of attack of 10° and ±6% for an angle of attack of 20°.

4. Park Avenue mean and turbulent statistics

The data considered for the present analysis were grouped by wind direction and atmospheric stability. Only winds nominally out of the south were considered (as determined by the Dugway PWID; see Table 2) and the upstream atmospheric stability conditions were classified into three broad categories (using the IU sonic anemometer data) in an attempt to clearly identify stability effects on turbulence statistics within the Park Avenue street canyon. Note that, ideally, the wind speed, wind direction, and stability would have all been determined at a single site; however, a single reliable instrument that provided all of the necessary data at one point was not available. Even though the IU tower was several kilometers upstream, the conclusions presented in this work, based on broad stability categories, should not be affected since the land cover and land use over the upstream region was relatively homogeneous.

The data were grouped into the following three \( z/L \) categories: stable \((z/L > 0.2)\), neutral \((-0.2 < z/L < 0.2)\), and unstable \((z/L < -0.2)\). Here, \( L \) is the Monin–Obukhov length scale and was calculated as follows:

\[
L = -\frac{u_0^3}{g \frac{k}{T_S} w T_S}
\]

where \( u_0 \) is the friction velocity, \( k \) is the von Kármán constant (taken to be 0.4), \( g \) is the gravitational acceleration constant, \( T_S \) is the mean absolute sonic temperature, and \( w T_S \) is an estimate of the 15-min-averaged local kinematic heat flux. In this paper, the coordinate system for the winds is defined according to the geometry of the street canyon and coincides with standard meteorological coordinates. That is, winds from the south are in the positive \( y \) direction (\( v \) velocity; denoted “cross canyon”) and winds from the west are in the positive \( x \) direction (\( u \) velocity; denoted “along canyon”). As indicated in Table 2, the mean winds at a height of 50 m measured upstream of the city were slightly out of the southwest and were relatively consistent. The average wind speeds at 50 m ranged between 6.4 and 8.3 m s\(^{-1}\) with the largest wind speeds occurring during the stable period. The higher wind speeds at the 50-m level during the night are consistent with the regular observation of a nocturnal jet upstream of Oklahoma City during the experiment (Lundquist and Mirocha 2006).

a. Mean velocity and temperature

Figures 4–6 show a limited set of dimensional vertical profiles of ensembles of 15-min averages of the along-canyon, cross-canyon, and vertical velocities for the three atmospheric stability cases considered for southerly upstream winds. A more complete analysis of the mean winds for a wider range of upstream conditions can be found in Pol and Brown (2006) and Nelson et al. (2007a). Note that the horizontal bars at each data
point represent the standard deviation in the ensemble average. In these plots, the vertical coordinate $Z$ is non-dimensionalized by the average height of the buildings directly surrounding the street canyon. For the towers analyzed on the western end of the canyon and in the center of the canyon, the along-canyon winds are predominately positive (from the west), while the ASU tower on the eastern edge of the canyon indicates a slight easterly flow (except during unstable periods). This is consistent with the observations of Pol and Brown (2006) and Nelson et al. (2007a). A near-surface wall-jet feature can be observed in the mean horizontal velocity profiles observed during the stable and neutral cases. Specifically, the velocities increase as the surface is approached before going to zero at the wall. Near-surface jets were also noted by Nelson et al. (2007a) in the Park Avenue street canyon. They conjectured that the jets form as a result of high-momentum fluid being diverted down into the canyon by the taller isolated buildings in the CBD. This high-momentum fluid is thought to impact the ground, forming divergence regions that produce outflow in the form of near-wall jets.

As might be expected, all velocity components are more uniformly distributed in the vertical direction for the unstable cases as a result of enhanced mixing during convective periods. In addition, the cross-canyon winds during the unstable periods are much smaller than the neutral and stable cases. For the periods considered in this work, the mean vertical velocities showed no obvious along-canyon vortex characteristic of idealized street canyons (Oke 1987). This is most likely a result of the nonidealized nature of the geometry of the street canyon (variable-height buildings, gaps in the street canyon, cars, trees, etc.). The mean vertical velocities were always positive except for the upper portion of the OU1 tower during neutral and stable periods.

Figure 7 shows vertical profiles of wind speed, wind direction, and the virtual potential temperature difference obtained from the tethered tower shown in Fig. 3. All three plots show relatively well mixed conditions for all stabilities and show evidence of the effect of a 5.5-m-tall deciduous tree located within 5 m of the tower at the 0.1$Z/H$ level. Above 0.2$Z/H$, the winds are relatively constant in strength and direction (westerly) with height. The U.S. Army Dugway Proving Ground (DPG) acquired similar data on the opposite side of the street (data not shown) that often showed flow in the opposite direction (easterly), indicating the presence of a wall-normal vortex that spanned the depth of the eastern end of the canyon. This wall-normal vortex has been described quite extensively by Brown et al. (2004) and Pol and Brown (2006) for the Park Avenue street canyon. For upstream winds normal to the street can-

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**Fig. 4.** As in Fig. 3, but for unstable upstream conditions.

**Fig. 5.** As in Fig. 4, but for neutral upstream conditions.

**Fig. 6.** As in Fig. 4, but for unstable upstream conditions.

**Fig. 7.** Vertical profiles of (a) wind speed, (b) wind direction, and (c) virtual potential temperature difference on the tethered tower for stable, neutral, and unstable upstream conditions as a function of $Z/H$. 
yon, this vortex is quite persistent in the Park Avenue canyon. This feature has also been observed in other street canyons such as the one described by Hoydysh and Dabberdt (1988).

Slightly stronger winds were observed within the canyon during the unstable periods. This is likely a result of enhanced turbulent momentum transport due to buoyancy during the day. The virtual temperature differences within the canyon were observed to be relatively small (less than ~0.5 K). This observation is consistent with the observations of Kanda et al. (2005) and Nakamura and Oke (1988) who found temperature differences of around 1 K. The virtual potential temperature difference above ~0.2Z/H decreases slightly with height to the top of the building, with the largest decrease associated with the unstable period. During the neutral upwind periods, the two temperature measurements nearest the ground were actually lower than at building-top measurement level. This kink near the surface may be attributed to the presence of the tree located just upstream of the two lowest sensors on the tower. Unfortunately, very little data were acquired for situations in which the sensors were upstream of the tree to verify this hypothesis. Also, care should be taken in interpreting the temperature results since the maximum differences in the temperatures are just under 0.5 K and the accuracy of the instrument is ±0.5°C. However, using the ensemble statistics, the standard error of the mean is ~0.05 K, yielding a 95% confidence interval of approximately ±0.1 K.

b. Turbulence statistics

Figure 8 shows nonnormalized turbulent stresses as a function of height for the four towers in the street canyon. For the neutral conditions shown (which are representative of the stable and unstable measurements also), the stresses are in general quite small. Near the surface, positive (\mu \w) fluxes are indicative of a local upward transport of along-canyon momentum. This observation is commensurate with the mean wind observations that suggested the existence of a near-surface jet. Above this level, (\mu \w) is extremely small but negative on the OU towers and positive on the UU3 tower. The vertical turbulent transport of the cross-canyon momentum (\nu \w) is downward and quite small for all of the towers below ~0.1Z/H. Above this level, (\nu \w) is still very small but upward. These data indicate a vertical convergence of (\mu \w) and divergence of (\nu \w) between ~0.05Z/H and 0.1Z/H.

Figures 9–11 are plots of the turbulence intensity calculated as the velocity variance normalized by the magnitude of the mean local velocity vector. The variances are...
given by $\sigma_u = \sqrt{\langle u'^2 \rangle}$, $\sigma_v = \sqrt{\langle v'^2 \rangle}$, and $\sigma_w = \sqrt{\langle w'^2 \rangle}$, while the magnitude of the mean local velocity vector is calculated using $|V| = \sqrt{\langle u'^2 + v'^2 + w'^2 \rangle}$. In general, in the lower third of the canyon, regardless of atmospheric stability, the turbulence intensities are quite large ($0.2 < \sigma_u/|V| < 0.65, 0.65 < \sigma_v/|V| < 0.4, 0.1 < \sigma_w/|V| < 0.4$) and the profile shapes are very similar, with $\sigma_u/|V|$ decreasing more rapidly as the ground is approached. The intensities at the edges of the canyon (ASU and OU3) are larger than those at the center of the canyon (OU1 and OU2). This may be a result of the large shear present at the interface of the north–south-oriented street canyons (aligned with the dominant upstream wind direction) and the east–west-oriented Park Avenue street canyon. All of the local turbulence intensities appear to be more uniform with height during the unstable periods than the stable and neutral cases, but the magnitudes are very similar for all cases.

Figure 12 is a plot of the ensemble-averaged turbulent kinetic energy, $TKE = \langle \frac{1}{2}(u'^2 + v'^2 + w'^2) \rangle$, normalized by a local scaling velocity $V_s$ that represents the local magnitude of the vertical transport of the horizontal momentum given by $V_s(x, y, z) = \sqrt{\langle u'w'(x, y, z)^2 + \langle w'w'(x, y, z)^2 \rangle^{1/4}}$. As shown in Fig. 12, this normalization produces a reasonable collapse of the data for all stabilities. Away from the ground ($Z/H > 0.1$), the ratio appears to approach a constant value of approximately 4–7 during stable periods, 4–10 during neutral periods, and 8–12 during the unstable periods. These values for the neutral case appear to approach similar ratios measured under neutral conditions in the roughness sublayer above idealized urban roughness elements where $TKE/V_s^2 \sim 4.3$ (Macdonald et al. 2002) and within the classical inertial sublayer (ISL) where $TKE/\bar{u}_s^2 \sim 5.5$ (Panofsky and Dutton 1984). In the inertial sublayer studies, $\bar{u}_s$ is the constant friction velocity. In addition, the general behavior of increasing $TKE/V_s^2$ values with decreasing stability is also consistent with classical ISL work (Panofsky et al. 1977).

As shown in Fig. 12, as the ground is approached ($ZH < 0.1$), there is a rapid increase in the $TKE/V_s^2$ ratio, that is, a decoupling from the ISL ratio regardless of the atmospheric stability. The increased $TKE/V_s^2$ is commensurate with the street canyon observations described in Nelson et al. (2007a,b) and also described by Rotach (1993). That is, as the ground surface is approached, there is a sharp drop in correlation between the normal and shear stresses that is a result of a more rapid decrease of the shear stresses than the normal stresses. Since this $TKE/V_s^2$ behavior is relatively insensitive to stability (and time of day), it is not likely a result of factors such as traffic-produced turbulence (e.g., Di Sabatino et al. 2003) or other urban activity that is much stronger during the day than at night.

Figures 13–15 are plots of the kinematic heat flux within the street canyon given by $\langle u' T_S \rangle$, $\langle v' T_S \rangle$, and $\langle w' T_S \rangle$. The magnitudes of all three heat fluxes are quite similar ($0 < \langle u' T_S \rangle < 0.08$ $\text{m K s}^{-1}$), but exhibit significant spatial variability depending on the atmospheric stability. The along-canyon heat flux $\langle u' T_S \rangle$ for all of the towers is from east to west for all stabilities. The magnitude, spatial variation (both horizontal and vertical), and the variance about the ensemble average (indicated by the horizontal error bars in the figures) of $\langle u' T_S \rangle$ increases with increasing instability; the largest horizontal variation of $\langle u' T_S \rangle$ occurs during unstable periods at the base of the canyon. This spatial variation is likely a result of local heating associated with different building materials and radiant exposure.

Near the ground, the cross-canyon heat fluxes $\langle u' T_S \rangle$ are nearly as large as the vertical heat fluxes but de-
crease approaching zero with increasing height for the stable and neutral periods. For the neutral and stable periods, \( \langle w' T_S \rangle \) is generally from south to north, while in the unstable case the turbulent flux is from north to south. This can be explained by the solar heating of the southerly facing building faces during midday and more northerly oriented faces early in the morning and in the evening. Also, during the unstable periods there is a strong cross-canyon heat convergence near the ground. Figure 15b shows \( \langle w' T_S \rangle \) as measured by OU towers that were directly opposite each other in the cross-canyon direction.

As might be expected in an urban area, the vertical heat flux \( \langle w' T_S \rangle \) is always positive regardless of the up-stream atmospheric stability. The observations (Figs. 13–15) indicate an increase in \( \langle w' T_S \rangle \) from the ground to a maximum at \( Z/H \sim 0.06 \). The vertical heat flux then decreases with height in the canyon. In the neutral and stable cases, \( \langle w' T_S \rangle \) is still positive up to \( Z/H \sim 0.3 \) but is very small. In the unstable case, \( \langle w' T_S \rangle \sim 0.03 \) m K s\(^{-1}\) at \( Z/H \sim 0.3 \). Figure 15c also indicates that the horizontal spatial variation of \( \langle w' T_S \rangle \) is greatest in the lowest 20% of the street canyon during unstable periods and tends to approach a common value near \( Z/H \sim 0.3 \). As noted above, this variation is likely a result of heterogeneous surface heating associated with different urban materials and variable solar heating during the day.

Because of the large spatial variations of the turbulent heat fluxes in the canyon, it is expected that warming within the street canyon should at least be partially caused by a turbulent heat flux convergence. That is, the time rate of change of temperature in the canyon should be proportional to (e.g., Stull 1988)

\[
- \left( \frac{\partial \langle w' T_S \rangle}{\partial x} + \frac{\partial \langle w' T_S \rangle}{\partial y} + \frac{\partial \langle w' T_S \rangle}{\partial z} \right). \tag{1}
\]

Using the UU and OU towers during the unstable periods, each of the terms in Eq. (1) has been estimated using very simple finite-difference approximations. The UU3 and OU1 towers can be used to estimate the difference between the along-canyon heat flux at \( Z/H \sim 0.06 \). Here, \( \Delta \langle u' T_S \rangle \sim -0.085 \) m K s\(^{-1}\) over a tower separation distance of \( \Delta x \sim 32.8 \) m that contributes to canyon warming. Meanwhile, the cross-canyon convergence of the heat flux at the lowest level can be estimated by the difference between the cross-canyon heat flux \( \Delta \langle v' T_S \rangle \sim -0.045 \) m K s\(^{-1}\) over the OU1 and OU2 tower separation distance of \( \Delta y \sim 7.6 \) m. Hence, the cross-canyon heat flux also contributes to canyon warming. For the vertical heat flux above \( Z/H \sim 0.06 \), the difference between the vertical heat flux measured...
by sensors separated by a distance of $\Delta z \sim 14.2 \text{ m}$ was about $\Delta(w^{-1}T_{\theta}^{-1}) \sim -0.07 \text{ m K s}^{-1}$, which is similar to the along-canyon and cross-canyon heat flux convergences. While the exact magnitudes of these estimates are questionable because of the poor spatial resolution of the measurements, these simple estimates do indicate that all three flux gradients contribute to a net warming of the canyon.

5. Conclusions

The JU2003 Park Avenue street canyon field study has produced a large unique wind and concentration dataset that has helped add to the knowledge base associated with flow within urban areas. The data presented here focus on turbulence statistics in the lower 30% of a street canyon, a region in which it is particularly difficult to obtain laboratory measurements. Since this is the region where humans spend most of their time and where most pollutants are emitted, it is of great interest. The purpose of this work was to add insight into a number of questions regarding the effect of upstream atmospheric stability on turbulence statistics deep within an urban street canyon. While all field experiments represent case studies that are difficult to generalize, an attempt has been made here to extract and describe more generic features associated with real urban canyon flows subjected to a limited range of varying upstream stabilities.

Three broad stability classification regimes were chosen for nominally southerly winds: stable ($z/L > 0.2$), neutral ($-0.2 < z/L < 0.2$), and unstable ($z/L < -0.2$). In general, most of the momentum-related turbulence statistics were insensitive to upstream atmospheric stability, while the energy-related statistics (potential temperatures and kinematic heat fluxes) were more sensitive. In particular, the local turbulence intensity inside the street canyon varied little with atmospheric stability, but always had quite large magnitudes. The turbulent kinetic energy normalized by a local shear stress velocity showed a clear repeatable pattern that was stability invariant. In particular, $\text{TKE}/V_a^2$ begins to rapidly increase as the ground is approached below a height of approximately $Z/H \sim 0.1$. If this behavior can be validated by additional experiments, it will be particularly useful for dispersion modelers attempting to parameterize turbulence in urban areas. For example, understanding this behavior is particularly useful for Lagrangian dispersion models that must relate variances to the local turbulent stress (e.g., Williams et al. 2002).

For energy transport, the findings here are similar to the findings of Nakamura and Oke (1988) and Santa-mouris et al. (1999) for real cities. The mean potential temperatures almost always decrease with increasing height within the street canyon and the vertical heat fluxes are always positive regardless of the atmospheric stability. The magnitude of all three components of the heat flux and the variability of the heat flux decreases with increasing atmospheric stability. This is likely a result of localized heating within the canyon. In addition, the cross-canyon and along-canyon fluxes are as large as the vertical component of the heat fluxes. Estimates of the gradients of the kinematic heat fluxes (i.e., heat flux convergence) during unstable conditions indicate that in the lower portion of the street canyon the contributions from all three components are nearly equal. These heat flux findings may be particularly useful for developing urban energy balance models that utilize spatially explicit sensible heat flux parameterizations (e.g., Masson 2000).

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