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INVESTIGATION OF REYNOLDS STRESSES IN A 3D IDEALIZED URBAN AREA USING LARGE EDDY SIMULATION

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1. INTRODUCTION:

Understanding the relationship between turbulent flow characteristics and surface geometry is very important for extenuating urban atmospheric problems such as air pollution, the heat island effect and other transport urban phenomenon. The mean flow and turbulent statistics in and around urban areas have been extensively studied by laboratory experiments, field campaigns, and numerical simulations (e.g., Uehara et al., 2000, Klein and Rotach, 2003; Brown et al., 2004; Kanda et al., 2000). Urban geometry, even with simple obstacle arrays, has spatial heterogeneity, which makes it difficult to obtain a precise representative picture of the flow characteristics. Uehara et al. (2000) conducted wind tunnel experiments to study the turbulent characteristic for flow over a regular array of cubical building and reported detailed mean and turbulent velocity data. The study further observed distinctly different values of Reynolds stresses inside the street canyon as compared to just above the street canyon. Klein and Rotach (2004) studied a detailed model of an urban landscape in the wind tunnel and the flow structure inside and above the urban canopy has been investigated. According to the study, flow structure inside the canopy could be distinguished into two types of velocity profiles. Within street canyons, the mean wind velocities are almost zero or negative below roof level, while close to intersections, significantly higher mean velocities were observed. Klein et al. also suggested that the significance of spatially averaged profiles (Raupach, 1980; MacDonald, 2000; Cheng and Castro 2002) is questionable for urban street-canyon configurations, at least if they are characterized by skimming flow regimes as in urban sites with skimming-flow characteristics, horizontal advection is highly variable and depends on the particular location and on the wind direction.

Over the last few years several urban dispersion field campaigns of varying size and scope have been conducted in various parts of the U.S. and Europe. A few examples of such experiments are: The Urban 2000 experiment conducted in Salt Lake City, UT during the fall of 2000 (Allwine et al. 2002); The Basel UrBan Boundary-Layer Experiment (BUBBLE) conducted in Basel, Switzerland summer 2002 (Rotach et al. 2005); The first Dispersion of Air Pollution and its Penetration into the Local Environment (DAPPLE) conducted in central London, UK in spring 2003 (Arnold et al. 2004). Two of these multiorganizational field campaigns have been conducted in the U.S.A.: the Mock Urban Setting Test in Utah's West Desert at U.S Army Dugway Proving Ground and the Joint Urban 2003 in Oklahoma City, Oklahoma (Allwine et al. 2004). Nelson et al. (2006) studied the above two field campaigns and suggested the existence of a disorganized sub-layer (DSL). The DSL was characterized by decoupling of the Reynolds normal and shear stresses from their inertial sub-layer (ISL) proportional relationship due to the rapid decay of the shear stresses with depth into the canopy. Also, "Disorganized" behavior results in small net vertical fluxes of horizontal momentum as evidenced by the significant contributions to all four quadrants of a quadrant analysis.

Recently, many large eddy simulation studies have been performed for flow over regular array of buildings in order to study mean and turbulent flow characteristics. Kanda at al. (2005) studied the turbulent organized structures (TOS) above building arrays using a large-eddy simulation (LES) model. Xie and Castro (2006) performed large eddy simulation to calculate the turbulent flow over staggered wall-mounted cubes and staggered random arrays of obstacles with area density 25%, at Reynolds numbers between 5000 and 5,000,000, based on the free stream velocity and the obstacle height emphasizing Reynolds number independence for such flows. Coceal et al. (2006) performed direct numerical simulations of turbulent flow over regular arrays of urban-like, cubical obstacles and the results were analyzed in terms of a formal spatial averaging procedure to enable interpretation of the flow within the arrays as a canopy flow, and of the flow above as a rough wall boundary layer.

As a part of this work, large-eddy simulations have been performed for fully developed turbulent flow within and above explicitly resolved simple cube arrays. The results from our model are shown to agree with laboratory experiments. The temporally and spatially-averaged flow structure confirmed the existence of conventionally described canyon flow regimes. However, the intermittency of the canyon flow was quite large and the stream patterns were never persistent. The mean and turbulent

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statistics inside the canopy has been studied in order to understand the turbulent characteristics inside an urban street canyon. Turbulent characteristics in these cases are highly variable and depend on the particular location and on the wind direction. To study the differences, the urban boundary layer is conceptually broken down into three distinct regions: (a) the urban roughness sub-layer, (b) street channels (roads with axis aligned with mean wind direction aloft) and (c) street canyons (roads with axis normal to the mean wind direction aloft). The distribution of the Reynolds stresses differ significantly amongst these regions and we hypothesize that the low stresses in the lower half of the canopy can been attributed to the temporary instability of the above mentioned regions at different periods of time.

2. NUMERICAL APPROACH:

2.1 Model description and domain set-up:

The Navier–Stokes equations are discretised using second-order central finite volume in space and a second–order Adams–Bashforth scheme in time, based on the fractional step method (Kim and Moin, 1985). The Poisson equation for pressure *p* is solved by a multigrid method. Figure 1 shows a plan view of the computational domain. Periodic boundary conditions are imposed both laterally and stream-wise to simulate an infinite array. The boundary condition at the top of the domain is free slip. At all solid surfaces, the local profile of the tangential velocity component is taken to be logarithmic and the normal velocity component is zero. The local roughness length is assumed constant at 0.001 m, and the initial flow field is assumed to be uniform. The flow is maintained by a height-independent stream-wise pressure gradient of magnitude u_τ^2/H, where u_τ is the total wall friction velocity and H is the total domain height. The Reynolds number of the flow, based on the velocity at the top of the domain and the cube height h, is Re = 5, 000. The roughness Reynolds number $R_\tau \equiv u_\tau h/v$ = 500, which is in the fully rough regime (Snyder , 2003).

2.2 Integration times:

To ensure temporal convergence to a statistically steady state, all the simulations were run for an initial duration of about 200T, where $T = h/u_\tau$ is an eddy turnover time for the largest eddies shed by the cubes. Statistics were then collected and averaged over a further duration of 400T to ensure statistical convergence. The time step used in the simulations was 0.002T at the resolution Δ = h/10. Therefore, statistics were summed over a total number of 0.3 million time steps for Δ = h/10.

3. MODEL EVALUATION:

Here we compare results from the simulation to the laboratory experiments of Uehara et al. (2000). The vertical profiles of mean and turbulent statistics at the canyon centre are shown in Figure 3, the experiment and simulation are in good quantitative agreement, especially above the canopy. The modeled turbulent stresses are added to the resolved turbulent stresses and it was observed that they contribute to less then 10% of the total value. Within the canyon, a small, but distinctive upward turbulent momentum flux in the middle of the canyon is well simulated. The mean flow structure in the x-z cross-section at the centre of the street canyon is shown in Figure 2. Compared with the experiment we found the following points of agreement. The centre of recirculation is close to, but slightly shifted upward and leeward from, the canyon centre. The downward motion occurs in a broader region and is stronger than the upward motion. This was also found in the observations of Brown et al. (2000). A strong downward (negative) momentum flux occurs towards the leeward edge of the canopy top, whereas upward (positive) momentum flux occurs within the canopy.

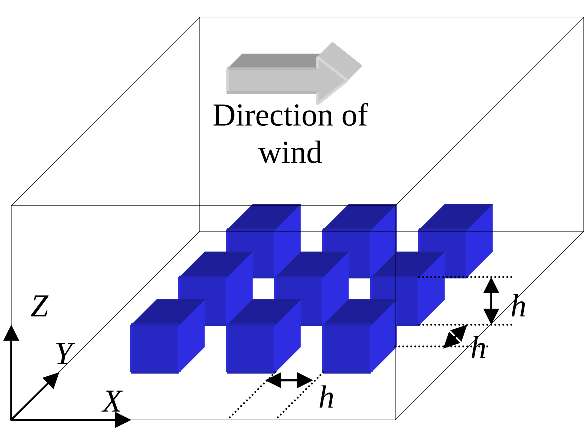

Figure 1: Schematic of the computational domain.

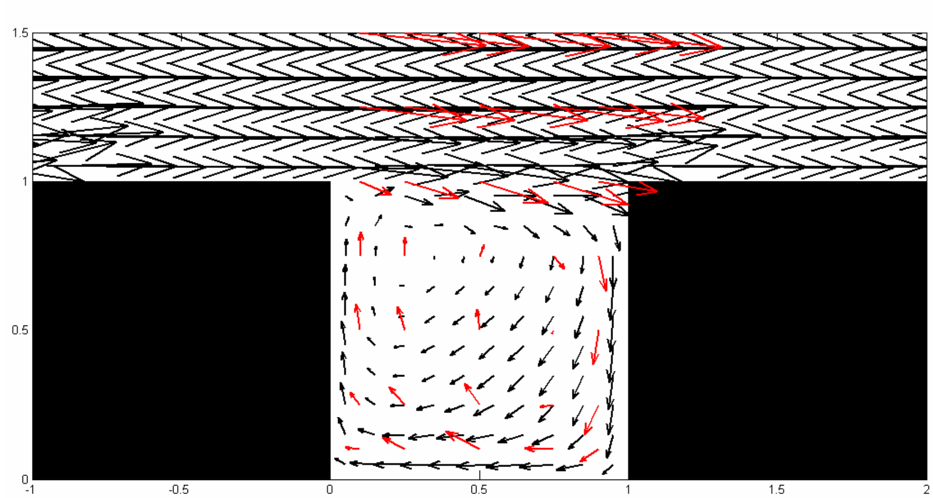

Fig 2: Velocity vectors in a vertical plane (x-z) along the center plane of the street canyon. Simulation (black) and wind tunnel data (Uehara et al. 2000, red).

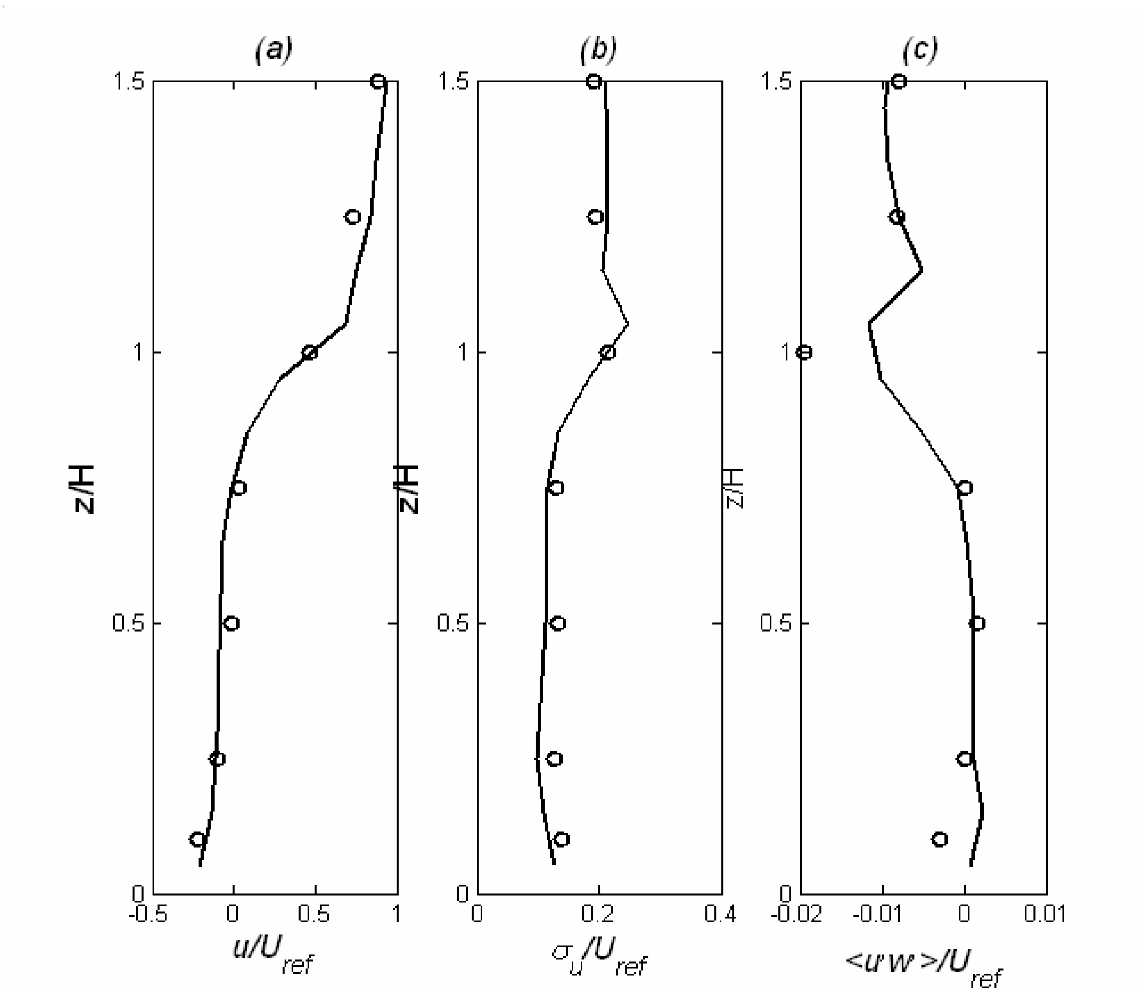

Fig 3: Vertical profiles of (a) stream-wise velocity (*u*), (b) *rms* of stream-wise velocity and (c) Time averaged Reynolds stress at the center of the street canyon. Simulation (_) and wind tunnel data (Uehara et al. 2000, -o).

4. RESULTS AND DISCUSSION:

Figure 3 and 4 clearly show that inside a street canyon, there exists a region of very low but positive Reynolds stress. This signifies that there is a net upward flux of horizontal momentum in this region. The joint-probability density functions (JPDF) and weighted joint-probability density functions (WJPDF) of *u'* and *w'* measured at z/H=0.5 and z/H=1.5 in a street canyon are presented in Fig. 5. Each *u'w'* pair of the JPDF contour represents the fraction of instances of that particular *u'w'* pair to the total number of measurements. Each pair in a WJPDF contour represents that particular *u'w'* pair contribution to the total covariance. The observed behavior shown in Fig. 5b and d (z/H= 1.5) is similar to that which is typical of the inertial sub-layer (ISL) with quadrants II and IV dominating, i.e., the mean flux of momentum moving from the high-momentum fluid aloft down toward the ground. The JPDF and WJPDF shown in Fig. 5a and c (z/H =0.5) show very different behavior. The contribution from quadrants I and III are almost as large as those from II and IV yielding a small Reynolds stress. Rotach (1993) observed the fact that significant contributions were found in all four quadrants of a quadrant analysis within the canopy. Similar characteristics can be seen in the Reynolds stress and TKE data presented in studies of full-scale urban areas by Rotach (1993 and 1999), wind tunnel models of real urban areas by Kastner-Klein and Rotach (Klein and Rotach, 2004), in regular arrays of obstacles by MacDonald et al. (2002), and large-eddy simulations of aligned simple obstacle arrays by Kanda et al. (2004). Similar analysis was carried out at street channels (roads with axis aligned with mean wind direction aloft). The joint-probability density functions (JPDF) and weighted joint-probability density functions (WJPDF) of *u'* and *w'* measured at z/H=0.5 and z/H=1.5 in a street channel are presented in Fig. 6. The observed behavior shown in Fig. 6b and d (z/H= 1.5) is similar to that which is typical of the inertial sub-layer (ISL) with quadrants II and IV dominating, i.e., the mean flux of momentum moving from the high-momentum fluid aloft down toward the ground. However, in contrast to observation made in a street canyon; behavior similar to ISL is also observed at height z/H=0.5, indicating no decoupling of Reynolds stresses. This emphasizes the existence of distinct regions inside the urban roughness sub-layer which have significantly different turbulent characteristics. Therefore, this decoupling of the Reynolds normal and shear stresses which appeared to be a general feature of urban and urban-like roughnesses, is actually specific to location inside the urban canopy layer (UCL).

As observed earlier, this decoupling of Reynolds stresses is specific to locations inside of UCL as horizontal advection is highly variable and depends on the particular location and on the wind direction. It is hypothesized that the decoupling of Reynolds stresses in a street canyon is due to the fact that this region is sheltered from the inertial flow (Fig. 7). As a result, this region does not exhibit the characteristics observed in the ISL. Also, due to sheltering, this flow in the region becomes more three dimensional and looses its unidirectionality. Further, since the street channel region are not sheltered by any buildings, these region are influenced by the ISL and hence do not show any decoupling from the ISL characteristic.

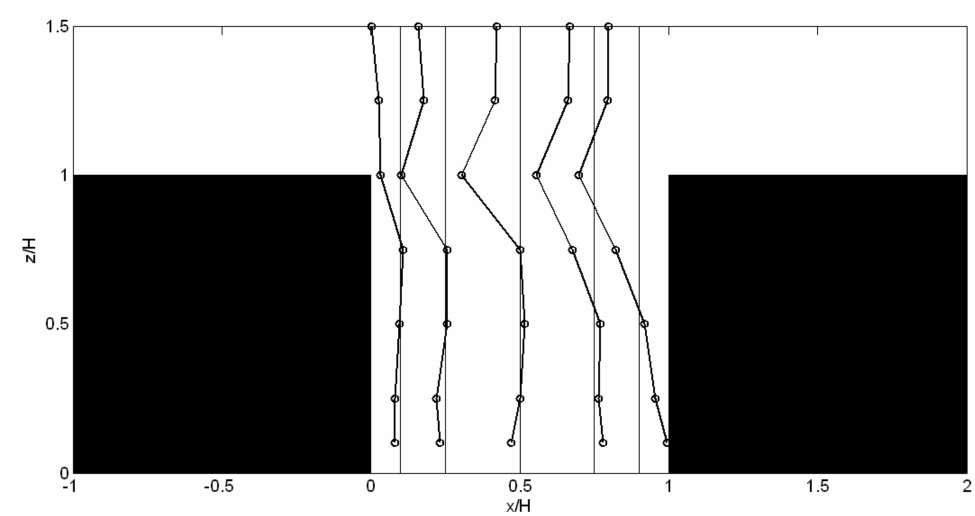

Fig 4: Vertical profiles of time averaged Reynolds stress along the center plane at different stream-wise location for flow in a street canyon (Uehara et al., 2000).

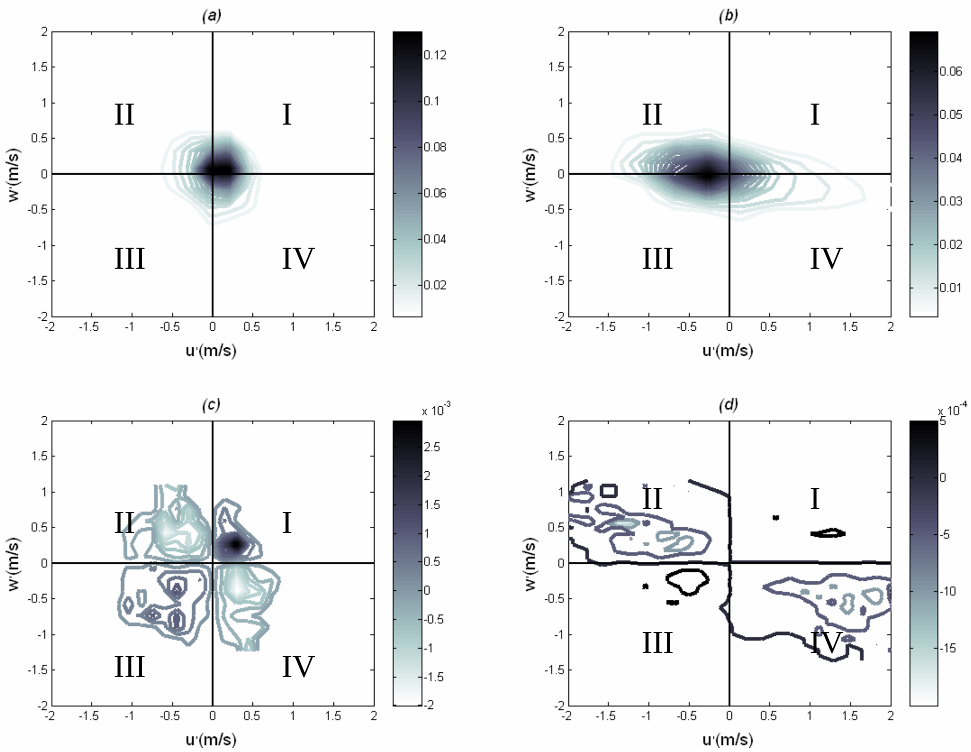

Fig 5: 2D Joint PDF of fluctuating stream-wise and vertical component of velocity at (a) z/H=0.5 and (b) z/H= 1.5 and 2D weighted Joint PDF of fluctuating stream-wise and vertical component of velocity at (c) z/H=0.5 and (d) z/H= 1.5 in a street canyon.

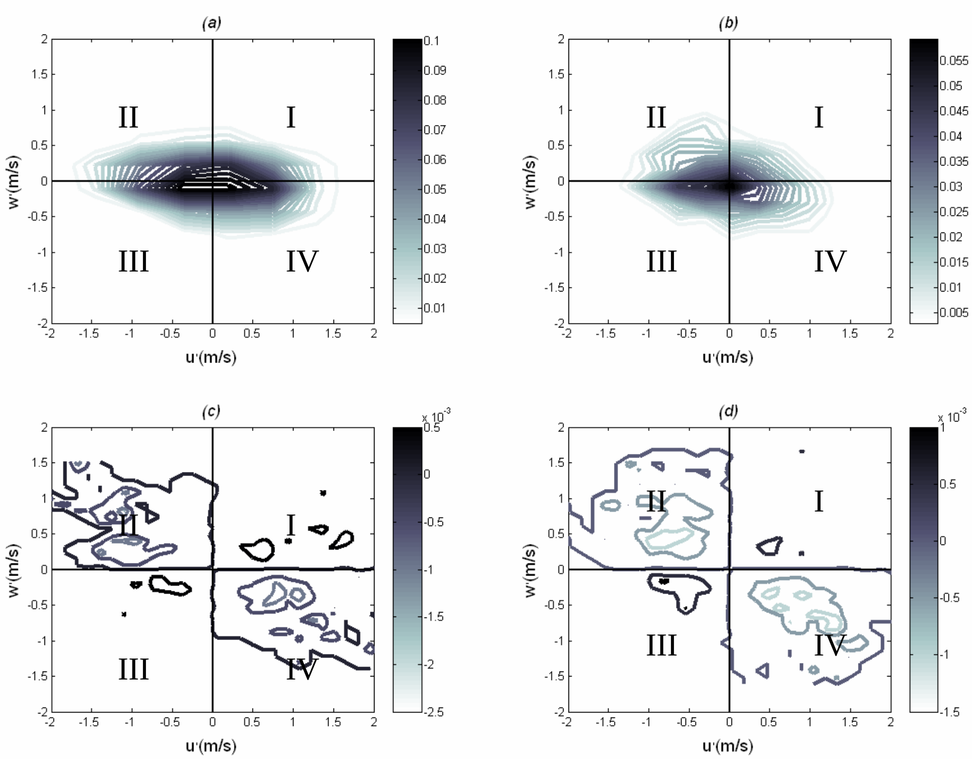

Fig 6: 2D Joint PDF of fluctuating stream-wise and vertical component of velocity at (a) z/H=0.5 and (b) z/H= 1.5 and 2D weighted Joint PDF of fluctuating stream-wise and vertical component of velocity at (c) z/H=0.5 and (d) z/H= 1.5 in a street channel.

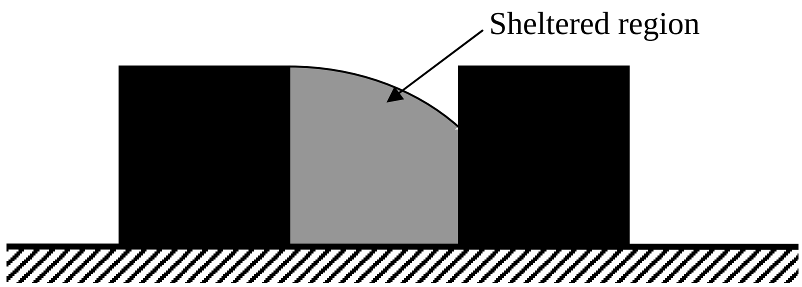

Fig 7: schematic of the sheltered region formed inside a street canyon.

To extend this hypothesis, Reynolds stresses behind a single wall mounted cube were observed. Fig. 8 shows the Reynolds stresses around a wall mounted cube observed by Martinuzzi and Tropea (1993) in a wind tunnel experiment. As seen before, very low value of Reynolds stresses were observed in the sheltered region, indicating decoupling of Reynolds stresses. The joint-probability density functions (JPDF) and weighted joint-probability density functions (WJPDF) of u' and w' measured at z/H=0.5 and z/H=1.5 in a street canyon are presented in Fig. 9. The observed behavior shown in Fig. 9b and d (z/H= 1.5) is similar to that which is typical of the inertial sub-layer (ISL) with quadrants II and IV dominating, i.e., the mean flux of momentum moving from the high-momentum fluid aloft down toward the ground. The JPDF and WJPDF from shown in Fig. 9a and c (z/H =0.5) show very different behavior. The contribution from quadrants I and III are almost as large as those from II and IV yielding a small Reynolds stress.

5. CONCLUSION:

Periodic flow over a regular array of cubical buildings was studied using large eddy simulation. The LES model is used to investigate the physical mechanisms that lead to the low turbulent stresses that have been reported in the lower half of the urban canopy layer (UCL). It was observed that regions having significantly different distribution of the Reynolds stresses exist in the UCL, namely the street channels and the street canyons. Strong decoupling of Reynolds stresses from the ISL flow was observed in the street canyon region, where as no such phenomenon was observed in the street channel. It is hypothesized that this phenomenon exists in the street canyon as this region is sheltered from the inertial flow and hence the turbulent characteristics in this region are decoupled from the ISL.

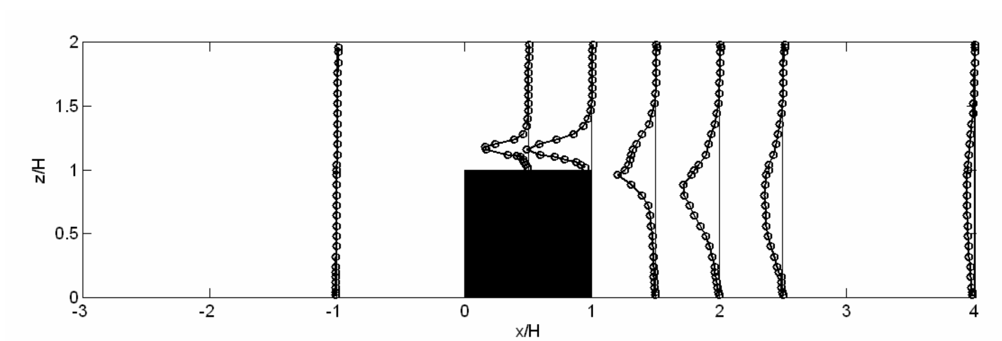

Fig 8: Vertical profiles of time averaged Reynolds stress along the center plane at different stream-wise location for flow around a wall mounted cube (wind tunnel data, Martinuzzi and Tropea, 1993).

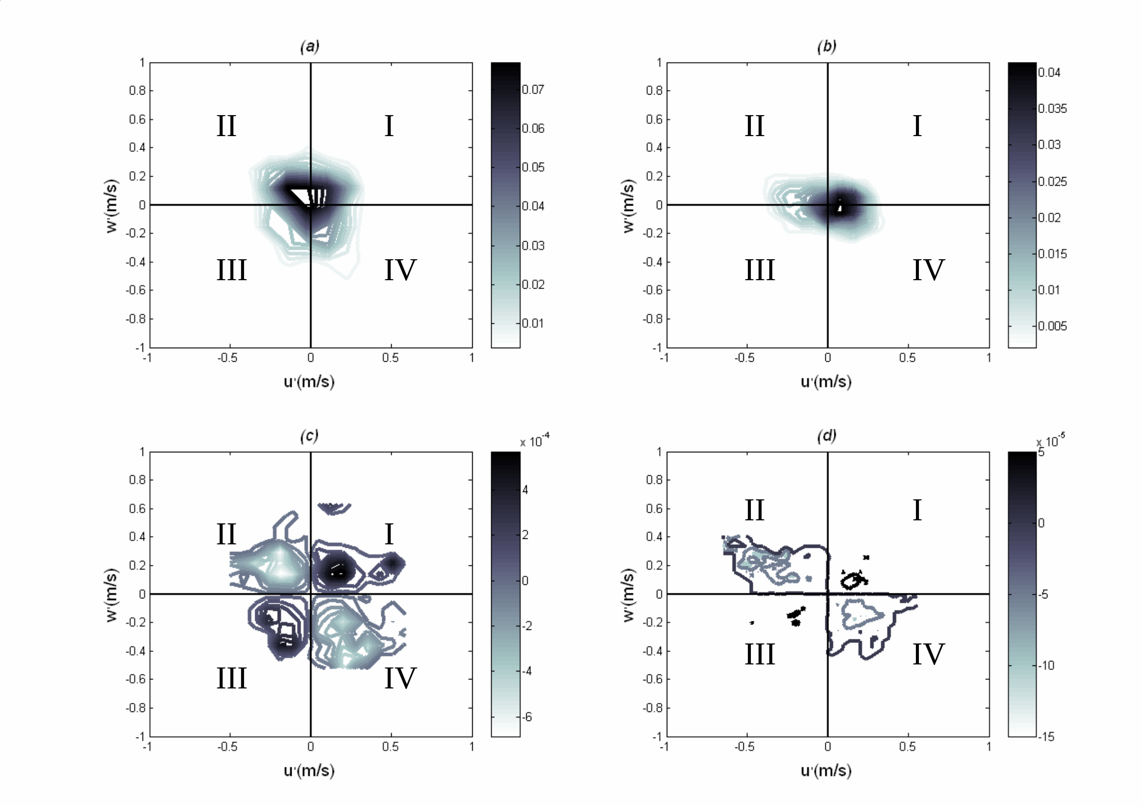

Fig 9: 2D Joint PDF of fluctuating stream-wise and vertical component of velocity at (a) z/H=0.5 and (b) z/H= 1.5 and 2D weighted Joint PDF of fluctuating stream-wise and vertical component of velocity at (c) z/H=0.5 and (d) z/H= 1.5 behind a single wall mounted cube.

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