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ARTICLE

Momentum and Turbulent Kinetic Energy Budgets Within the Park Avenue Street Canyon During the Joint Urban 2003 Field Campaign

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Abstract Very few attempts have so far been made to quantify the momentum and turbulent kinetic energy (TKE) budgets within real urban canopies. In this study, sonic anemometer data obtained during the Joint Urban 2003 field campaign in Oklahoma City, U.S.A. were used for calculating the momentum and TKE budgets within a real-world urban street canyon. Sonic anemometers were deployed on multiple towers in the lower half of the canyon. Gradients in all three principal directions were included in the analyses. The storage and buoyancy terms were found to have negligible contributions to both the momentum and TKE budgets. The momentum budgets were generally found to be more complex than a simple balance of two physical processes. The horizontal terms were found to have significant and sometimes dominant contributions to the momentum and TKE budgets.

Keywords Momentum budget · Street canyon · Turbulent kinetic energy budget · Urban turbulence

1 Introduction

Urban areas dramatically affect the flow characteristics of the atmospheric surface layer through a variety of mechanisms including advection, enhanced shear, wake diffusion, etc. (Roth 2000). The urban roughness produces a flow in the urban canopy layer (UCL) and urban roughness sublayer (URSL) that is three-dimensional (3D) and heterogeneous, invalidating

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the assumptions typically used for simplifying budget analyses in the inertial sublayer (ISL). Hence, very few terms in the turbulent kinetic energy (TKE) and momentum budgets can be systematically neglected a priori. Examples of TKE budget analyses within real UCLs and URSLs include the studies of Louka et al. (2000) and Christen et al. (2009). In addition, the flow characteristics within the UCL are often treated in the area-averaged sense (Gayev and Savory 1999; MacDonald 2000; Cheng and Castro 2002; Bentham and Britter 2003) and are therefore approximations to the actual flow phenomena that occur locally.

The limited number of field studies is principally due to the complex nature of the flow in urban areas and the inherent difficulties in siting instruments in actual urban areas. As a result of this lack of observations, a great deal of uncertainty remains in understanding the dominant physical processes and the extent to which these processes interact with each other. This study uses the 3D sonic anemometer data taken from multiple towers in Oklahoma City's Park Avenue street canyon during the Joint Urban 2003 (JU2003) field campaign to explore the TKE and momentum budgets within the UCL of a real-world urban core. The contributions from all of the terms of the storage (unsteady), advection, and turbulent transport terms of all three velocity components are calculated. In addition, all the components of the storage, advection, buoyant production/destruction, mechanical shear production, and turbulent transport terms in the TKE budget are calculated. The results from the 3D budget analyses are compared with the commonly used ISL assumptions that have been employed in previous urban TKE budget analyses. In addition, an error analysis of the finite difference gradient computation method, the method used for calculating the various terms of the momentum and TKE budgets in the Park Avenue street canyon, was performed using data from a wind-tunnel model of the Park Avenue street canyon.

2 Experimental Details

The Joint Urban 2003 field campaign was performed from 29 June through 30 July 2003 in Oklahoma City, Oklahoma, USA (Allwine et al. 2004; Brown et al. 2004). Oklahoma City consists of a relatively large urban area located in idealized terrain devoid of major topological features. A section of Park Avenue found in the urban core of Oklahoma City was selected to concentrate a large number of measurements in a single urban canyon (Nelson et al. 2007a,b; Ramamurthy et al. 2007; Klein and Clark 2007). The average building height (H) for the selected urban canyon was approximately 50 m with a corresponding canyon separation (S_1) of approximately 25 m and canyon length (L) of approximately 150 m, yielding $HS_1^{-1} \approx 2$. An analysis of the building dataset in the urban core of Oklahoma City performed by Burian et al. (2003) found the plan area fraction (λ_p) to be 0.35 and the frontal area index (λ_f) to range between 0.14 and 0.22 depending on wind direction. A value of λ_f of 0.14 corresponded to winds out of the east and west, while $\lambda_f \approx 0.19$ for winds out of the north and south. The largest value of 0.22 corresponded to winds that were oblique to the orientation of the streets in the urban core (i.e. nominally north-easterly, north-westerly, south-easterly, or south-westerly winds). Winds during the experiment were typically south, south-easterly, or south-westerly. Based on the suggestions of Grimmond and Oke (1999), which are intended to characterize the average flow over a large region and not an individual street canyon, these morphometric parameters indicate that the observed street canyon flow should be in a transition regime between wake interference and skimming flow. However, when looking at the flow at individual street canyons and intersections in real urban areas, the flow is much more complex than is suggested by the simple morphometric parametrizations (Belcher 2005; Dobre et al. 2005; Nelson et al. 2007b; Pol and Brown 2006).

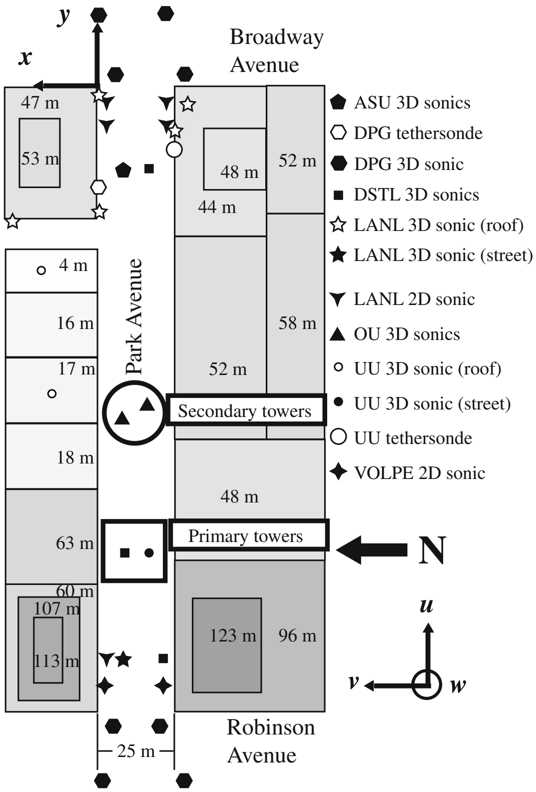


Fig. 1 Plan view schematic showing the relative locations of the sonic anemometers deployed in and around the Park Avenue street canyon. Sonic locations are measured relative to the south-east corner of the north-east most building in the canyon. A *box* surrounds the primary towers used for computing the momentum and TKE budgets. A *circle* surrounds the secondary towers that were used in obtaining the along-canyon gradients. The *numbers* on top of the buildings indicate the building height. The diagram is not to scale

Figure 1 shows the relative locations of the wind instruments deployed in the Park Avenue urban canyon. Forty-three 3D sonic anemometers (sonics) were placed in and around the urban canyon, acquiring nearly continuous data throughout the entire month of July. Several agencies were involved in the acquisition of the data including Arizona State University (ASU), US Army Dugway Proving Ground (DPG), UK Defence Science Technology Laboratory (DSTL), Los Alamos National Laboratory (LANL), University of Oklahoma (OU), University of Utah (UU) and John A. Volpe National Transportation Systems Center (VOLPE). During ten intensive observation periods (IOPs), when dispersion experiments were performed, an additional two 3D sonic anemometers and seven two-dimensional (2D) sonic anemometers were deployed on tripods at the ends of the canyon. Further details regarding the actual locations can be found in Nelson et al. (2007b).

The computation of the TKE and momentum budgets within the Park Avenue street canyon centre around four sonic anemometers listed as primary instruments in Table 1. These four anemometers, two on the DSTL tower and two on the UU tower both at the western end of the canyon interior (see Figs. 1, 2), were chosen for this analysis because they could be paired with other anemometers aligned in all the three principal directions within the canyon: along-canyon (x), cross-canyon (y) and vertical (z). This allows the gradients in all the three directions to be approximated. The principal towers used are encompassed in a black box, while the towers used for calculating the along-canyon gradients are encompassed in a black circle. The vertical gradients were approximated from a second-order polynomial curve fit of the data from three sonic anemometers following the algorithm found in Chapra and Canale (1998). It is noted that, in the Park Avenue street canyon, the along-canyon and cross-canyon

Table 1 Park Avenue 3D sonic anemometers used for budget analyses

Make and model	Tower label	Instrument class	X^a (m)	Y^a (m)	Z (m a.g.l.)	OF^b (Hz)
Gill ultrasonic	DSTL	Primary	−118	−8.4	3	1
Navy 3D		Secondary			5	
		Primary			10	
RM young	OU-1	Secondary	−90	−8.3	3.0	10
81000		Secondary			9.9	
RM young	OU-2	Secondary	−85.3	−15.6	3.0	10
81000		Secondary			9.9	
Campbell	UU-1	Primary	−118	−15.6	3.2	10
CSAT-3		Secondary			4.2	
		Secondary			5.0	
		Secondary			7.2	

[a] Distances are in the coordinate system defined in Fig. 1
[b] The listed output frequency (OF) of the DSTL instruments is actually 1-sec averages of the original 10-Hz data

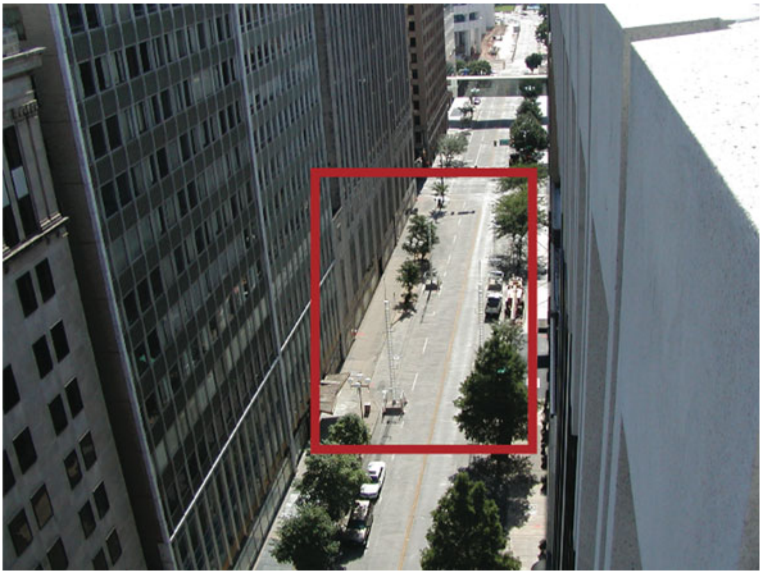


Fig. 2 Photograph taken from the roof of the building at the north-eastern corner of the Park Avenue street canyon looking west. Instrumented towers used for performing budget analyses are surrounded by a *red box*

directions correspond to the standard meteorological coordinates (i.e. positive u for winds from west to east and positive v for winds from south to north).

3 Data Processing

Nelson et al. (2007b) found that southerly and south-easterly winds produced very complex flow patterns in the canyon interior and hypothesized that such flow patterns were due to

Table 2 Time periods and prevailing conditions used for budget analyses

Start of time period	IOP	U_H (m s^{-1})	Direction (°)	u_* (S) (m s^{-1})	u_* (U) (m s^{-1})	HL^{-1} (S)	HL^{-1} (U)
13/7/2003 1100	5	4.3	221	0.37	0.27	−0.33	−0.82
16/7/2003 1300	6	4.9	186	0.58	0.52	−0.81	−0.64
16/7/2003 1400	6	4.8	188	0.54	0.52	−0.91	−0.58
16/7/2003 1500	6	5.2	184	0.50	0.45	−1.26	−0.81
28/7/2003 2300	10	5.5	190	0.54	0.35	0.038	−0.16
29/7/2003 0000	10	5.0	199	0.36	0.29	0.23	−0.29
29/7/2003 0100	10	4.5	209	0.26	0.18	0.60	−0.26
29/7/2003 0200	10	4.4	223	0.27	0.27	0.90	0.02
29/7/2003 0300	10	4.0	243	0.28	0.26	0.48	−0.13
29/7/2003 0400	10	3.7	250	0.26	0.27	0.51	0.05

The values for u_* and HL^{-1} are reported at both the suburban (S) and urban (U) sites

downdrafts of high momentum fluid into the canyon. It was also found that south-westerly winds produced westerly channelling throughout the canyon interior. Since the method used for approximating the horizontal gradients is necessarily crude due to the instrument spacing, the approximations of the gradients are insufficient to resolve excessively complicated flow phenomena. The amount of data available for analysis was restricted by the following factors: (1) All sonics on the towers involved in the analysis were required to be operational so that gradients in all three directions could be calculated. (2) Upwind direction was required to be from the south-west quadrant to ensure westerly channelling in the canyon. (3) The sum of the TKE production terms was required to be positive. The reasoning behind requirement 3 is that when these terms are negative, the measured flow is too complex for the crude method used for calculating gradients to be valid. Table 2 has the upwind conditions during the time periods that met the above mentioned criteria. The upwind wind speed (U_H) and the wind direction at the average building height (H) were measured at the Dugway Proving Ground prop-vane anemometer located above the roof of the post office building approximately 1 km south of the urban core (see Ramamurthy et al. (2007) for a map showing the location of the post office building relative to the Park Avenue street canyon). The upwind shear velocity (u_*) at H and Monin–Obukhov stability parameter (HL^{-1}) were measured at the Indiana University tower located in the suburban area approximately 6 km south of the urban core and on top of the building at the south-east corner of Park Avenue (see Fig. 1). The plots throughout the remainder of this study are grouped by daytime or nighttime periods.

The velocity data were sampled at 10 Hz; however, the only data available to the authors for the DSTL tower were 1-sec averages of the original 10-Hz data. The processed 1-Hz data from the DSTL tower were used for computing the flow statistics used in the budget analyses. Although this is unlikely to have a large effect on the mean velocities, it does potentially affect the turbulent fluxes. In addition, the flow within the UCL tends to be highly heterogeneous and three dimensional. Recent studies have shown that these conditions can cause errors in sonic anemometry measurements because of the fact that sonic anemometers are typically calibrated under conditions with little or no mean vertical velocity (Gash and Dolman 2003; Van der Mollen et al. 2004). Correcting for these effects requires the calibration of each of the various sonic anemometer geometries for a large range of angles of attack. The data presented here have not been corrected for these effects, since we do not have the proper calibration algorithms for each of the various makes and models of sonic anemometers used. However, in order to estimate the possible angle-of-attack errors, we first determined the maximum deviation from horizontal in the mean wind. It was 12° for the daytime hours and 24° for the nighttime hours. If the (co)sine corrections found for the Gill sonic anemometers in Gash and Dolman (2003) and Van der Mollen et al. (2004) are used for approximating the errors because of not correcting for angle of attack errors for all of the instruments used in this study, then the maximum mean angles of attack found in this dataset should result in ≈5% underestimate of the momentum flux measurements. This error is relatively small considering the gross simplification used for computing the gradients in this study, and should, therefore, have little effect on the conclusions presented herein.

Fluctuating quantities were computed using a 30-min running-block average to remove mesoscale meteorological effects. All of the data presented here are 1-hr averages with the exception of the storage terms which were computed by taking the finite difference of the two 30-min time periods, which were then used for computing the time derivative during the 1-hr averaging period. Typically budget analyses performed in the ISL involve rotating the coordinate system into the mean wind direction. However, the use of a finite difference gradient estimation requires the coordinate system to be aligned with the orthogonal directions in the sensor array to facilitate the calculation of as many terms as possible within the budgets.

4 Budget Analyses

4.1 Momentum Budget

The momentum budget can be formulated as (following Stull 1988):

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\delta_{i3} g + f_c \varepsilon_{ij3} \overline{U}_j - \frac{1}{\rho} \frac{\partial \overline{P}}{\partial x_i} + \nu \frac{\partial^2 \overline{U}_i}{\partial x_j^2} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j}. \quad (1)$$

where the overbar represents time averaging. However, due to the fact that the Coriolis term is only significant at very large scales and the viscous term acts over very small scales, both terms are neglected in the present analysis because of the scales of interest. The following equation is thus used for the analysis:

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\delta_{i3} g - \frac{1}{\rho} \frac{\partial \overline{P}}{\partial x_i} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j}. \quad (2)$$

The pressure (P) is separated into a portion that satisfies the hydrostatic balance (P_h) and a deviation from that balance (δP). Using the Bousinesseq approximation, the changes in density are equivalent to changes in virtual potential temperature (θ_V). Since by definition $-\rho^{-1} \partial P_\mathrm{h} / \partial z = g$, the terms of the vertical momentum budget associated with the hydrostatic balance cancel each other out yielding

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = \delta_{i3} g \frac{\overline{\delta \theta_\mathrm{V}}}{\overline{\theta_\mathrm{V0}}} - \frac{1}{\rho} \frac{\partial \overline{\delta P}}{\partial x_i} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j}. \quad (3)$$

The approximation of the momentum budget used herein is formed by taking the storage and the advection terms to the right-hand side of the equation and replacing the partial derivatives with finite differences.

$$0 = S + A + T + R_m. \quad (4)$$

Specifically the various terms of the momentum budget have been approximated as follows:

$$
\begin{array}{ll}
S = -\partial \overline{U}_i / \partial t & \text{Storage,} \\
A = -\overline{U}_j \partial \overline{U}_i / \partial x_j & \text{Advection,} \\
T = -\partial \overline{u_i' u_j'} / \partial x_j & \text{Turbulent transport,} \\
R_m = \delta_{i3} g \overline{\delta \theta_V} / \overline{\theta_{V0}} - \rho^{-1} \partial \overline{\delta P} / \partial x_i + \text{Errors} & \text{Residual.}
\end{array}
$$

The sonic anemometers used for the budget analyses (see Table 1) make it possible to explicitly calculate all of the storage, advection, and turbulent transport terms on both the UU and DSTL towers. The 3D sonic anemometers also measure a sonic temperature, which is often used for calculating the sensible heat flux (Schotanus et al. 1983; Hignett 1992). This sonic temperature could, in theory, be used for calculating the temperature gradient for the buoyancy term of the momentum budget. Unfortunately, we have found through personal experience in the field that the inter-instrument variation in magnitude of the temperature measured by sonic anemometers is large relative to the lapse rate measured within the Park Avenue street canyon (Ramamurthy et al. 2007). The temperature as measured by the sonic anemometers is therefore unsuitable for purposes of calculating differences between instruments. Only the UU tower had fine-wire thermocouples to accurately measure the temperature differences between instruments that are needed for the calculation of the buoyancy term in the vertical momentum budget. Unfortunately these instruments are extremely delicate and many were not operational during the time periods analyzed in this study. Ideally, a spatial average of the temperatures throughout the canopy would be used for obtaining the reference temperature. In the case of the Park Avenue dataset, only the measurements from the UU tower (when the fine-wire thermocouples were functioning) and the UU and Dugway Proving Ground (DPG) tethersondes at the far east end of the canyon are likely to have temperature measurements accurate enough to quantify the buoyancy term. These measurements were deemed insufficient to provide a reference temperature that could confidently be used for calculating the buoyancy term in the vertical momentum budget at the location of the UU and DSTL towers. The remaining terms that cannot be calculated from the existing data (i.e. the pressure gradient and the buoyancy terms) have been lumped together with all of the errors introduced through calculation methods, approximations, neglected terms, etc. to form the residual term, which takes on the value required to satisfy the momentum budget.

It is important to consider potential error sources in the methods used for performing the budget analyses presented in this study. Table 1 and Figs. 1–3 show that the horizontal gradients need to be approximated using simple forward or backward differences over rather large distances, especially in the along-canyon direction. Ideally the gradients needed to calculate the terms in the momentum and TKE budgets would be measured locally rather than spanning the large distances that are used due to the layout of the sensor array. As a result of the coarse spatial resolution of the sensor array in the horizontal direction, it is possible that we have under sampled some of the flow structures being measured. This could lead to erroneous interpretation of the data. To understand these effects better, we have utilized wind-tunnel data for the Park Avenue street canyon (Leitl and Schatzmann 2005; Klein et al. 2007). The wind-tunnel model provides a dataset with velocity measurements at a much higher resolution than that was achievable in the actual street canyon (effectively 3 m apart in the horizontal plane). Table 3 presents a comparison between the finite difference method and a gradient approximated using a second-order polynomial fit to the local data using a horizontal plane (effectively, 10 m a.g.l. at full scale) of normalized horizontal velocities from the wind-tunnel dataset. The wind-tunnel model was rotated to simulate Park Avenue

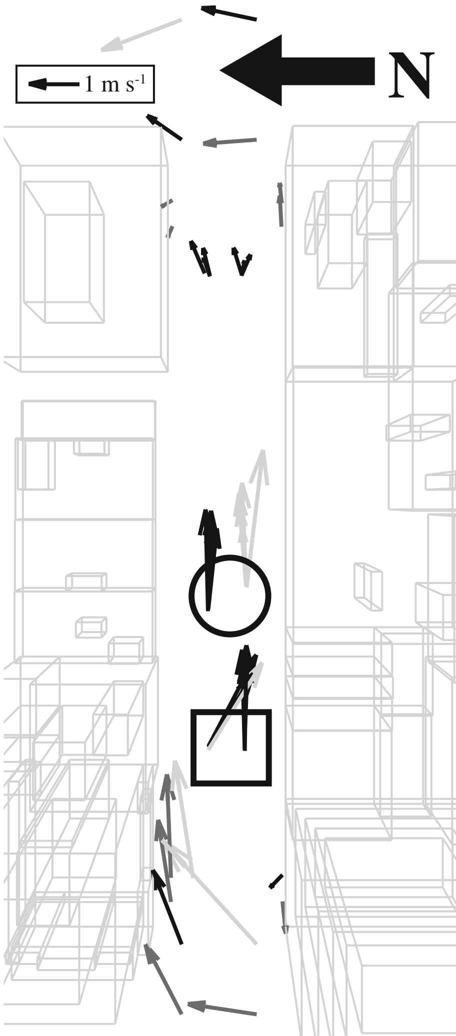


Fig. 3 Mean wind vectors at street level within the Park Avenue street canyon during IOP 10. The *vector colours* indicate vertical velocity: $\overline{W} < 0$ are *black*; $\overline{W} > 0$ are *light grey*; and 2D measurements are *dark grey*. Instruments used for budget analyses have been indicated as seen in Fig. 1. The diagram is to scale

under prevailing winds from 190° that produced westerly channelling flow similar to that which was used for these analyses (see Fig. 4).

At the primary sites, it can be seen that the largest gradients occur in the cross-canyon gradient of $\overline{V}$. For the largest gradients, the finite difference method overestimates the gradient calculated using the polynomial method by 31% at the UU tower location and by 17% at the DSTL tower location. Much more relative error is observed in the smaller gradients since they are often underestimated by an order of magnitude or even change sign. The errors in the smaller gradients are typical of numerical differentiation, which tends to amplify small uncertainties. Fortunately, the dominant gradient is an order of magnitude larger than any of the other gradients. Hence, the analyses presented below should be thought of as a first-order attempt to identify and quantify the dominant features and terms in the budgets in part of a single street canyon. The results presented here should not be interpreted as being

Table 3 Comparison of horizontal velocity gradient calculation methods using the Leitl and Schatzmann (2005) wind-tunnel data

Gradient	UU FD	UU poly	DSTL FD	DSTL poly	OU-1 poly	OU-2 poly
$H\partial(\overline{U}U_H^{-1})/\partial x$	0.0081	0.13	0.014	−0.024	−0.28	0.11
$H\partial(\overline{V}U_H^{-1})/\partial x$	−0.22	−0.35	0.040	−0.12	0.011	0.071
$H\partial(\overline{U}U_H^{-1})/\partial y$	−0.012	0.081	−0.012	0.19	0.68	0.71
$H\partial(\overline{V}U_H^{-1})/\partial y$	−2.1	−1.6	−2.1	−1.8	0.21	0.024

FD indicates the use of a finite difference method and *poly* indicates the use of a second-order polynomial approximation. All gradients have been normalized by the average building height and the upwind velocity at that height

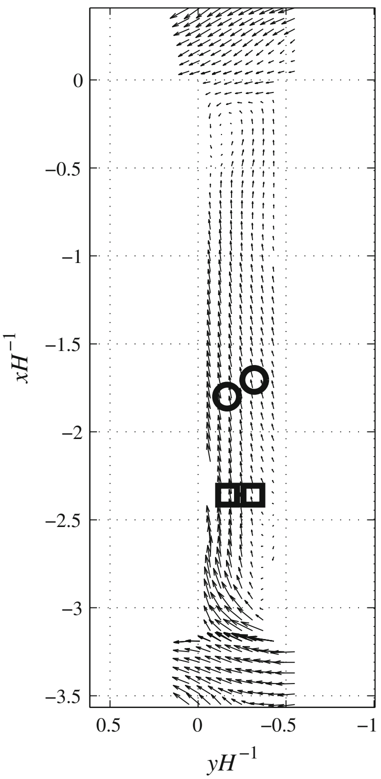


Fig. 4 Normalized velocity vectors at $z/H = 0.2$ from the wind-tunnel data of Leitl and Schatzmann (2005). Locations of the towers used in this analysis are indicated by the *squares* (primary) and *circles* (secondary)

representative of the UCL. A far more extensive instrument array would be required to obtain representative momentum and TKE budgets within the UCL.

4.2 Turbulent Kinetic Energy Budget

Similarly the TKE equation (Eq. 5 below) has been rearranged, the partial derivatives replaced with finite differences, and the term that cannot be calculated from the existing data (i.e. the pressure correlation term) has been lumped together with the errors to form a residual term that takes on the value required to satisfy the TKE budget equation,

$$\frac{\partial \overline{e}}{\partial t} + \overline{U}_j \frac{\partial \overline{e}}{\partial x_j} = \delta_{i3} \frac{g}{\overline{\theta_{\mathrm{V}}}} \overline{u_i' \theta_{\mathrm{V}}'} - \overline{u_i' u_j'} \frac{\partial \overline{U}_i}{\partial x_j} - \frac{\partial \overline{u_j' e}}{\partial x_j} - \frac{1}{\rho} \frac{\partial \overline{u_i' p'}}{\partial x_i} - \varepsilon, \tag{5}$$

and,

$$0 = S + A + B + P + T + D + R_{\mathrm{TKE}}. \tag{6}$$

Specifically, each of the terms in the TKE budget has been approximated as follows:

$S = -\partial \overline{e}/\partial t$	Storage,
$A = -\overline{U}_j \partial \overline{e}/\partial x_j$	Advection,
$B = \delta_{i3} g \overline{u_i' \theta_{\mathrm{V}}'}/\overline{\theta_{\mathrm{V}}}$	Buoyancy,
$P = -\overline{u_i' u_j'} \partial \overline{U}_i/\partial x_j$	Shear production,
$T = -\partial \overline{u_j' e}/\partial x_j$	Turbulent transport,
$D = -\varepsilon$	Dissipation rate,
$R_{\mathrm{TKE}} = -\rho^{-1} \partial \overline{u_i' p'}/\partial x_i + \mathrm{Errors}$	Residual.

To accurately measure the sensible heat flux, the measurements should be adjusted for humidity (Schotanus et al. 1983; Hignett 1992). Because the temperature measured by a sonic anemometer is based on the speed of sound in the air, humidity effects are inherently included in the measurement. The analysis performed by Hignett (1992) showed that not correcting for humidity caused an overestimation of the sensible heat flux measurement, due to the inclusion of the latent heat flux in the measurement. Thus, the heat flux measured by the sonic anemometers is more of a total heat flux as opposed to only a sensible heat flux, and is, therefore, more appropriate for purposes of calculating the buoyancy flux than a sensible heat flux measurement.

The dissipation rate is calculated from the velocity power spectral energy density in the inertial subrange as done by Louka et al. (2000) and Christen et al. (2009). Calculation of the dissipation rate employing Kolmogorov's similarity relationship and Taylor's hypothesis as outlined in Panofsky and Dutton (1984), namely

$$\varepsilon = \frac{2\pi f}{U} \left(\frac{f \Phi(u)}{\alpha} \right)^{3/2}. \tag{7}$$

The value of the Kolmogorov constant (α) has been taken as 0.53, the same one as proposed by Yeung and Zhou (1997). This method relies on the validity of Taylor's frozen turbulence hypothesis (Taylor 1938) and assumes that an undisturbed inertial subrange exists with local isotropy. Taylor's hypothesis fails when large fluctuations cause different wavenumbers to be transported at different velocities or when the effects of temporal variation are significant (Wyngaard and Clifford 1977), which are both likely to occur within the UCL. Thus, the validity of the use of Taylor's hypothesis is highly questionable in this region. It was also found in Nelson et al. (2007a) that the onset of the $-5/3$ slope, typical of the inertial subrange, was not indicative of the onset of local isotropy and that sonic anemometers were unable to adequately resolve the scales where local isotropy occurs. Given these factors, the dissipation rate values reported here should be viewed with caution.

5 Budget Analyses

5.1 Momentum Budget

The mean momentum budgets for the along-canyon, cross-canyon, and vertical directions within the Park Avenue street canyon for the selected daytime and nighttime hours are presented in Figs. 5 and 6, respectively. The terms S', A', T', R'_M in Figs. 5 and 6 are the terms in the momentum budgets normalized by $U_H^2 H^{-1}$. Lines are used for connecting the data points between the two vertical levels to assist in tracking the changes in the individual terms and not for implying that these lines are indicative of the behaviour of the budget in between the two levels. The first feature that is readily apparent is that the storage terms do not significantly contribute to any of the momentum budgets, suggesting that on the time scales used in this analysis, the flow can be considered to be quasi-steady state.

The residual terms are dominant in both of horizontal budgets for the daytime hours (Fig. 5a, b), indicating the importance of the pressure gradient term in these budgets (assuming that the errors in the analysis are small). The extreme values of the cross-canyon budget indicate that this budget can be dominant. The cross-canyon budget (Fig. 5b) is also primarily a balance between the advective and residual (pressure) terms. The balance between the advective and residual (pressure) terms is even stronger in the nighttime data (Fig. 6b). Further investigation of the cross-canyon budget indicates that the largest analysis errors in the calculation of the advective term were ≈31% (see Table 3). As a result, this constitutes an

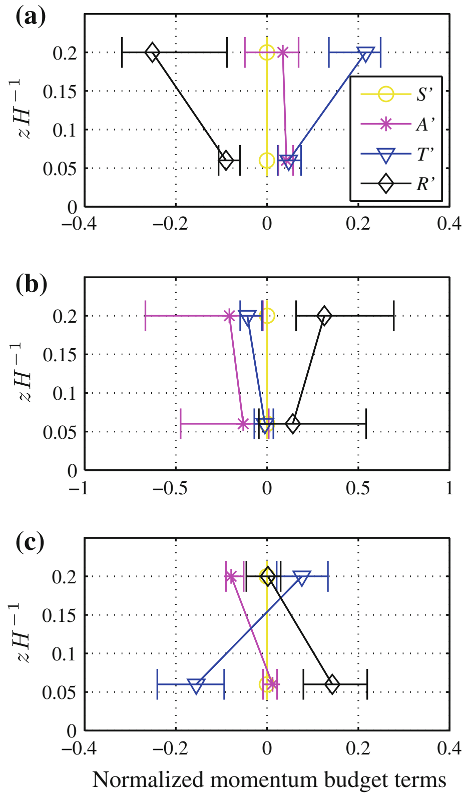
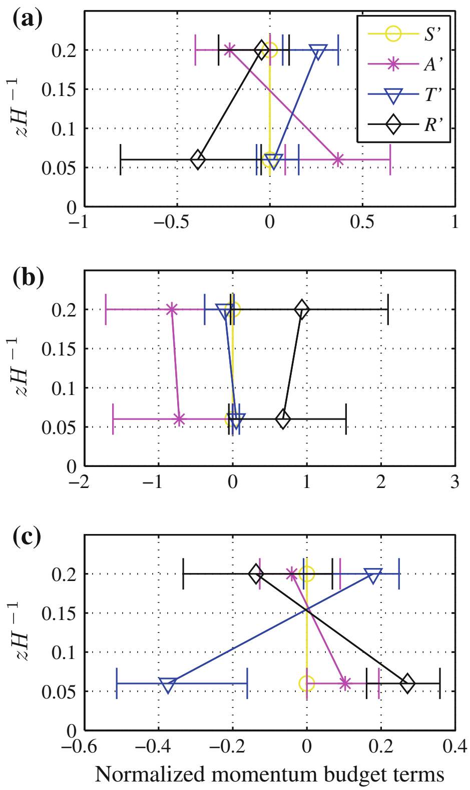


Fig. 5 Along-canyon (**a**), cross-canyon (**b**), and vertical (**c**) momentum budgets on the DSTL and UU towers during the selected hours of IOPs 5 and 6. The *horizontal bars* denote the extreme 1-hr average values for each term. The *prime symbol* indicates that the terms are normalized by $U_H^2 H^{-1}$

Fig. 6 Along-canyon (**a**), cross-canyon (**b**) and vertical (**c**) momentum budgets on the DSTL and UU towers during the selected hours of IOP 10. The *horizontal bars* denote the extreme 1-hr average values for each term. The *prime symbol* indicates that the terms are normalized by $U_H^2 H^{-1}$



approximate balance between the advection and pressure gradient terms in the cross-canyon budget. The significant terms in the cross-canyon budget are also about twice as large as the significant terms in the other two momentum budgets, which agrees with the gradient calculations from the wind-tunnel model of Park Avenue in Table 3 where the cross-canyon gradient of $\overline{V}$ was found to be at least an order of magnitude larger than the other gradients. Examining the mean velocity vectors in Fig. 3, it appears that this is due to the end vortex that is formed at the entrance of the canyon. Hence, these results should not be viewed as representative of the urban canopy in general but rather are localized phenomena. This assertion is also supported by the fact that the cross-canyon gradient of $\overline{U}$ is the dominant gradient in the wind-tunnel data at the OU tower locations (see Table 3).

The residual in the vertical momentum budget is more difficult to interpret than that in the horizontal budgets because it includes both the buoyancy and pressure gradient terms in addition to the analysis errors. The nighttime along-canyon (Fig. 6a) and vertical (Fig. 6c) budgets illustrate the difficulty in formulating a similarity theory for UCL flow. Since a simple two-term balance is not there, similarity analyses that rely on a balance of two physical processes cannot be used.

As mentioned above, the buoyancy term was not explicitly included in the vertical momentum budgets (Figs. 5c, 6c) because of the inability of the instruments at the primary towers to accurately measure mean temperature differences between instruments. However, the two tethersonde systems located at the eastern end of the canyon can be used as an estimate of the magnitude of the buoyancy term at the primary towers. The profile of buoyancy term is

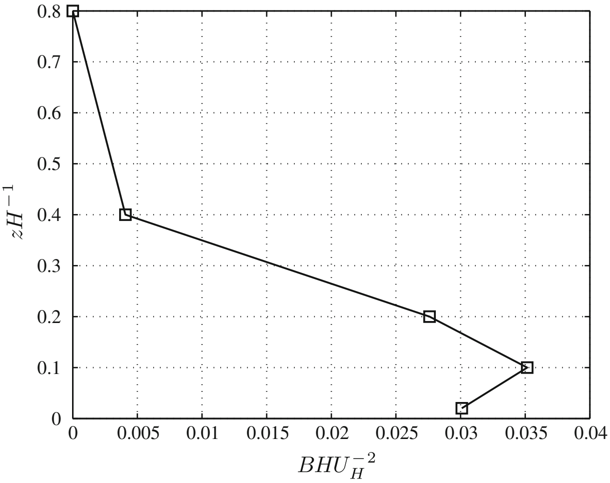


Fig. 7 Profile of the buoyancy term computed using the tethersonde data at the east end of the canyon during IOP 10

presented in Fig. 7. This profile was computed using the average temperature between the top level of the two tethersonde systems as the reference virtual potential temperature and measuring the difference between an adiabatic lapse rate and the measured virtual potential temperatures at the lower levels in the Park Avenue street canyon. As was found by Ramamurthy et al. (2007), the Park Avenue street canyon tends to be unstable even during the night, resulting in a positive contribution to the TKE buoyancy term during the nighttime hours of IOP 10 seen in Fig. 7. The results of Ramamurthy et al. (2007) are consistent with other investigations into the effects of thermal stability in urban areas such as Nakamura and Oke (1988). A comparison of the magnitude of the buoyancy terms in Fig. 7 with the vertical momentum budget residual term in Fig. 6c reveals that the buoyancy term measured at the east end of the canyon is 5–10 times smaller than the 6-hr averaged residual term. This indicates that if (i) the errors in the analysis are relatively small compared to the significant terms, and (ii) the measurements made at the eastern end of the canyon are representative of the flow at the western end of the canyon, then the residual term is principally due to the pressure gradient. The negligible effect of buoyancy indicates that, as one might expect, momentum transfer within Park Avenue street canyon is dominated by mechanical processes.

5.2 Turbulent Kinetic Energy Budget

The TKE budget on the DSTL and UU towers during selected daytime and nighttime hours are shown in Figs. 8 and 9, respectively. The terms S', A', B', P', T', D' and R'_{TKE} in Figs. 8 and 9 are the terms in the TKE budgets normalized by $U_H^3 H^{-1}$. Both the daytime and nighttime TKE budgets are complex, but there are some features that stand out, and they are easy to interpret. Similar to what was found in the momentum budgets, the storage and buoyancy terms have negligible contributions to the TKE budgets. The negligible storage term indicates that over these time scales, the TKE budget in Park Avenue can be considered to be in a quasi-steady state. The buoyancy term also has a negligible contribution to the TKE budget (Ramamurthy et al. 2007) even though the daytime hours were under unstable conditions and the nighttime hours were under thermally stable atmospheric conditions upstream

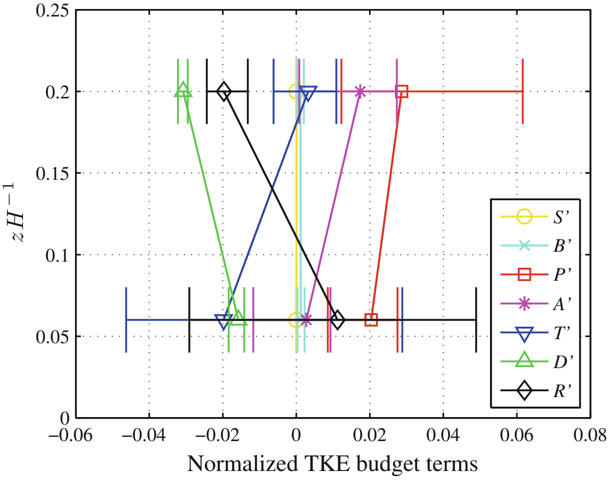


Fig. 8 Average TKE budget on the DSTL and UU towers for the selected hours of IOPs 5 and 6. *Error bars* denote the extreme 1-hr average values for each term. The *prime symbol* indicates that the terms are normalized by $U_H^3 H^{-1}$

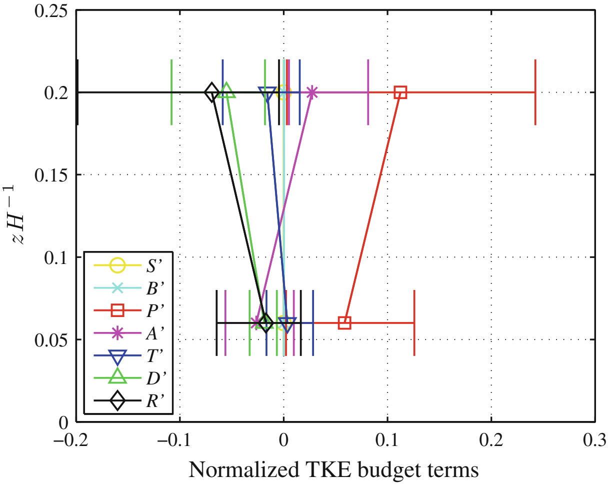


Fig. 9 Average TKE budget on the DSTL and UU towers for the selected hours of IOP10. *Error bars* denote the extreme 1-hr average values for each term. The *prime symbol* indicates that the terms are normalized by $U_H^3 H^{-1}$

of the Park Avenue street canyon (see Table 2). This is consistent with TKE analysis of Christen et al. (2009) who found that the buoyancy term in Basel, Switzerland was negligible. The negligible buoyancy term indicates that TKE within Park Avenue is also dominated by mechanical processes.

The shear production and dissipation terms have significant contributions to both the daytime and nighttime TKE budgets. In fact, the shear production term is the dominant positive term during both the daytime and nighttime hours. Dissipation is clearly the dominant negative term in the upper level of the daytime TKE budget and has a negative contribution

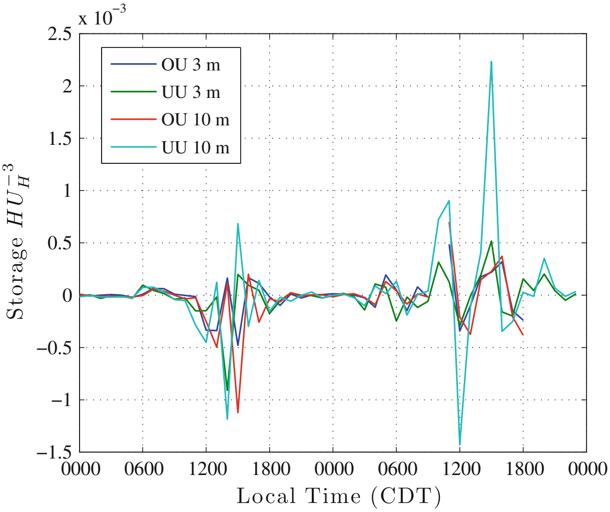


Fig. 10 The TKE storage term 2-day time series measured within the Park Avenue street canyon

comparable to the turbulent transport term on the lower level. The nighttime TKE budget is primarily a balance of production and a combination of dissipation and residual (pressure) terms, though there is also a significant negative contribution from advection on the lower level.

The advection and turbulent transport terms provide small but still significant contributions to the budget during both the daytime and the nighttime periods. This is due to significant positive and negative contributions in the individual 1-hr periods yielding a small net contribution rather than simply having small 1-hr averages, as was the case with the storage and buoyancy terms.

Since the storage term was found to be a negligible contributor in the TKE and momentum budgets, a time series of the TKE storage term over two days, including IOP 10, 28 July at 0000 to 30 July at 0000 CDT, is presented in Fig. 10. Even the largest spikes in the storage term are still two orders of magnitude smaller than the significant terms in the TKE budget (Figs. 8, 9). Similarly, the buoyancy production/destruction term of the TKE budget over the same two days is presented in Fig. 11. As expected, the diurnal variation is evident in the buoyancy term time series. The magnitude of the buoyancy term is an order of magnitude larger during the day than it is during the nocturnal time periods such as IOP 10. However, even though this time series of the buoyancy production/destruction term was taken in the middle of summer, the largest values measured in the heat of the day were still two orders of magnitude smaller than the significant terms in the TKE budget. Thus, rather than being a peculiarity in the IOP 10 data, this behaviour appears to be characteristic of the Park Avenue street canyon.

To gain further insight into the mechanisms dominating the production and transport of TKE within the street canyon, the advection, mechanical shear production, and turbulent transport terms from the IOP10 data have been further separated into the individual components of the terms in Figs. 12, 13, and 14, respectively. The daytime data broken down into individual components do not demonstrate anything beyond what is seen in the nighttime data, and so only the nighttime data will be shown here. The along-canyon component dominates the advection of TKE (Fig. 12) at the 10-m level. This is not unexpected

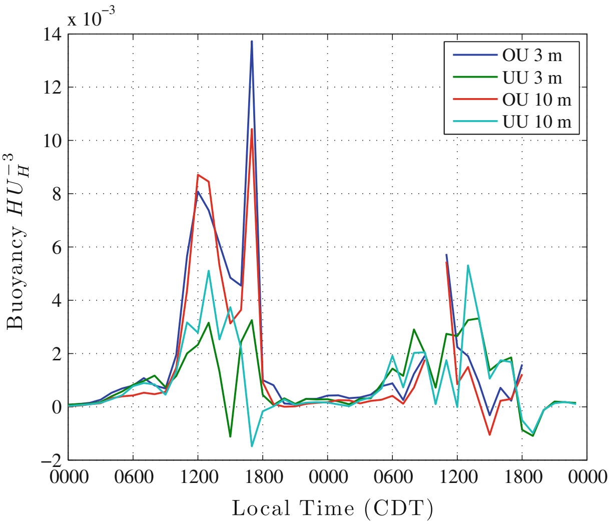


Fig. 11 The TKE buoyancy production/destruction term 2-day time series measured within the Park Avenue street canyon

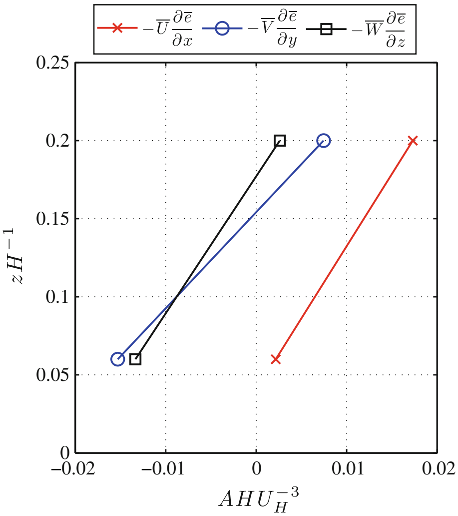


Fig. 12 Individual components of the TKE advection term measured on the UU and DSTL towers during IOP 10

given the westerly channelling flow within the canyon during IOP 10 (see Fig. 3). However, at the 3-m level the other two components dominate over the along-canyon component.

The bulk mechanical shear production term consists of nine individual components, the contribution from each of these components is presented in Fig. 13. In standard ISL TKE budget analyses the coordinate system is rotated into the mean wind and horizontal homogeneity and negligible subsidence are assumed reducing the bulk term to a single significant term $\overline{u'w'}\partial\overline{U}/\partial z$. In the non-rotated coordinate system of the street canyon, this result might lead one to believe that the dominant terms are likely to be $\overline{u'w'}\partial\overline{U}/\partial z$ and $\overline{v'w'}\partial\overline{V}/\partial z$. Interestingly, Fig. 13 shows that only one of these quantities, $\overline{u'w'}\partial\overline{U}/\partial z$, is really significant and it contributes about as much to the net production of TKE as the term related to

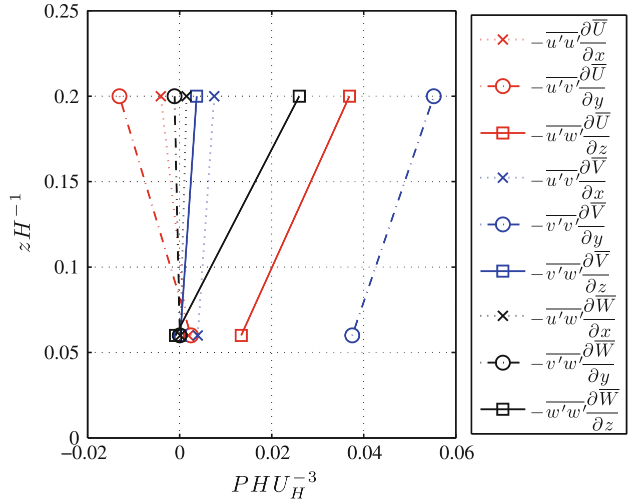


Fig. 13 Individual components of the TKE mechanical shear production term measured on the UU and DSTL towers during IOP 10

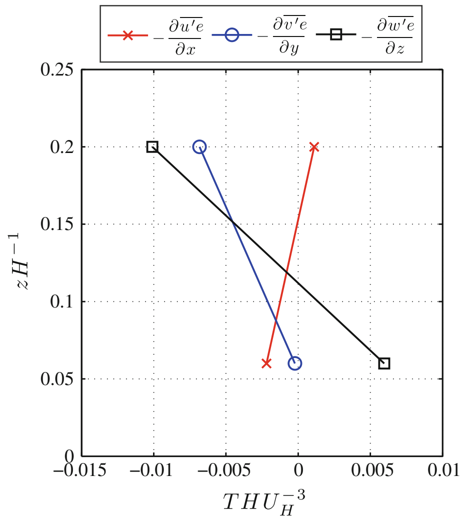


Fig. 14 Individual components of the TKE advection term measured on the UU and DSTL towers during IOP 10

subsidence, $\overline{w'w'}\partial\overline{W}/\partial z$. The $\overline{v'v'}\partial\overline{V}/\partial y$ obviously dominates the production of TKE at this location in the street canyon. It seems plausible that the dominance of this term in the production is related to the end vortex at the entrance of the street canyon and the dominance of the cross-canyon momentum budget (Fig. 6). It is also interesting to note that some of the quantities are actually negative contributions to the production of TKE, e.g. $\overline{u'v'}\partial\overline{U}/\partial y$. This requires the Reynolds stress to work against the gradient of the mean wind and may suggest that the Reynolds stresses are not due entirely to local mean wind gradients. Figure 13 also suggests that the methods and assumptions typically used in the ISL to determine the mechanical shear production of TKE are unlikely to capture all of the contributions and may omit the dominant contributions to the production term in the UCL.

In the ISL, the bulk turbulent transport of TKE is simplified through similar assumptions to those used for simplifying the bulk mechanical shear production term. Employing the typical ISL assumptions and rotating into the mean wind leaves the vertical turbulent transport of TKE as the only significant term. The individual turbulent transport terms shown in Fig. 14 indicate that while the vertical term is significant at both levels in the Park Avenue street canyon, it only dominates the bulk term at the lower level. At the upper level, the cross-canyon and the vertical components have comparable contributions to the bulk term. Thus, Fig. 14 also suggests that employing the typical ISL simplifying assumptions to the UCL will not capture all of the significant turbulent transport terms in the TKE budget.

6 Conclusions

TKE and momentum budget analyses were performed at the base of a street canyon located in the urban core of a city devoid of major surrounding topographical features using only those instruments that allowed for the approximation of gradients in all three principal directions. This methodology is different than previous budget analyses in the urban canopies that have employed a surrogate spatial averaging technique over a wide range of wind angles (Louka et al. 2000; Christen et al. 2009).

As Ramamurthy et al. (2007) found, the thermal stability within the Park Avenue tends to be slightly unstable even during the night. The fact that urban areas tend to be slightly thermally unstable or occasionally neutral is consistent with Nakamura and Oke (1988). Similar to what was found in the vertical momentum budget (and consistent with the study of Christen et al. (2009)), the buoyancy term in the TKE budget was found to be a negligible contributor over the 10 hr that were examined in this study. An examination of the 2-day time series of the TKE buoyancy production/destruction term reveals that even the relatively large values that were measured during the day were two orders of magnitude smaller than the significant terms measured in the TKE budget during IOP 10. The peaks in the momentum buoyancy term in Fig. 7 were 5–10 times lower than the significant terms in vertical momentum budget (Fig. 6c). Thus, buoyancy appears to have a greater effect on the mean flow than it does on the turbulence within the UCL where advection driven pressure forces dominates. In addition, on the 1-hr time scale considered here, both the momentum and TKE budgets could be considered in a quasi-steady state.

A simple method for obtaining horizontal gradients between instruments was employed to estimate terms in the momentum and TKE balances. In spite of the simplicity, the analysis shows that the application of the simplifying assumptions typical of ISL budget analyses is insufficient for capturing all the significant contributions to the budget within the UCL. In fact, the current results show that (in at least some regions), within the UCL, the horizontal gradients can be more significant than the vertical gradients. The current analyses were, however, limited spatially and temporally. Thus, further research is needed to determine the spatial and temporal extent of the dominance of the horizontal terms within the UCL. However, it is evident from the current analyses that capturing all of the significant contributions to the TKE and momentum budgets within the UCL requires a high density of measurements configured to facilitate the calculation of gradients in all three principal directions.

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