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Comparison of Centerline Velocity Measurements Obtained Around 2D and 3D Building Arrays in a Wind Tunnel

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Introduction

High-resolution measurements of the three components of the mean and turbulent velocity statistics were obtained around 2D and 3D arrays of model buildings in the USEPA meteorological wind tunnel. The experiments were conducted in order to obtain high-quality and spatially dense data with which to evaluate computational fluid dynamics (CFD) models in urban flow regimes (e.g., Chan et al., 2001). In this paper we compare velocity measurements along the centerline plane for a 2D array of wide buildings and a 3D array of cubical buildings. Salient differences were found in the velocity and turbulent kinetic energy (TKE) fields upstream and downstream of the building arrays and within the canyons and above the rooftops. Being able to simulate these differences will provide strong tests for CFD codes.

Background

As compared to single building flow and dispersion experiments, there have been relatively fewer measurement campaigns around groups of buildings. There have been a number of outdoor urban street canyon experiments measuring concentrations, velocities, and/or temperatures (e.g., Johnson et al. (1973), DePaul and Sheih (1985), Yamartino and Wiegand (1986), Nakamura and Oke (1988), Kitabayashi (1992), Rotach (1995), Nielson (2000)). Although the experiments referenced above contain valuable information, it is difficult to use this data for rigorous CFD model validation due to sparsity of measurements and lack of knowledge of the upstream boundary conditions. More measurements can, in general, be obtained in wind-tunnel experiments and the upstream boundary conditions can be accurately defined. Although wind-tunnel experiments have their own limitations, many of these result from trying to relate wind-tunnel results to full-scale experiments in the atmosphere, a process which is unneccessary for CFD model testing. We have performed relatively high resolution wind velocity measurements in a wind tunnel for two different regular building arrays that should complement other building array experiments that have been performed (e.g., Theurer et al. (1992), Raifailidis and Schatzmann (1995), MacDonald et al. (1998a), Roth and Ueda (1998)).

Experimental Set-up

The experiments were carried out the U.S. Environmental Protection Agency's Fluid Modeling Facility wind tunnel (Snyder, 1979). The wind-tunnel is open-return with a test section 3.7 m wide, 2.1 m high and 18.3 m long. Airspeed in the test section can be varied from about 0.3 to 8 m/s. The ceiling of the test section is adjustable in height to compensate for blockage effects due to large models or to compensate for the growth of a thick floor boundary layer by allowing for a non-accelerating freestream flow. An automated instrument carriage system provides the capability for positioning a probe anywhere in the test section, acquiring data, then moving to the next measurement location and repeating the process without intervention.

The 2D array consisted of 7 rectangular blocks (0.15 x 0.15 x 3.7m) placed with their long face perpendicular to the flow and with a spacing of one building height (H) between the buildings in the alongwind direction (Fig. 1). The 3D array consisted of 7 x 11 cubes (0.15 x 0.15 x 0.15m) with one H spacing (Fig. 1). With S/H ratios of one, the 2D and 3D arrays should be somewhere between the skimming and wake interference flow regimes (Oke, 1987). For both cases, the building models were immersed in a simulated neutral atmospheric boundary layer created using spires and floor roughness elements. This combination produced a simulated boundary layer with depth of 1.8m, a roughness length of 1mm, and a power law exponent of 0.16. The array was located 10.9m from the leading edge of the spires to allow sufficient upstream fetch for the boundary layer to grow to equilibrium. Using a length scale equal to H and a reference velocity of 3 m/s at z = H, the Reynolds number was approximately 30,000, well above the critical value required for Reynolds number independence.

A pulsed-wire anemometer (PWA) was used to measure velocity time series within and around the array. The PWA measures the transit time of a heat pulse from a central wire to either of two sensor wires located on either side of the central wire. The central wire is pulsed with a high current for a few microseconds, raising the temperature of the wire to several hundred ºC and releasing a tracer of heated air which is convected away at the instantaneous flow velocity. The sensor wires are operated as resistance thermometers and are used to measure the time-of-arrival of the heated air parcel. The use of two sensor wires, one on either side of the pulsed wire, ensures that the flow direction is unambiguously determined. While the PWA probe can sense only one velocity component at a time, it can be oriented to measure velocity components in all three coordinate directions. PWA calibrations were performed against a Pitot-static tube mounted in the free-stream of the wind tunnel in the absence of the spires. All PWA measurements were obtained using a pulsing rate of 10Hz and an averaging time of 120 seconds.

Multiple vertical profiles along centerline were taken from 3.3H upstream of the building arrays to 7.5H downstream of the arrays. For the 2D array, vertical profile measurements were taken at high density along the centerline only, while for the 3D array measurements were taken longitudinally along building centerline and street canyon centerline, as well as laterally across buildings and in street canyons. In addition, surface pressure coefficient was measured on the upstream, rooftop and downstream faces of each building in the 2D array, while concentration fields emanating from point source releases were obtained in the 3D array. Comparisons of the centerline measurements in the x-z plane for the two building arrays will be described in this paper.

Results

Figure 2 depicts the mean wind flow and turbulent kinetic energy (TKE) along the center plane upstream, within, and above the first three rows of the 2D and 3D building arrays. One of the most noticeable differences between the two cases is the larger TKE for the 2D array at the leading edge and over the rooftop of the first building row. This most likely results from the stronger jetting - and hence stronger shear - that occurs above the 2D array due to the wider buildings forcing the flow over the top. The wind vectors are seen to be weaker just upstream of the top corner of the 3D array, as the flow has the option of going around the cubical buildings in addition to going over the top. There is significantly more vertical motion at several building heights above and just upstream of the first building row for the 2D array, whereas the flow becomes nearly parallel to the ground for the 3D array at much lower heights. Further downstream, the magnitude of TKE remains relatively high above rooftop level for the 2D array case, resulting from the advection of TKE from where it's produced at the leading edge.

A larger rotor is apparent upstream of the first building row for the 2D array case. Again this is most likely due to the wider building resulting in more flow blockage and hence a stronger recirculation on the upstream face. Also noticeable are elevated levels of TKE on the upstream side of the first building row for the 2D array case. The stagnation point on the upwind face is slightly lower for the 2D array (~0.5 H) as compared to the 3D array (~ 0.7H). Mean recirculation is apparent on the first building rooftop of the 2D array, but at 1/10 H above the 3D array it is not. Smoke visualization indicated that there was intermittent recirculation that formed on the rooftop of the 3D array due to separation at the leading edge. No recirculation is apparent on any of the building rooftops beyond the first row for both cases.

Distinct differences are also found in the vortex circulation that develops within the canyons. For the 2D array, the mean vertical motion is downwards in the downwind half of the canyon and upwards in the upwind half. For the 3D array, the recirculation is asymmetric, with the downward motion extending upstream about 3/4 of the canyon width from the downwind face. The center of the vortex appears to be on the upwind half of the canyon, while for the 2D array it is approximately in the center of the canyon. The differences are most likely due to building edge effects for the 3D array case, thereby introducing mean cross-stream (lateral) motion in the canyon flow. We will evaluate lateral traverses more fully in a follow-on paper.

Figure 3 shows the mean wind and TKE fields downstream of the building arrays. The cavity is much larger for the 2D array case, extending about 4H downstream from the back edge as compared to a little over 1H for the 3D array. The TKE distributions are also very different for the two cases, with the maxima near roof level and about 1H downstream for the 3D array, and below roof level and from 3 to 5H downstream of the 2D array. Zooming in close near the back edge, we can see a small counter-clockwise mean recirculation embedded within the cavity for the 2D array (Fig. 4). For both cases, the flow is very weak within the cavity.

As summarized by Oke (1987), a single vortex develops between buildings for skimming flow ($S/H < 1$) and two counter-rotating vortices may develop for wake interference flow ($1 < S/H < 3$). With the closest measurement within 1/10H of the wall, our mean flow measurements show a single vortex in each canyon. In agreement with the smoke visualization studies performed by Meroney et al. (1996), we found that rooftop recirculation zones do not form on a series of buildings of equal height, except for the one furthest upstream. The behavior of the upstream reattachment point, the size of upwind rotor, and the strength of the rooftop recirculation is similar to that found for single buildings as the cross-stream width is changed (Snyder and Lawson, 1994). However, Snyder and Lawson found that the upstream stagnation point (z =

2/3H) did not change as the building width (W) was changed from 1H to 10H, whereas we found that the stagnation height was lower (0.5H) for the 2D array. They found the cavity length downstream of the single buildings varied from 1.4H for W = 1H to 5.6H for W = 10H. This agrees with results from our 3D array, but our 2D array reattachment point appears to be smaller (~ 4H). The large values of TKE above the first row of buildings in the 2D array at about z = 1.25 H was shown to compare well with urban canyon experiments performed by Kastner-Klein et al. (2000). Further comparisons will be done with other data sets recently published (e.g., Macdonald et al., 1998b).

Summary & Conclusions

Comparisons of mean velocity vectors and turbulent kinetic energy fields in the alongwind centerplane were performed for a 2D building array (1x7 wide rectangular obstacles) and a 3D building array (11x7 cubical obstacles). Significant differences were found in the flow fields both upstream, within, and downwind of the arrays. These data sets should prove useful for CFD model validation studies.

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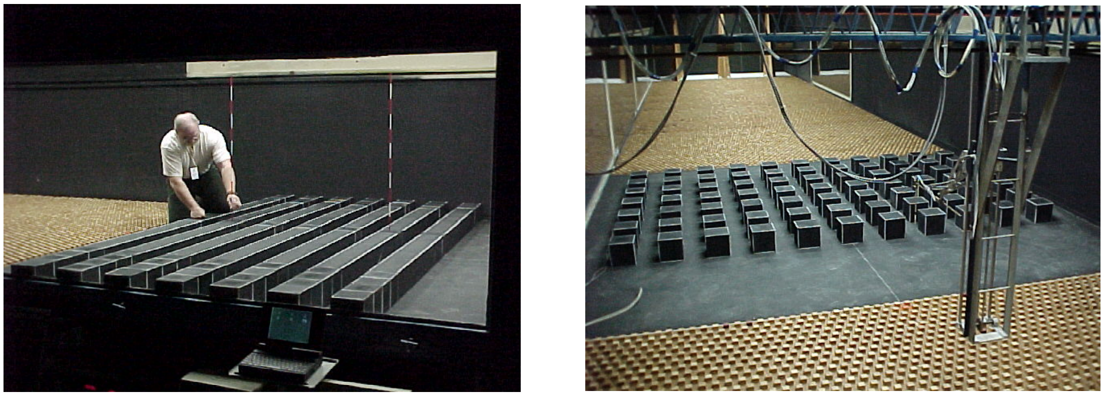

Figure 1. 2D and 3D building arrays in the USEPA meteorological wind tunnel.

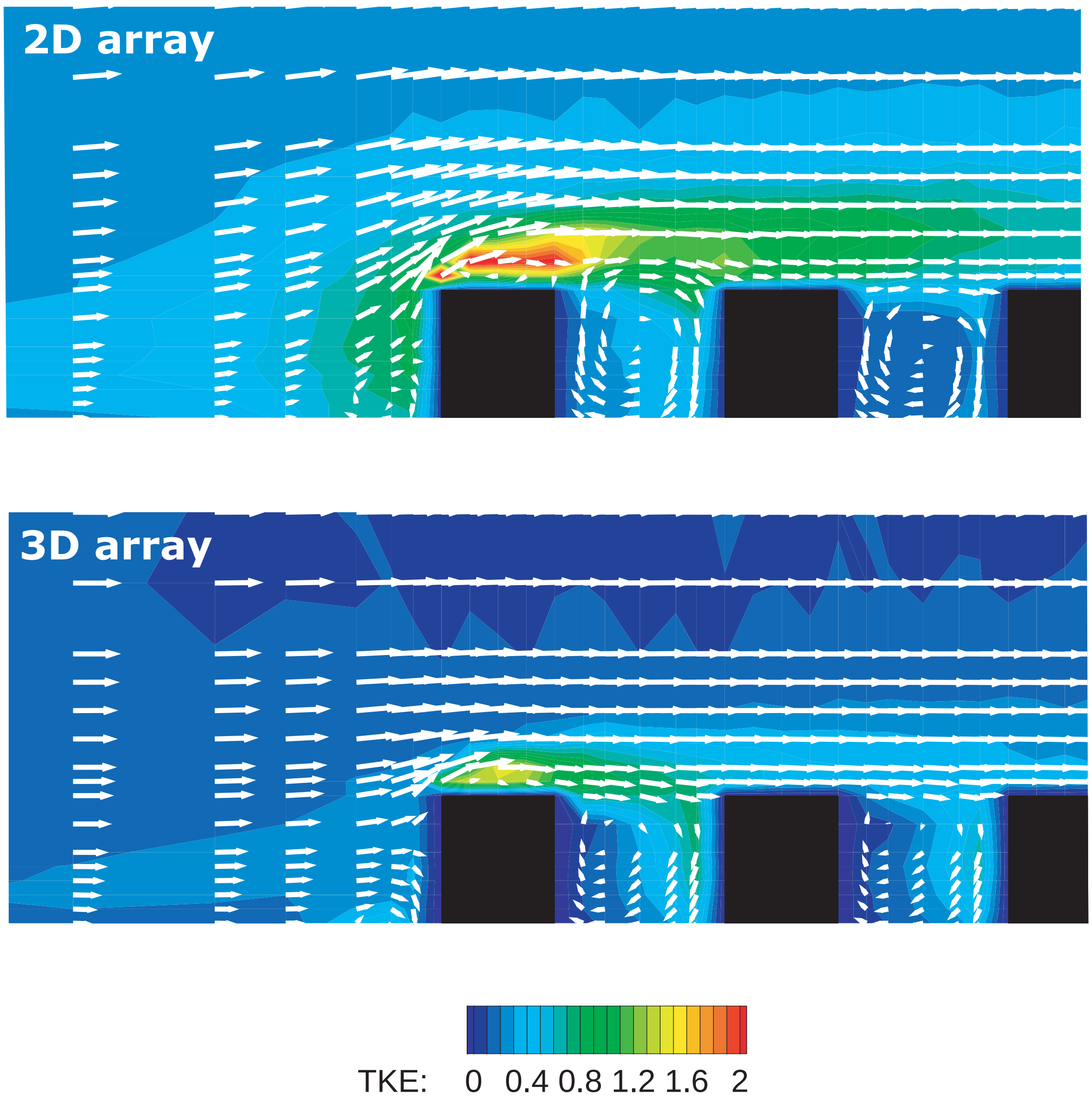

Figure 2. Measurements of mean velocity and turbulent kinetic energy (m^2/s^2) upstream of the 3^{rd} building row covering the alongwind centerplane.

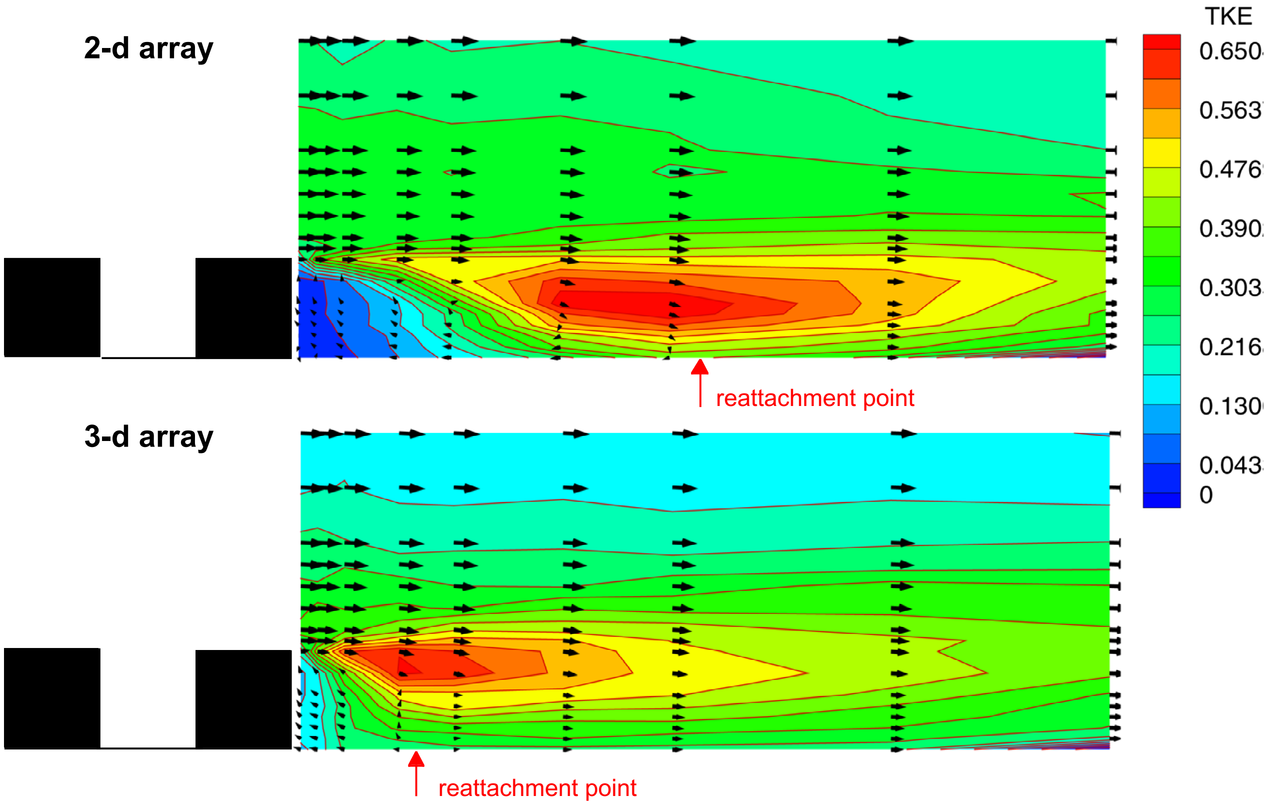

Figure 3. Wind vector and turbulent kinetic energy measurements downstream of the 2D and 3D building arrays covering the alongwind centerplane.

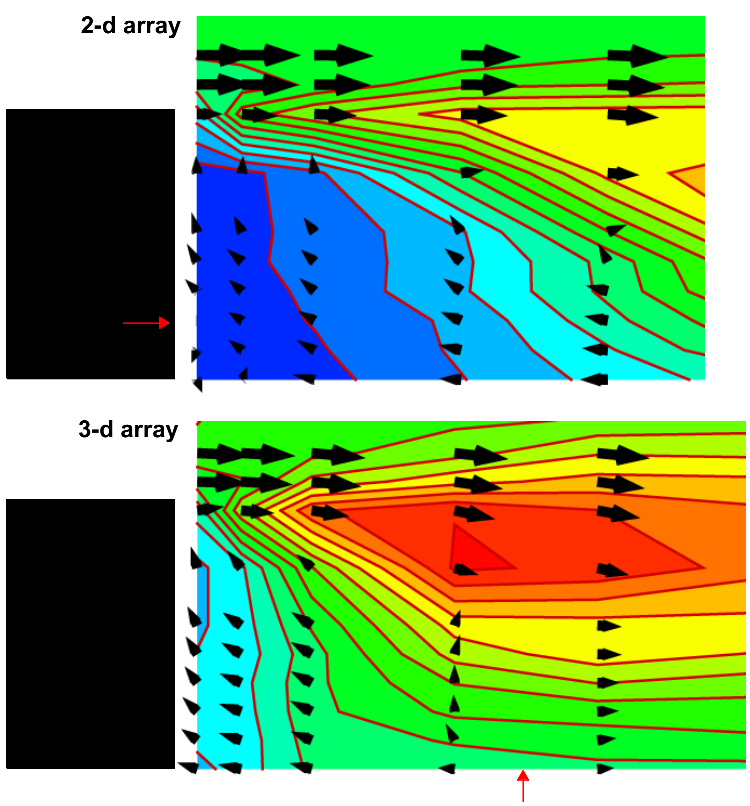

Figure 4. Wind vector and turbulent kinetic energy measurements immediately downstream of the 2D and 3D building arrays covering the alongwind centerplane.