3.4 Spatial and Temporal Variability of Turbulent Fluxes in the Joint Urban 2003 Street Canyon

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1. Introduction

As part of the Joint Urban 2003 field campaign a street canyon study was conducted in downtown Oklahoma City (OKC), Oklahoma, USA. More than fifty sonic anemometers were installed in an east-west running street. One of the main objectives of the study was to understand the turbulent processes happening inside the canyon. The turbulence inside the canyon is very sensitive to upwind conditions and to local surface properties. Various studies have been conducted in this regard to understand the turbulence inside the urban roughness sub-layer.

In the past full-scale field experiments were a rarity due to the cost and logistics incurred. During the summer of 1976, (Clarke et al., 1987) conducted a full scale field campaign in St. Louis, MO. They had sensors installed at two urban sites and a nearby rural site. One of their main objective was to analyze the variability of turbulence in the surface layer. Comparisons were conducted in the context of spectral analysis, analyzing the TKE equation and investigating the normalized velocity variances. It was found that the dominant length scales at each site were distinctly different and in urban sites they were particularly smaller. The TKE equation suggested the importance of horizontal advection at urban sites. The inadequacy of similarity theory to describe turbulence in urban areas was also noted. It was concluded that the difference between an urban terrain and an ideal one is mainly due to the building wake effects, subtle changes in upwind roughness and also due to urban heat island effects.

One other more recent major field campaign was the Basel Urban Boundary Layer Experiment (BUBBLE) conducted in the city of Basel, Switzerland (Christen et al., 2003). Six energy balance sites with eddy covariance instrumentation were operated in and around the city during summer 2002. Of these six sites, three were installed in an urban environment, two in a sub-urban neighborhood and one at a rural background site. This led researchers to effectively compare turbulent fluxes from various locations. It was found that the high surface area per plan area at the built-up sites led to additional storage heat fluxes that are two to three times higher than over the flat terrain, (Christen et al., 2003). Moreover, the maximum heat flux values were found at suburban sites, as much of the radiation at the urban sites were absorbed at the roof level.

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Recently, reduced scale models of cities have been created and analyzed inside a wind tunnel. These studies not only help in detailed analysis of specific regions, but can also be compared to data obtained from full-scale experiments and the validity of these studies can be verified. In one of these studies, conducted by Kastner Klein and Rotach (2004) , a $1 : 200$ scaled model of building structures located in the central part of Nantes was reconstructed inside a wind tunnel. Vortex generators were used to form a boundary layer in the approach flow. The wind tunnel model covered an equivalent full scale region of 400 m in diameter. The main objective of the study was to investigate the flow structure inside and above the urban canopy. Two distinct regions were identified in the study, with respect to mean wind velocities; the street intersections where mean wind velocities were significantly higher and the region between the buildings where mean wind velocities were found to be lower. Even turbulent velocities exhibited the same pattern. In both these cases turbulent kinetic energy and shear stress profiles seemed to show a maximum at the roof level. Based on these experimental results a shear-stress parameterization was introduced. This parameterization utilized the level and magnitude of the shear stress peak value.

In this paper we analyze the turbulent fluxes from various places inside an urban street canyon for a variety of upwind conditions. Vertical profiles of heat and shear stresses are used to reveal the spatial variability of turbulence inside the canyon. From this initial analysis it was found that the conditions inside the canyon are entirely different from those at the rooftops. Turbulence quantities such as TKE and average momentum fluxes were found to be high on the rooftops, while their value at the bottom part of the canyon was very small.

2. Sites and Experimental Setup

As part of the JU2003 field experiment a street canyon study was conducted in downtown OKC. A large number of wind sensors were installed inside the canyon and also over the rooftops and street intersections. Fig. 1 from (Brown et al., 2004), shows the instrument layout inside the canyon. Three pairs of towers were installed at various locations inside the street canyon and they carried twenty-four 3D sonic anemometers. Two more towers were located on rooftops. Four 3D sonics were mounted to the sides of the buildings on the eastern end of the street (far right in Fig 1). Tethersondes were operated during Intensive Operating Periods (IOP's) to get profiles of wind speed, wind direction, temperature and relative

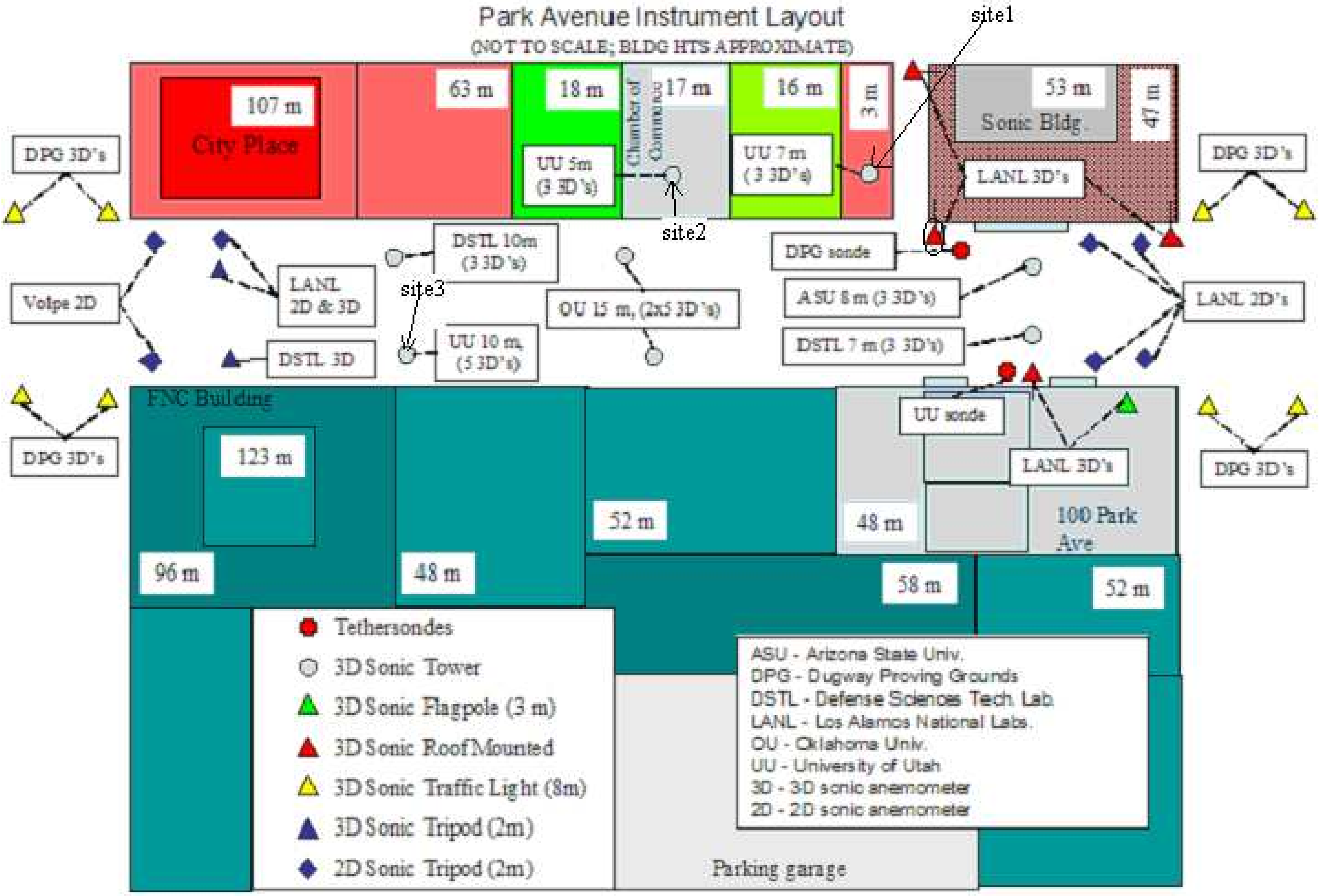

FIG. 1: Instrument layout inside the street canyon (buildings and instrument location not to scale), schematic courtesy: Brown (Data from sites 2, 3 and the circled LANL sonic was used to derive vertical profiles).

humidity. Several 2D sonics were placed in street intersections during the IOP's.

As part of this campaign, The University of Utah operated three sites inside the canyon. Site 1 had a 5 m tower which carried three sonics vertically mounted and was located in between two buildings. On the north side of the street on a 4 m tall building, Site 2 (Chamber of Commerce building) had a 7 m tower and also carried three sonics on top of a 17 m high building. Site 3 had a 10 m tower and operated from the south-west portion of the street.

Site 1 had three sonics at 5 m, 6.5 m and 8 m above ground level. Site 2 also had three sonics, each at 20 m, 22 m and 24 m above ground level. Both these sites collected data at 20Hz sampling frequency. Site 3 located in Park Avenue had a 10 m tower and sonics were mounted at 3.19 m, 4.19 m, 5.04 m, 7.24 m and 9.84 m above ground level. These sonics acquired data at a frequency of 10 Hz. All the sonic anemometers were Campbell scientific CSAT3 sonic anemometers and Campbell CR 5000 data loggers were used to collect the data from the sonics.

For calculating vertical profiles, site 2 and site 3 sonic anemometers were used along with LANL sonic anemometer mounted on the roof of a 47 m high building (Sonic Bldg, Fig. 1), facing the street canyon. In addition to this an Indiana University sonic anemometer mounted on top of a 80 m high tower was also used. This tower was located 5 km south of downtown. The IU tower was in the upstream Inertial Sub Layer (ISL). Data from this tower was compared to the data from within the urban canopy. Both the LANL and IU sonics were operated at 10 Hz sampling frequency.

3. Results

3.1 *Heat Flux*

Fig. 2 and Fig. 3 show profiles of stream-wise, span-wise and vertical heat fluxes inside the canyon, plotted from the sites mentioned above against Z/H, where $H = 50$ m is the mean building height. Here v represents the cross canyon velocity, u the along canyon velocity and w represents the vertical velocity and T represents temperature. The primes represent the fluctuating component of the signal which were linearly detrended from the instantaneous signal. All the profiles in the figure are 15 minute averages. For the daytime aggregate the up-winds were from the west and for the night time aggregate the up-winds were from the south. It can be seen from the figure that all three heat fluxes $< u'T' >$, $< v'T' >$ and $< w'T' >$ are of equal magnitude. The vertical heat flux $(< w'T' >)$ profile has a negative slope during the night and a positive slope during the day. Consider the conservation of heat equation,

$$\frac{\partial \overline{T}}{\partial t} + \frac{\overline{U}_j \partial \overline{T}}{\partial x_j} = \frac{\nu_T \partial^2 \overline{T}}{\partial x_j^2} - \frac{1}{\overline{\rho} C_p} \frac{\partial \overline{Q}_j^*}{\partial x_j} - \frac{L_v E}{\overline{\rho} C_p} - \frac{\partial (\overline{u_j' T'})}{\partial x_j} \quad (1)$$

The first term on the left represents the mean storage of heat flux followed by the advection of heat term. The first term on the right represents the mean molecular conduction of heat followed by the term representing the mean net body source associated with radiation divergence. The penultimate term represents latent heat release and the final term describes the divergence of turbulent heat flux (the above equation was referred from, (Stull, 1988)). It is seen from the equation that the heat storage term is directly proportional to the divergence of turbulent heat flux. The heat flux profiles in Fig. 2 and Fig. 3 describe the heat flux at different parts of the canyon at different time periods. The negative gradient during the night time indicates the higher heat storing capacity of the bottom part of the canyon. The positive gradient during the daytime is due to inhomogeneous solar insulation caused by shadow effects of the buildings.

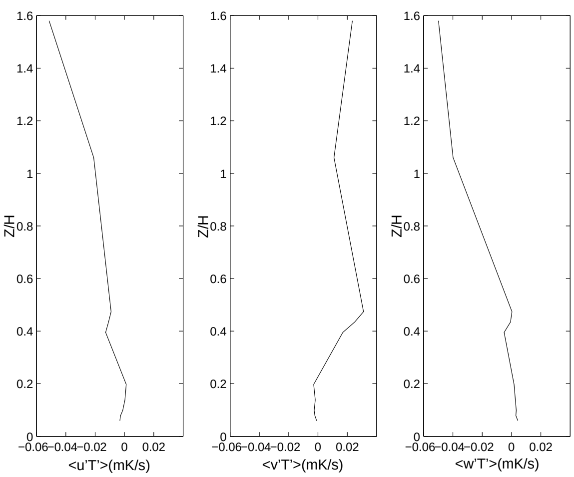

FIG. 2: 15 minute averaged Heat flux profiles 0000-0015 CDT 19 July 2003(southerly incident winds).

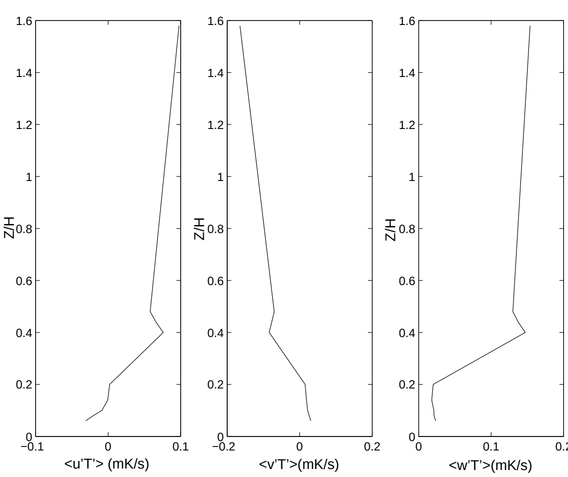

FIG. 3: 15 minute averaged Heat flux profiles 1400-1415 CDT 19 July 2003(westerly incident winds).

Fig. 4 depicts the sensible heat flux at three different places; inside the canyon (site 3), the space between two buildings (site 2) and outside the urban canopy (IU tower). Heat fluxes at all three sites peak at different times. While the site outside the canopy attains its maximum value around 1500 CDT, the ones inside the canopy reach their peaks around 1800-1900 CDT. One other feature is that the heat flux in the bottom part of the canyon (site3) never becomes negative, while the heat flux in the alley(site1) becomes negative during the night and oddly for a period during afternoon. This phenomenon is entirely influenced by incident solar radiation and the heat storing capacity of the surrounding building materials. The peak values at these sites also differ widely. The site outside the canopy attains a peak value of $220W/m^2$, whilst the sites inside the canopy have a maximum value of only $60W/m^2$. This is due to the fact that the bottom part of the canyon is under the shadow of the surrounding buildings for most of the day and this disrupts sunlight from reaching the ground .

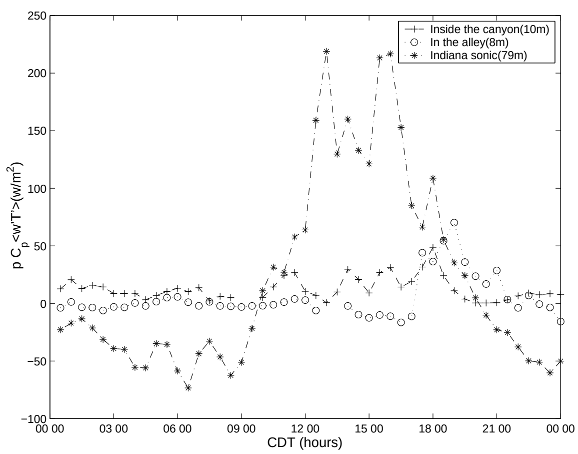

FIG. 4: 15 minute averaged $\rho c_p < w'T' >$ for 19 July 2003.

3.2 *Shear stress and TKE*

Fig. 5 shows shear stress profiles for the street canyon. All the values were measured during $0000 - 0015$ CDT 19 July 2003 and they are five minute averaged profiles. In this figure, v represents the cross canyon velocity , u represents the along canyon velocity and w represents the vertical velocity. The primes represent the fluctuating signal. The upwind direction during this period was from south. From the plot it is seen that all three stresses have very low values and they reach their respective maximums at $Z/H = 0.44$ which is the second sonic at site 2 (mounted on top of the Chamber of Commerce Bldg). This result is in accordance with the Nantes wind tunnel study (Kastner-Klein and Rotach, 2004).

Rotach and Kastner-Klein (2004) devised a shear stress parameterization based on the level and magnitude of shear stress peak value. According to the following model, shear stress at a certain height is given by;

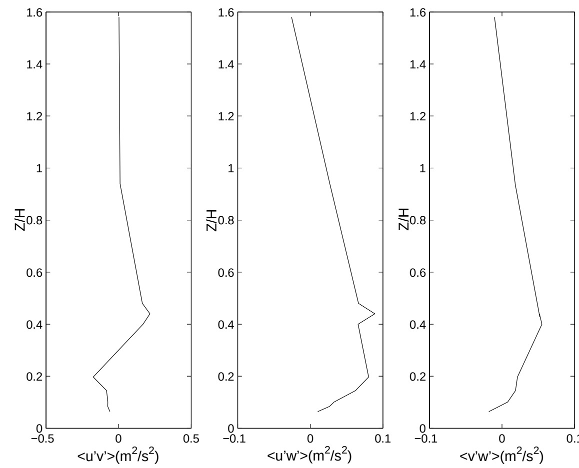

FIG. 5: Shear stress profiles for 0000-0015 CDT 19 July 2003 (southerly up-winds).

$$\frac{\overline{u'w'}}{\overline{u'w'}_s} = \left(\frac{z}{z_s}\right)^2 exp\{2\left(1 - \frac{z}{z_s}\right)\} \quad (2)$$

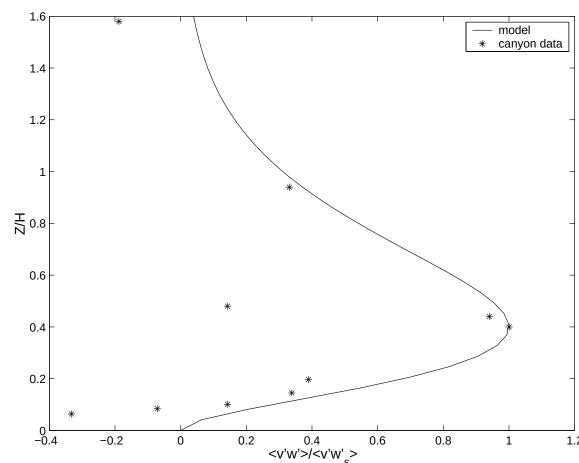

FIG. 6: Comparison between model with actual data and height Z normalized by H, the mean building height (southerly up-winds).

Where $\overline{u'w'}$ is the shear stress at height z and $\overline{u'w'}_s$ is the peak value of shear stress at height z_s. This empirical model was found to work well when applied to wind tunnel data from various studies. Fig. 6 shows a typical comparison between the actual shear stress data from the field canyon and the curve obtained from the model. It is seen that for this particular data set the model captures the increasing shear stress at the bottom part of the canyon, maximum at the rooftop and decreasing shear stress at the top of the urban canopy. The height in this plot is normalized by the mean building height inside the canyon which is 50 m. Fig. 7 shows the comparison between the model and the actual data, with height Z normalized by Z_s (The height of shear stress peak). Here too it is seen that the actual profile agrees with the model. Fig. 8 shows the upwind direction for 19 July 2003.

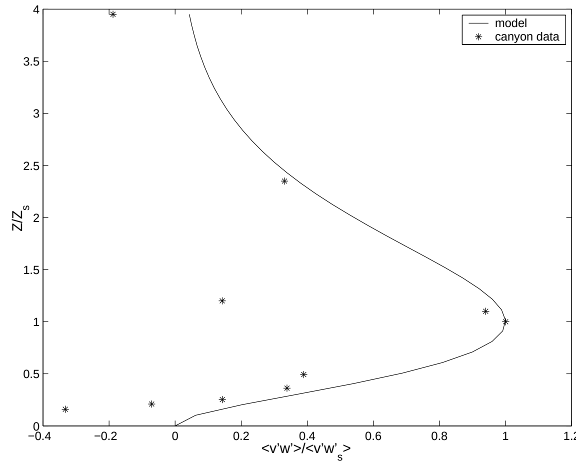

FIG. 7: Comparison between model with actual data, with Z normalized by Z_s (southerly up-winds).

The DPG and PNL sodar which were located inside the city clearly show that the winds initially, $(0000 - 0300)$ CDT were from the south. Inside the canyon there is strong channeling for most of the day which is indicated by the site 3 sonic.

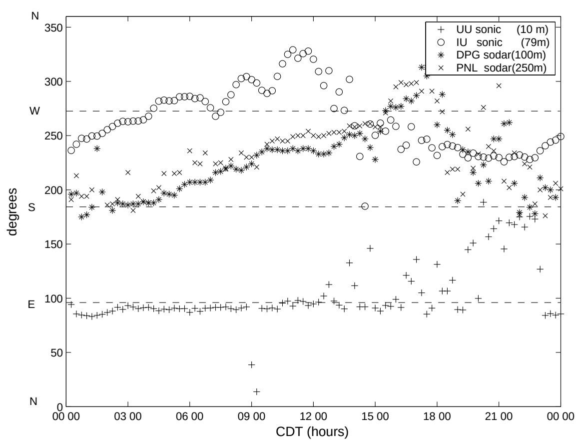

FIG. 8: Upwind direction for 19 July 2003.

In order to investigate how well the model works for different upwind conditions, a different day when the winds were from the west was chosen. Fig. 9 shows wind direction plot for 29 July 2003.

The incident wind at around 1000 CDT on 29 July 2003 was entirely from the west as indicated by the DPG and PNL sodars. The winds inside the canyon at this time were also from the west. Fig. 10 compares the actual data with the shear stress model at this particular time $(1000 - 1015)$ CDT July 29 2003. It is seen from the plot that the model does very well with the data but with a few exceptions. The peak shear stress value in this case is

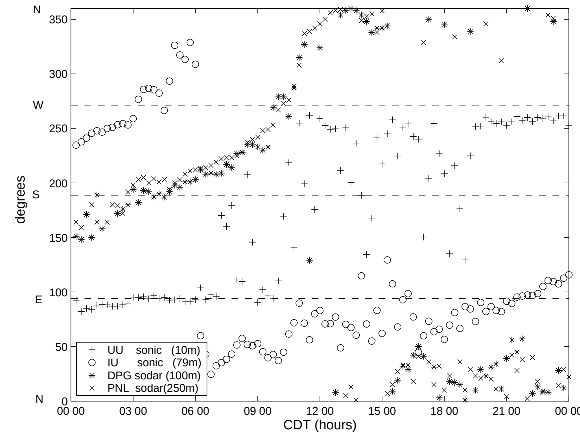

FIG. 9: Upwind direction for 29 July 2003.

with in the street, opposed to the rooftops, predicted by the model.

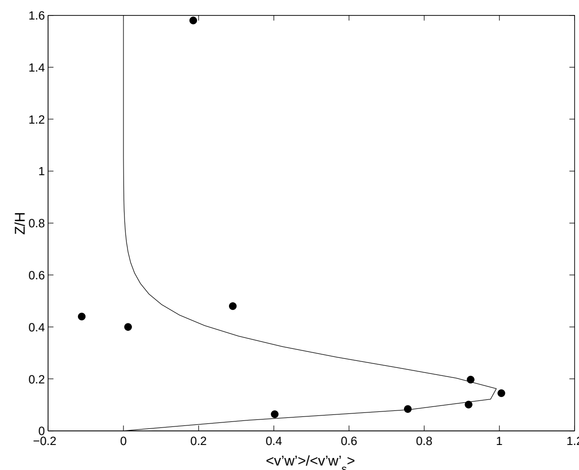

FIG. 10: Comparison between shear stress model and actual data for westerly up-winds.

Fig. 11 shows profiles of TKE and V_* normalized by TKE and V_* at the top level, where $V_* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{\frac{1}{4}}$, (Nelson et al., 2004). This velocity scale does not represent the shear velocity u_* even though it is computed in the same manner. This is the local average Reynolds shear stress. The profiles clearly indicate lower TKE and V_* values at the bottom part of the canyon and peaks at the rooftop. This suggests that the turbulence at the bottom part of the canyon is low compared to the rooftop, and it is due to the increased shear at the rooftops.

A time averaged plot of $< v'w' >$ at 3 m and 10 m is shown in Fig. 12 . The plot shows contrasting behavior at 3 m and 10 m. While the momentum flux is positive at 10 m, it is negative at 3 m. This situation alternates early in the morning (0600)CDT. At noon both have negative values. This plot indicates the existence of a mean vertical gradient of the stresses most of the time that contribute

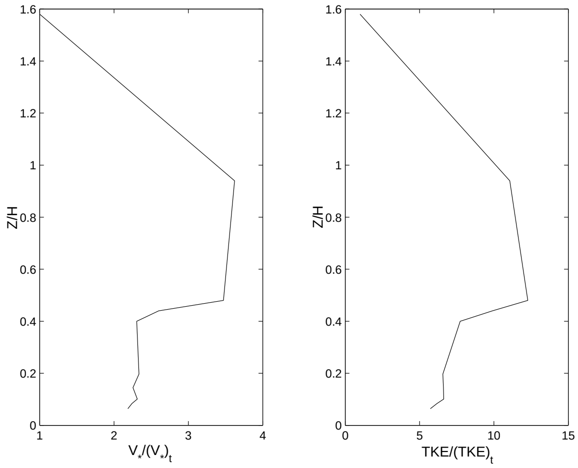

FIG. 11: Turbulent Kinetic Energy (TKE) and V_* Profile for 0400-0415 CDT 19 July 2003.

directly to the momentum equation balance.

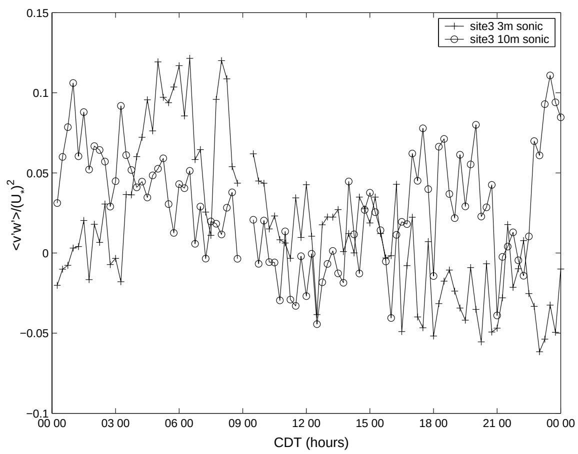

FIG. 12: 5-minute averaged shear stress ($< v'w' >$) for 19 July 2003.

4. Conclusion:

From the above discussion,it was found that the heat flux inside the canyon is dependent on the heat storing capacity of the surrounding materials. It was found that the heat flux peak value inside the canyon is lower than the heat flux value in the ISL which is due to inhomogenous solar radiation associated with the shadow effects of the tall buildings.

The shear stress inside the canyon was found to be sensitive to upwind condition. It was also found that the maxmimum shear stress value does occur inside the canyon when the upwinds were from a differnt direction. The shear stress parameterisation introduced by Kastner-Klein and Rotach (2004) was found to work well for differnt upwind conditions and differnt normalization. The TKE and V_* profiles had maximum values at the rooftops while their values at the bottom part of the canyon were relatively low.

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