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# SUMMARY OF CFD-URBAN RESULTS IN SUPPORT OF THE MADISON SQUARE GARDEN AND URBAN DISPERSION PROGRAM FIELD TESTS

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## 1. INTRODUCTION

This paper describes the results from a series of Computational Fluid Dynamics (CFD) simulations that have been made in support of the Madison Square Garden 2005 (MSG05) and Urban Dispersion Program 2005 (UDP Midtown) field tests. In support of the MSG05 test, the transport and dispersion of tracer gas released at five locations near Madison Square Garden has been modeled using CFD-Urban. (CFD-Urban is a Computational Fluid Dynamics model that is specialized for performing urban area transport and dispersion calculations, and is described in companion papers at this conference ([Coirier et al., 2006.a,b] ). As shown in [Coirier et al., 2005.b], these calculations indicate the strong influence of large buildings near the release upon both the near source flow and turbulence fields, as well as the near-field and far-field dispersion behavior. Extensive vertical mixing, street level flow energization and lateral as well as upstream spreading of the tracer gas, caused by the presence of large buidlings (1 Penn Plaza and 2 Penn Plaza) near the release locations is noted. A paper summarizing the results of four different Computational Fluid Dynamics models has been prepared for this conference ([Camelli et al., 2006]), of which CFD-Urban is one of four models evaluated. In support of the UDP Midtown test, similar calculations have been made in an area slightly to the North of the MSG area, and results from these simulations exhibit the same vertical mixing and lateral as well as upstream spreading of contaminant caused by the energization of the street level flow by the tall buildings.

In this paper, a short description of the CFD model used for this study is first made, followed by the results of the study for each of the field tests. For each of these summaries, the test is briefly described, followed by detailed velocity and contaminant field results.

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## 2. CFD-URBAN MODEL

CFD-Urban is a suite of Computational Fluid Dynamics modeling software that is being used to simulate the wind, turbulence and dispersion fields in urban areas [Coirier et al., 2003.a, 2005.a,b]. CFD-Urban has been developed under a program sponsored by the Defense Threat Reduction Agency [Coirier et al., 2003.b], and has been built using parts of a commercially available software suite, CFD-ACE+ [ACE+ 2003]. It solves the Reynolds-Averaged Navier-Stokes equations using a collocated, Finite-Volume method implemented upon structured, unstructured and adaptively-refined grids using a pressure-based approach based upon the SIMPLE algorithm [Jiang, 1994, Jiang, 1999]. Turbulence closure is found by solving a variant of the standard k-ε model [Launder, 1974]. Buildings are modeled either explicitly, by resolving the buildings themselves, and/or implicitly, by modeling the effects of the buildings upon the flow by the introduction of source terms in the momentum and turbulence model equations [Coirier 2003.b]. CFD-Urban solves the steady-state and unsteady Reynolds Averaged Navier-Stokes (RANS) equations, as well as by using a Large Eddy Simulation (LES) approach. Since CFD-Urban solves the governing mass and momentum conservation laws at scales smaller than the buildings themselves, important urban aerodynamic features are naturally accounted for, including effects such as channeling, enhanced vertical mixing, downwash and street level flow energization.

## 3. MSG05 FIELD TEST DESCRIPTION

The MSG05 Field Test was sponsored by the Department of Homeland Security under the Urban Dispersion Program (UDP), and the Defense Threat Reduction Agency, with collaborative support from other United States, Canadian and United Kingdom agencies [Hanna et al., 2004]. The test focused upon the area near Madison Square Garden, to better understand the flow and dispersion interactions influenced by large scale buildings (notably the 1 Penn Plaza and 2 Penn Plaza buildings) in the densely packed, deep street canyons exhibited in large cities, such as New York.

Two Intensive Operating Periods (IOPs) were conducted on 10 March and 14 March, 2005. Six different PFT tracer gas releases were made at five locations near the Madison Square Garden. Gas samplers were located at nominal radial distances of 200 and 400 meters from the MSG as shown in Figure 1 (from Hanna et al., 2004) , where the release locations are denoted with a red star, and gas sampler locations with a black triangle.

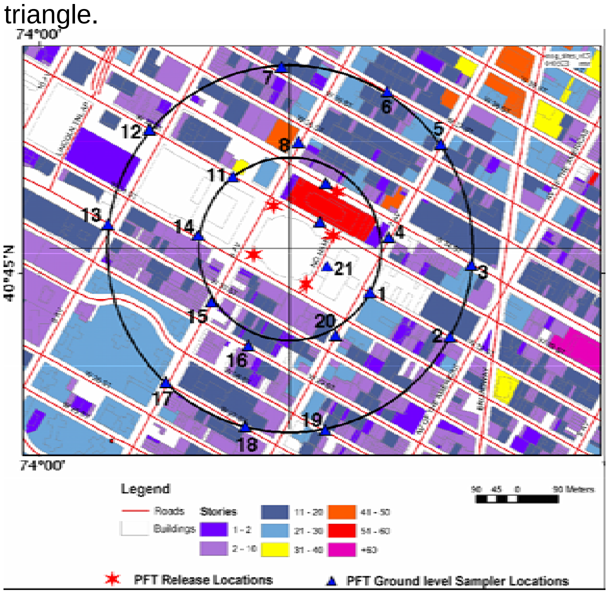


Figure 1. Locations of PFT Releases (Stars) and Stationary PFT Samplers (Triangles) During MSG05 (from Hanna et al., 2004).

Meteorological data was also taken during the test at street level and on rooftops. This data has only recently been processed and made available, and is presented in a paper at this conference [Hanna et al., 2005].

## 4. MSG05 CFD SUPPORT CALCULATIONS AND RESULTS

Wind rose data supplied to the modelers by Los Alamos National Lab members [Brown, 2005] was used to develop appropriate far field boundary conditions for the CFD calculations. The wind rose data was from the JFK, Newark and LaGuardia airports, and represented the statistical wind speeds and directions taken over a many year period. Based upon these wind roses, we assumed a prevailing wind direction of 225 degrees (from SouthWest) with a wind speed of 5.25 m/s at a 10 meter height. The far field boundary conditions for the solver were then made accordingly, using Monin-Obukhov similarity (MOS) profiles, with a length scale of 100 meters, friction velocity $u_*$=0.52639 meters/second and a roughness length of $z_0$=0.25 meters.

The CFD model mesh was constructed for the MSG05 calculations using a quadtree-prismatic/octree, Cartesian model generator that is specialized for generating meshes in urban areas, and is described in a companion paper presented at this conference [Coirier et al., 2006.a]. The underlying GIS data of the NYC area has been supplied to the modelers by the EPA, who obtained the data from the Vexcel Corporation, where figure 2 shows the section of New York being simulated. The three ESRI shp file format data sets supplied were concatenated into a single dataset, which was then rotated clockwise 28.2$^o$ about the data centroid, to orient the majority of the street canyons with the model Cartesian axes. The computational mesh covers a domain of 3.5 by 3.1 by 0.6 kilometers, and has approximately 2.1x10$^6$ cells, with a lateral resolution of approximately 3 meters in MSG area growing to approximately 250 meters near the domain boundaries. The mesh is clustered vertically to be approximately 1 meter in size near the ground plane growing to 40 meters hear the upper boundary. Computational cells that lie completely within buildings are removed, while buildings that occupy partial cells are modeled using a drag model. The corresponding mesh is shown in figure 3, which shows the surface mesh on the ground plane from an overview and closeup perspective of the MSG area.

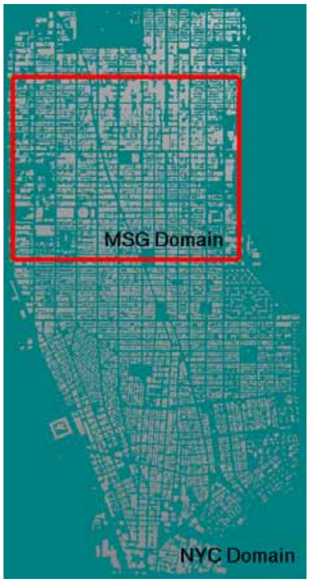


Figure 2: Overview of the NYC area and the computational domain for the MSG05 simulations
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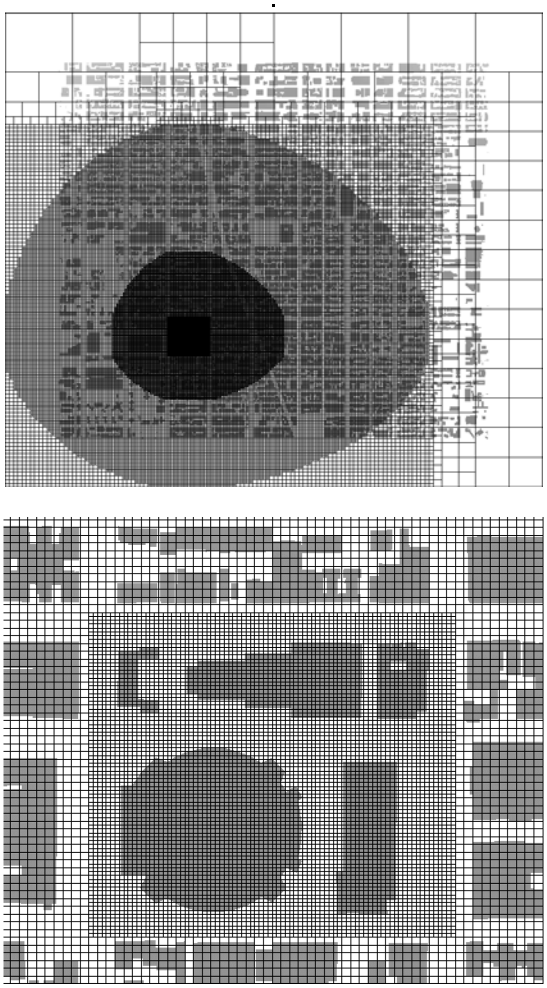

Figure 3. Overview of domain (top) and closeup of the MSG area.

CFD-Urban calculations were made corresponding to a steady prevailing condition, and to an unsteady prevailing condition which simulated a meandering wind via a simple sinusoidal variation of the approaching flow angle. For the meandering flow conditions, fully unsteady and quasi-unsteady calculations were made using the prevailing flow condition angle shown in Figure 4, and the results from the calculations are described below.

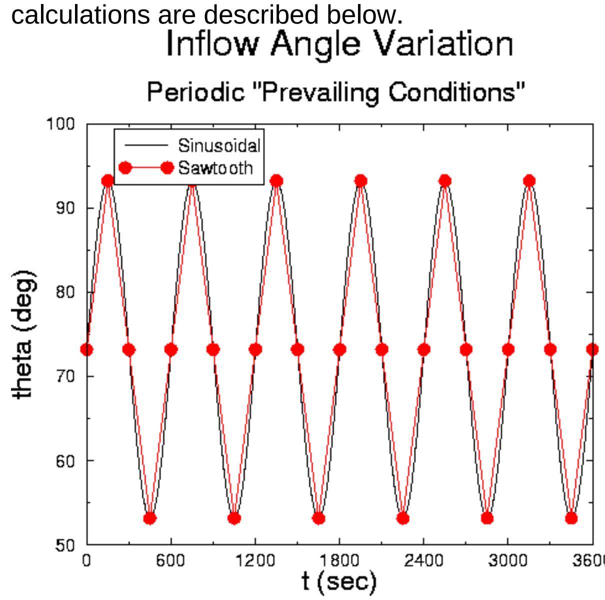


Figure 4: Variation of inflow angles (referenced to a model coordinate system) for the unsteady (black) and wind library (red) calculations.

### *4.1 Wind and Turbulence Fields*

Here, we summarize the important features noted in the MSG area based upon our calculations. Our results and those from other CFD models using similar, yet not identical, flow conditions are shown in a separate paper at this conference [Camelli et al., 2006]. The steady and unsteady calculations exhibited similar features, but the most notable was the relative ineffectiveness of the meandering wind to induce significantly wider lateral contaminant spreading when compared to the steady results (shown in a later section). This is attributed to the deep street canyons relative insensitivity to the above canyon flow direction, and the primary effect of tall buildings upon the local flow features.

The primary features noted in the flow and turbulence fields near the Madison Square Garden may be summarized as:

<u>Downwash and Street Level Flow Energization:</u> The 1 Penn Plaza building is the first tall building

that the approaching, above-city flow encounters before entering the Midtown area. This tall and broad building produces an intense downwash as this above-city, high dynamic pressure air is deflected downward to the street level, as shown in Figure 5. This high velocity downwash energizes the flow at the street level, and causes significant upstream and lateral flow rates and features that have a first-order effect upon the transport and dispersion field. Figure 6 shows vertical velocity contours at 5 meters above ground level, which indicates the extensive downwash on the front of the 1 Penn Plaza and the resulting upwash on the MSG building which is directly across the street. This street level energization is evident at other locations of the domain and is a feature expected to be exhibited in all urban areas which maintain relatively isolated tall buildings inside deep street canyons.

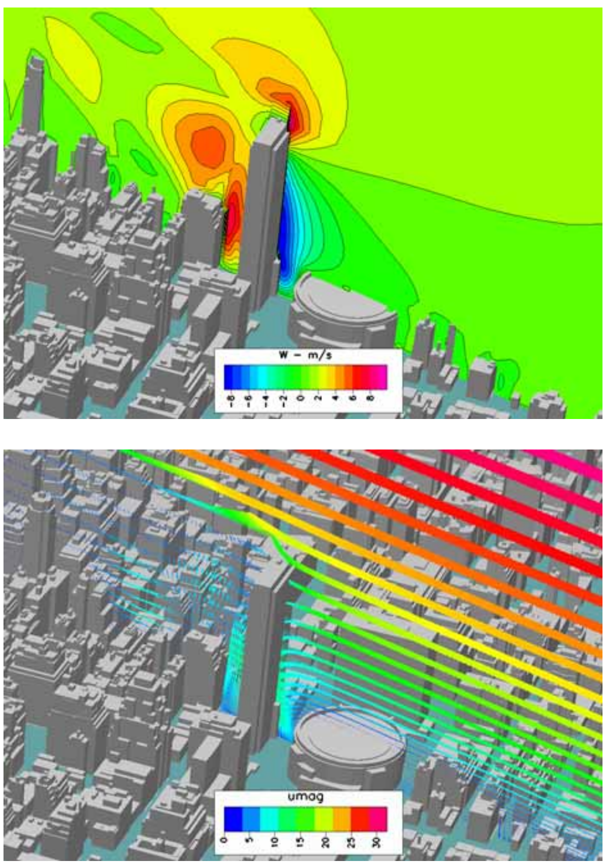

Figure 5: Contours of vertical velocity component and velocity vectors (colored by wind speed) in a plane through the 1 Penn Plaza building aligned with the prevailing flow direction, illustrating the intense downwash and upwash caused by 1 Penn Plaza.

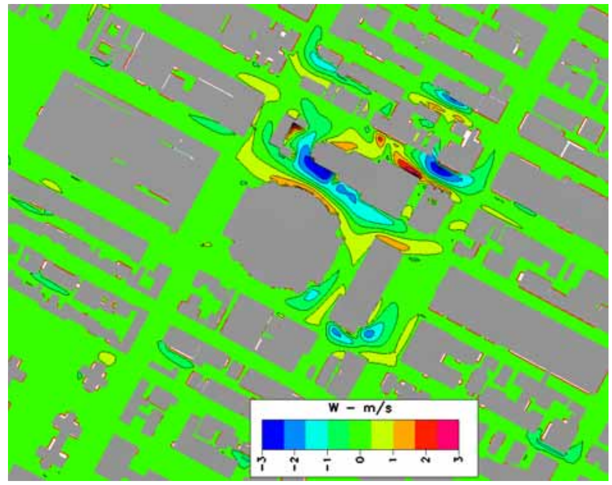

Figure 6. Vertical velocity contours at 5 meters above ground level, showing a significant down wash (negative w) in front of the 1 Penn Plaza, and the resulting upwash on the nearby Northern face of the Madison Square Garden.

<u>Vertical Mixing (Upwash)</u>: In addition to the intense downwash and street level flow energization caused by the 1 Penn Plaza building, this same building also exhibits extensive vertical mixing behind the building, as the low speed flow trapped in the trailing wake is affected by the significant vertical pressure gradient between the ground and upper air levels. This upwash traps contaminant released behind the building, and lofts it high above the city, where it is transported downstream and is actually reingested into the street level downstream. We show this effect via contaminant plume isosurface contours in Figure 7.

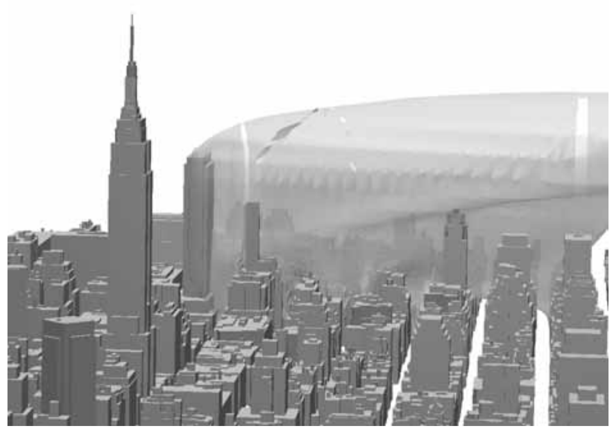
Figure 7. Mass fraction isosurface contours showing vertical mixing behind the 1 Penn Plaza building.

Street Channeling: A common feature of urban area flows is street channeling, where the flow is directed down street canyon axes, and channeled and energized by local geometric features. Examination of the unsteady calculations via animations of velocity magnitude contours at 10 meters AGL and 100 meters AGL shows some switching of flow directions down streets, but indicates less sensitivity to prevailing direction than calculations for lower planform density areas, such as those for the Salt Lake City area. Figure 8 shows the effect of street channeling by displaying velocity magnitude and velocity vectors at 5 meters above ground level.

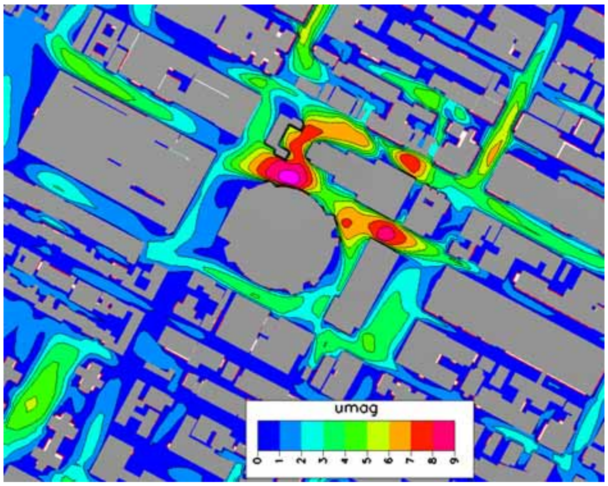

Figure 8. Velocity magnitude at 5m AGL

Enhanced Turbulence Production: The shear caused by the extensive vertical downwash enhances the turbulence levels near the MSG area, while the presence of the buildings themselves introduces mechanically generated turbulence due to the sharp edges and wake regions. Figure 9 shows turbulence kinetic energy contours at 5 meters above ground level near the MSG.

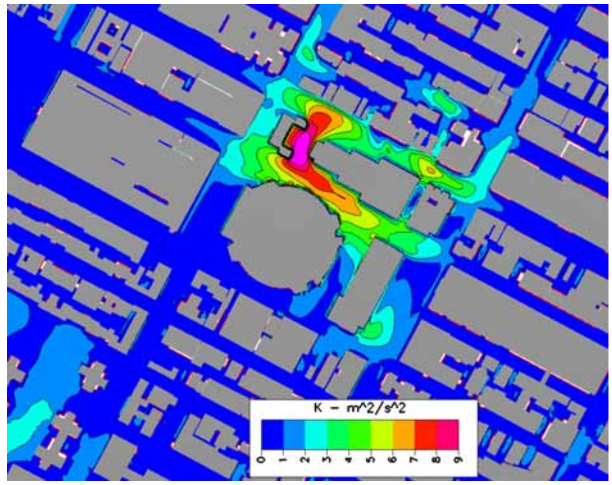

Figure 9. Turbulence kinetic energy at 5m AGL

### *4.2 Transport and Dispersion Fields*

Contaminant transport calculations were made with 5 separately identifiable tracer gases, with release locations and rates replicating those of the experiment. For all of the tracer gases the source was “on” for 1800 seconds, and the transport calculations were made for 3600 seconds total time. The locations of the releases and corresponding tracer gas naming conventions are shown in Figure 10.

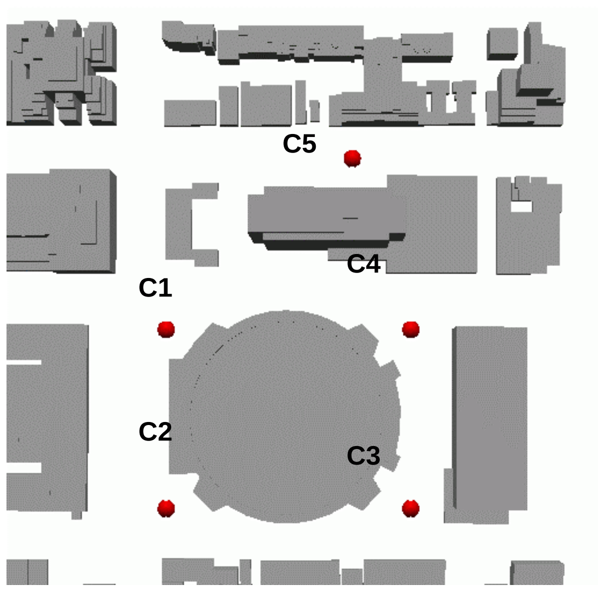

Figure 10. Contaminant release locations.

The contaminant fields were found by solving unsteady, Eulerian, contaminant transport equations for each of the tracer gases. For the fully unsteady calculations, these are solved along with the (unsteady) RANS and turbulence model equations. For the steady and quasi-steady calculations, the unified frozen hydrodynamics solver approach, described in [Coirier et al., 2006.a] is used. The meandering wind calculations using the quasi-steady approach interpolates the steady-state velocity and turbulence fields from three calculations (corresponding to the mean, minimum and maximum angles shown in Figure 4) in time using a periodic "sawtooth" function. The steady prevailing conditions simulations use the steady state flow and turbulence field corresponding to the mean value of the flow angle for all time in the contaminant field evolution equations.

The following plots all show contours of maximum ground level mass fractions, where the mass fraction of the k-th tracer is defined as:

$$Y_k = \frac{\rho_k}{\rho_{mix}} \qquad (1)$$

First, the effect of release location is examined, and then the effect of unsteadiness in the prevailing conditions is assessed using the three approaches described above.

### 4.2.1 Source Location Dependency

Due to the flow and turbulence effects of the 1 Penn Plaza, the five different release locations exhibit significantly different contaminant footprints. The most notable behavior amongst all five release locations is the extensive upstream and lateral spreading: For some of the locations, contaminant is spread upstream 250 meters and laterally nearly 500 meters. Release locations 1 and 2 (Figures 11 and 12) both show similar behavior, as they both are dominated by the same flow from the 1 Penn Plaza downwash that is channeled to the South along the street to the immediate West of the MSG. Location 3 (Figure 13) shows a large, wide area of high concentration centered around the MSG building, and a wide lateral spreading as well. Location 4 (Figure 14) shows a more downwind elongated footprint, with significant lateral and upstream spreading. The most significantly different footprint amongst all 5 release locations is release location 5, located immediately behind 1 Penn Plaza, directly in the upwash region (Figure 15). The contaminant is entrained in the building wake region, and is lofted to the building height (Figure 7), and then is reingested to street level downstream. Due to this lofting and enhanced vertical mixing, the ground footprint is significantly lower in maximum values than the others.

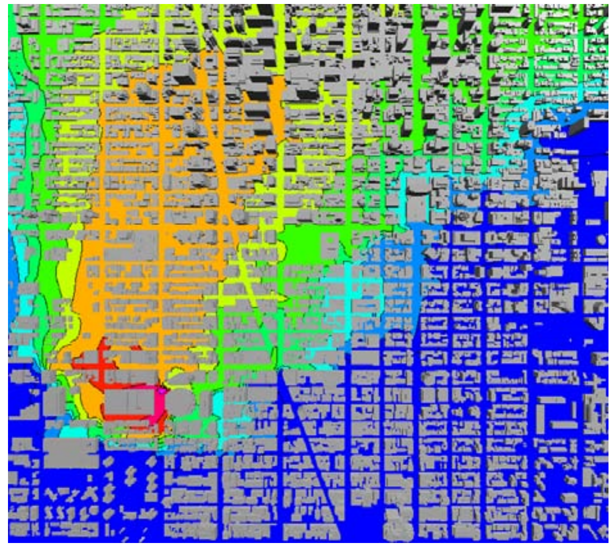

Figure 11: Release location 1 maximum ground level mass fraction concentrations, $\log_{10}(Y_1)$

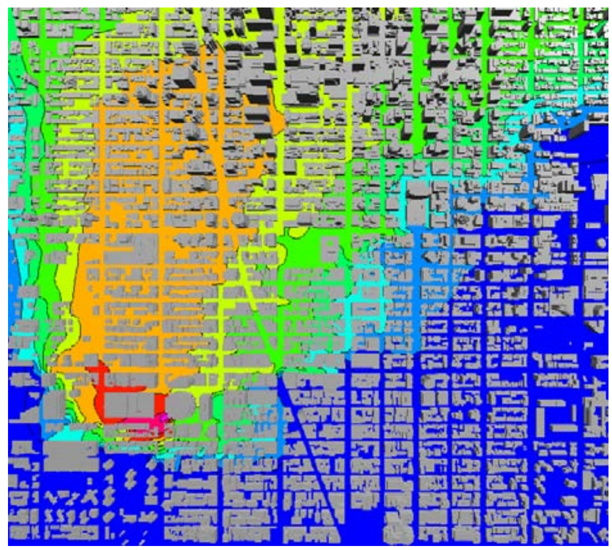

Figure 12: Release location 2 maximum ground level mass fraction concentrations $\log_{10}(Y_2)$

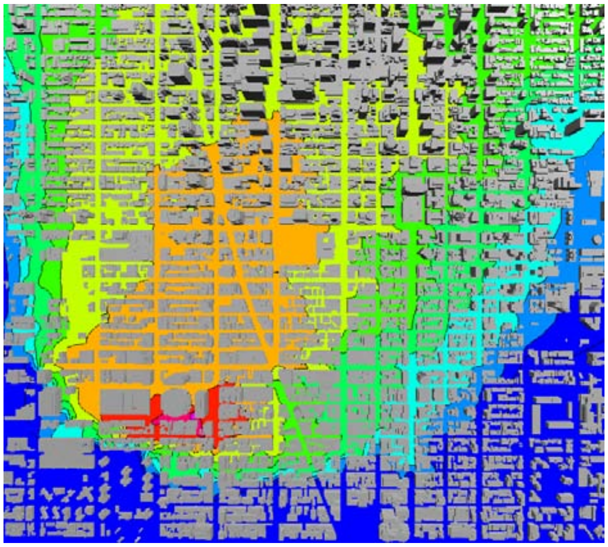

Figure 13: Release location 3 maximum ground level mass fraction concentrations, $\log_{10}(Y_3)$.

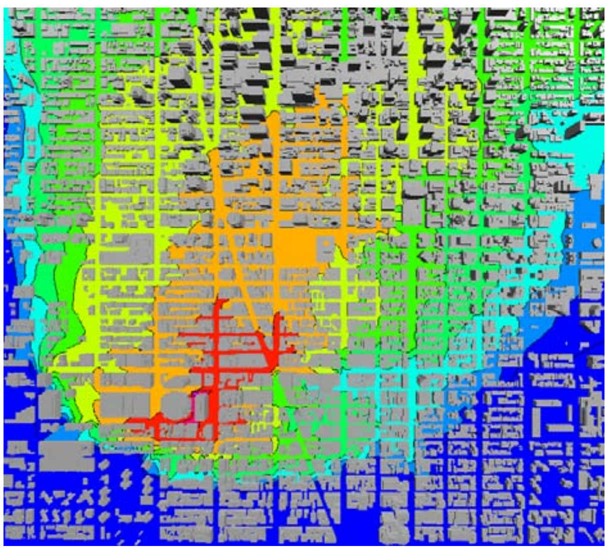

Figure 14: Release location 4 maximum ground level mass fraction concentrations $\log_{10}(Y_4)$.

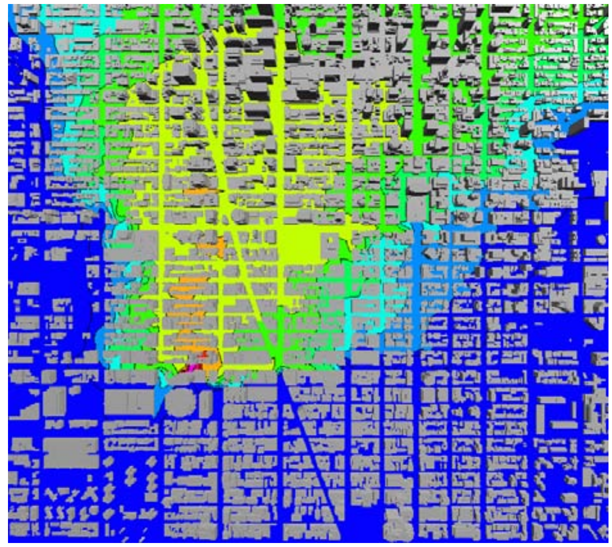

Figure 15: Release location 5 maximum ground level mass fraction concentrations, $\log_{10}(Y_5)$.

#### 4.2.2 Sensitivity to Prevailing Condition Unsteadiness

Figures 16, 17 and 18 show maximum ground level mass fractions for the steady and unsteady prevailing conditions (computed solving the unsteady equations and with the quasi-steady, wind library approach). These contour plots show the log base 10 of the sum of the 5 individual component mass fractions.

$$Y_{sum} = Y_1 + Y_2 + Y_3 + Y_4 + Y_5 \qquad (2)$$

Although there is more spreading caused by the meandering wind, the effect of the above-city flow angle variation is lessened in the deep, relatively quiescent street canyons, which causes the concentration footprints to be very similar. This behavior is caused by the relatively high planform density of the area, and contrasts with results seen in Salt Lake City, which has a lower planform density [Coirier at al., 2005.b]. The contaminant footprints from meandering calculations using the unsteady mode differ very little from those of the quasi-steady calculations. This is noteworthy since the quasi-steady calculations take a fraction of the computing time as the unsteady model.

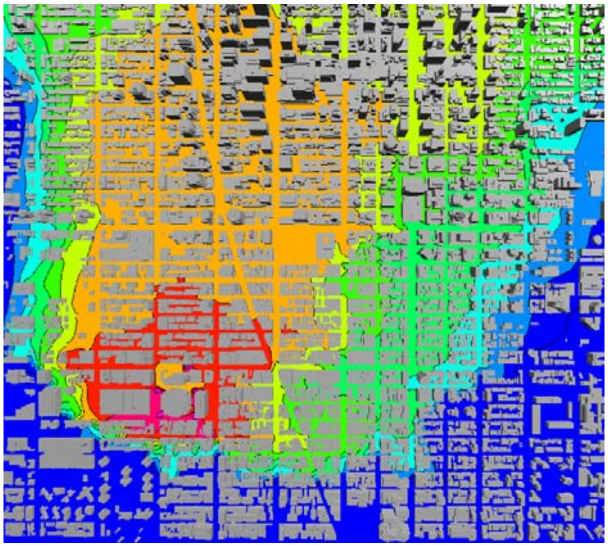

Figure 16: Steady prevailing conditions, maximum $\log_{10}(Y_{sum})$ concentrations.

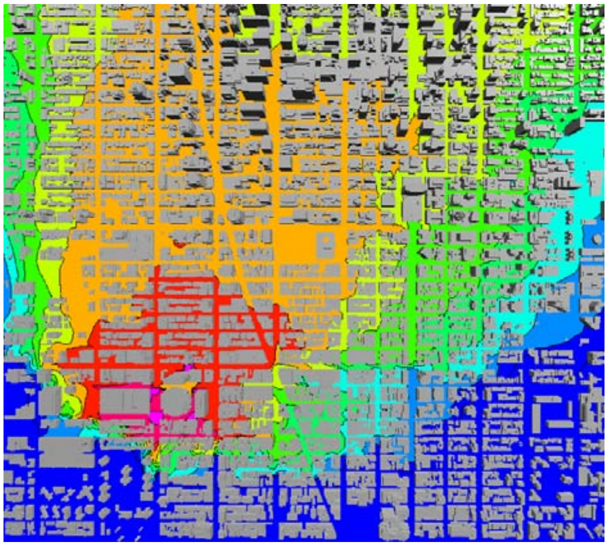

Figure 17: Unsteady prevailing conditions, unsteady simulation mode, maximum $\log_{10}(Y_{sum})$ concentrations.

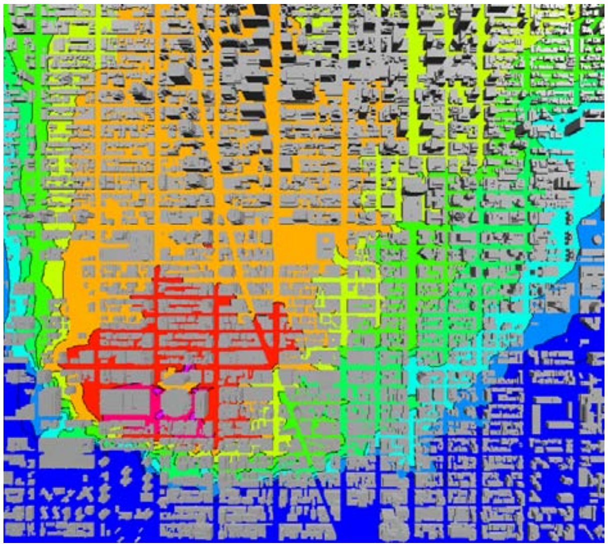

Figure 18: Unsteady prevailing conditions, quasi-steady simulation mode, maximum $\log_{10}(Y_{sum})$ concentrations.

## 5. UDP MIDTOWN SUPPORT CALCULATIONS AND RESULTS

In August of 2005, the Urban Dispersion Program (UDP) performed a field test to the North of the MSG05 test, in the Manhattan Midtown area. To assist the planners, we have performed a series of transport and dispersion calculations corresponding to three release locations of PFT, where the prevailing conditions have been represented by using three different velocity and turbulence profiles (logarithmic, Monin-Obukhov similarity and Urban Canopy Model). To maintain a reasonable paper length, the effects of these different profiles upon the flow and dispersion are deferred for future publications and presentations. The focus in this paper is upon the results using a logarithmic profile.

For the UDP Midtown simulations, a computational mesh was constructed using the same approach as the MSG05 test, over a domain shown in Figure 19 .


Figure 19: UDP Midtown calculation domain.

The mesh spans 2.25 by 2.5 by 1 kilometers, and contains approximately 610,000 cells. The lateral resolution is approximately 9 meters in a resolved region and grows to approximately 70 meters near the domain boundaries. The mesh is clustered vertically with a near ground resolution of 1.5 meter growing to 100 meters near the upper boundary. Computational cells that lie completely within buildings are removed, while buildings that occupy partial cells are modeled using the drag model. Figure 21 shows an overview of the ground surface of the computational mesh.

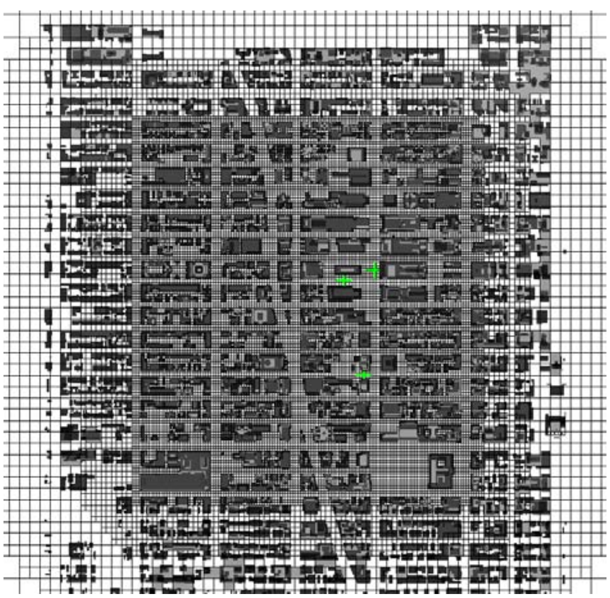

Figure 20: UDP Midtown model surface mesh.

### *5.1 Wind and Turbulence Fields*

A logarithmic profile has been used to specify the wind speed and turbulence, which uses the following equilibrium relations:

$$U = \frac{u_*}{\kappa}\log(\frac{z}{z_0}) \qquad (3)$$

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \qquad (4)$$

$$\varepsilon = \frac{u_*^3}{\kappa z} \qquad (5)$$

For these calculations, the flow is assumed to be steady and directly from the South, with a friction velocity, $u_* = 0.455$ m/s, and a roughness length $z_0 = 0.55$ m. Velocity magnitude contours are shown in Figure 22, vertical velocity contours in Figure 23 and turbulence kinetic energy contours in Figure 24, all at 10 meters above ground level. It is important to note that the turbulence kinetic energy levels are lower than what is observed in the MSG area, although there are peaks present where there is downwash and upwash from the taller buildings, and there are locations of significantly higher wind speed due to channeling.

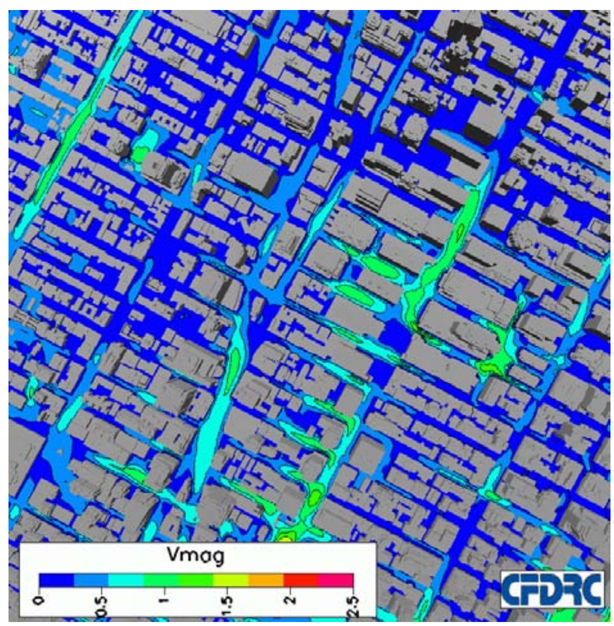


Figure 22. Velocity magnitude at 10m AGL.

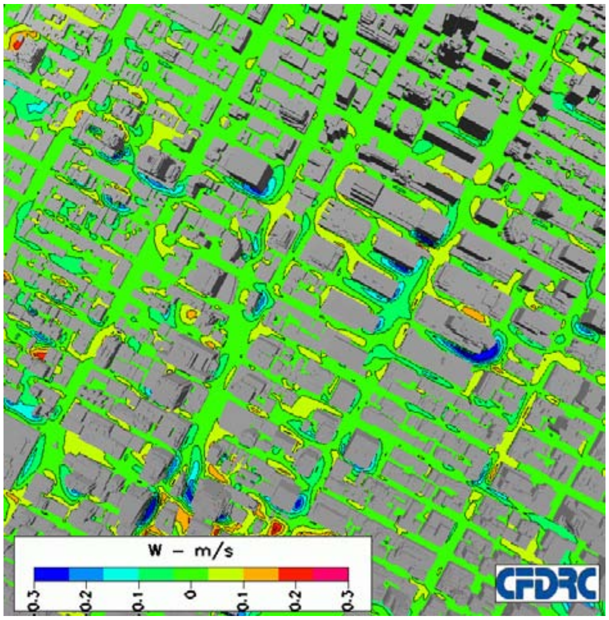

Figure 23. Vertical Velocities at 10m AGL.

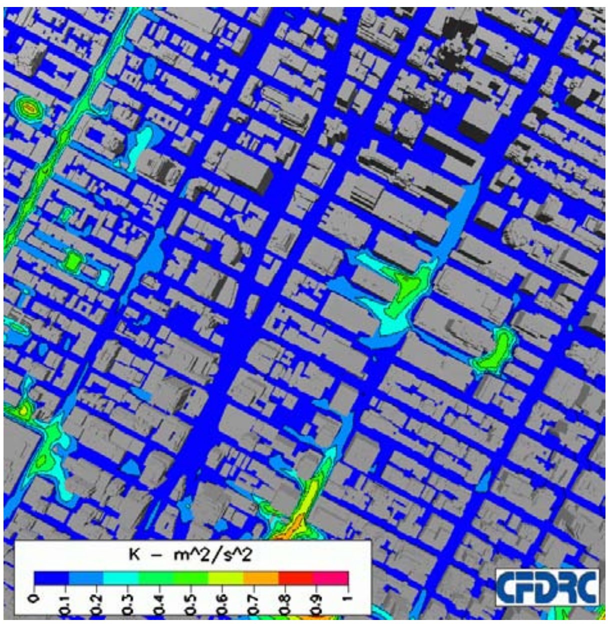

Figure 24. Turbulence Kinetic Energy at 10m AGL.

### *5.2 Transport and Dispersion Fields*

Corresponding to the releases in the test, we have performed PFT transport and dispersion calculations using source locations shown in Figure 25 for puff releases of a short duration, with the frozen hydrodynamics approach. The contaminant footprints for the three release locations are shown in Figures 26, 27 and 28. Release location 1 shows a very confined and channeled lateral spreading near the source, due to street channeling, and exhibits a more narrow footprint than the other release locations due to increased vertical mixing. Location 2 shows channeling also, but in this case, the channeling is aligned with the prevailing flow direction, and causes a less laterally displaced, yet wider, footprint with less vertical mixing. Location 3 exhibits a more North-South channeled plume, and also is spread laterally. Both locations 2 and 3 show a significant upstream and lateral spreading, and less vertical mixing than location 1. Contaminant footprints from the other inflow velocity profiles studied (not shown here) display behavior consistent with the inflow wind speed levels: Increased above city level wind speeds exhibited by the particular MOS profile induces more downwash and vertical mixing, with the accompanying lateral spreading and dilution due to vertical mixing.

Figure 25: Release locations for the UDP Midtown support calculations.

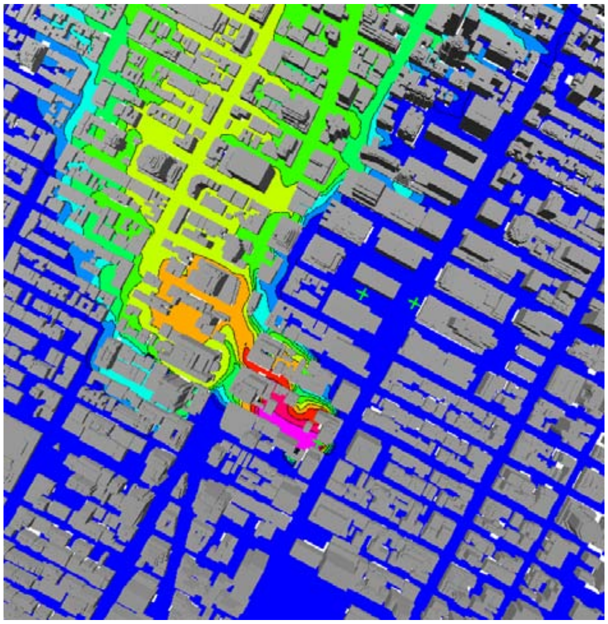

Figure 26: Release location 1 maximum ground level mass fraction concentrations, $\log_{10}(Y_1)$.

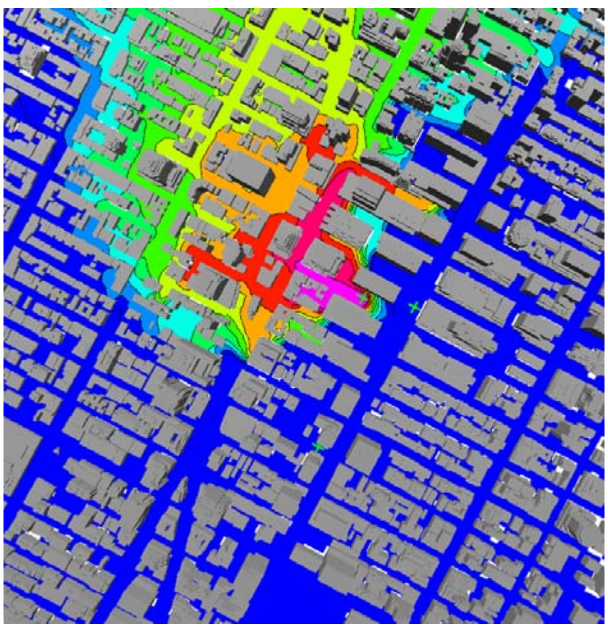

Figure 27: Release location 2 maximum ground level mass fraction concentrations, $\log_{10}(Y_2)$.

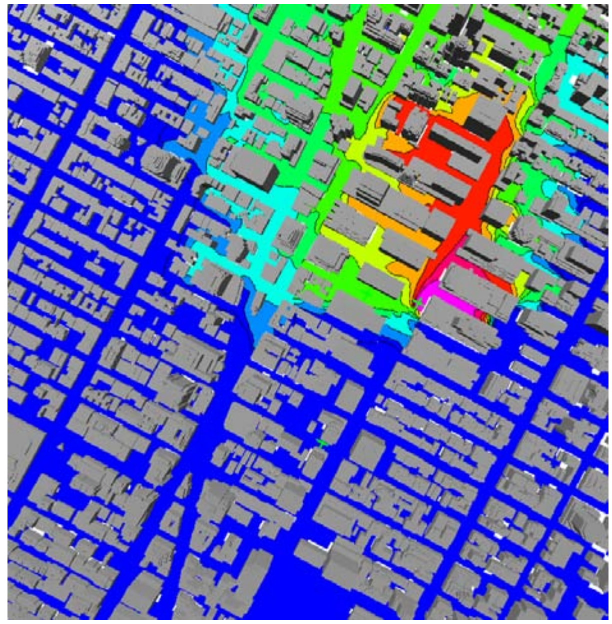

Figure 28: Release location 3 maximum ground level mass fraction concentrations, $\log_{10}(Y_3)$.

## 6. CONCLUSIONS

In this paper, we have described a series of Computational Fluid Dynamic calculations that have been made in support of the Urban Dispersion Program for the Madison Square Garden 2005 (MSG05) and UDP Midtown field tests. To assist the science team and test planners our calculations have used well resolved grids and have simulated different release locations corresponding to those in the test, in order to help determine the best sampler locations and to understand the complex flow and turbulent mixing processes near the Madison Square Garden area. In particular, we have noted the dominating effect of the 1 Penn Plaza building upon the MSG area flow, turbulence and dispersion, through an intensive downwash and accompanying street level flow energization, as well as increased vertical mixing behind the building, and the increased levels of turbulence and flow channeling nearby. Due to this effect, nearby release locations have significantly different tracer gas footprints, even though the releases are made relatively close to each other. In a similar manner, we have performed calculations in the Midtown Manhattan area, and have also noted very different tracer gas footprints amongst the three release locations evaluated there. We conclude that in order to predict the urban area transport and dispersion processes, for planning, first response or protection via optimization of sensor placement, these first order effects must be effectively modeled and understood. We recommend that continued computational analyses be conducted in conjunction with wind, turbulence and dispersion data gleaned from field tests in order to better understand and characterize this behavior.

## 7. ACKNOWLEDGEMENTS

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