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# HIGH-RESOLUTION CFD SIMULATION OF AIRFLOW AND TRACER DISPERSION IN NEW YORK CITY

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## 1. INTRODUCTION

In 2004, a research project - the New York City Urban Dispersion Program (NYC UDP) -was launched by the Department of Homeland Security with the goal to improve the permanent network of wind stations in and around New York City and to enhance the city's emergency response capabilities. Encompassing both field studies and computer modeling, one of the program's objectives is to improve and validate urban dispersion models using the data collected from field studies and to transfer the improved capabilities to NYC emergency agencies. The first two field studies were conducted in March and August 2005 respectively and an additional study is planned for the summer of 2006. Concurrently model simulations, using simple to sophisticated computational fluid dynamics (CFD) models, have been performed to aid the planning of field studies and also to evaluate the performance of such models.

Airflow and tracer dispersion in urban areas such as NYC are extremely complicated. Some of the contributing factors are complex geometry, variable terrain, coupling between local and larger scale flows, deep canyon mixing and updrafts/downdrafts caused by large buildings, street channeling and upstream transport, roof features, and heating effects, etc.

Sponsored by the U.S. Department of Energy (DOE) and Department of Homeland Security (DHS), we have developed a CFD model, FEM3MP, to address some of the above complexities. Our model is based on solving the three-dimensional, time-dependent, incompressible Navier-Stokes equations with appropriate physics for modeling airflow and dispersion in the urban environment. Also utilized in the model are finite-element discretization for effective treatment of complex geometries and a semi-implicit projection method for efficient time-integration. A description of the model can be found in Gresho and Chan (1998), Chan and Stevens (2000).

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Predictions from our model are continuously being verified against data from field studies, such as URBAN 2000 and the Joint URBAN 2003 experiments. Modeling studies comparing simulations to observations from these field experiments are discussed in Chan et al. (2001,2004), Chan and Leach (2004), Chan and Lundquist (2005), Humphreys et al. (2004), Lundquist and Chan (2005).

In the following, we first discuss briefly the field experiment being simulated, then present some preliminary results obtained for the wind field, and finally offer a few concluding remarks.

## 2. THE SIMULATED FIELD EXPERIMENT

In this study, the FEM3MP model was used to simulate one of the field experiment conducted in the vicinity of Madison Square Garden (MSG) in March 2005. The MSG experiments were conducted in late winter of 2005, with perfluorocarbon tracer releases on two days, March 10 and 14. Prior to those dates, meteorological instruments were deployed on

| Site | x (m) | y (m) | AGL (m) |
|---|---|---|---|
| S1 (R,V) | 53 | 117 | 3 |
| S2 (v) | -57 | 61 | 3 |
| S3 (V) | 11 | -58 | 3 |
| S4 (R,V) | 125 | 14 | 3 |
| S5 (R) | 192 | 68 | 3 |
| S6 (R) | 108 | 236 | 5 |
| R1 (R) | 110 | 135 | 233 |
| R2 (R) | 100 | -72 | 133 |
| R3 (V) | -125 | 248 | 34 |
| R7 (R) | 190 | -19 | 50 |

Table I. The street (S) and Rooftop (R) stations used in the study. The (R or V) indicates an R.M. Young 3-d sonic anemometer of Vaisala WXT 501 weather station. (x,y) are relative to the origin at the center of MSG.

rooftops in a semi-permanent network established to support the UDP efforts. In addition, for each of the two days that tracers were released, portable weather stations were deployed at street level around Madison Square Garden and in the immediate vicinity. The locations are described in Table I, along with the type of instruments that were deployed. The R.M. Young sonic anemometers were sampled at 10Hz, and therefore provide a source to calculate turbulence intensity in addition to the mean wind. The Vaisala WXT 501 weather station samples once every 3 seconds, observes the two-dimensional wind vector (u,v) and basic meteorological variables such as temperature, humidity and barometric pressure.

In this study, the comparisons to the CFD model simulations are restricted to the mean wind vectors as observed by the street level and rooftop sensors.

## 3. WIND FLOW RESULTS

In the numerical simulations, a computational domain of 1,750 m x 1,200 m x 800 m (in the longitudinal, lateral, and vertical directions), together with a mesh consisting of 351 x 241 x 151 (~12.7 million) grid points, was used. The mesh has a 5 m grid resolution in both horizontal directions and variable resolution in the vertical direction with a minimum of 2 m near the ground and 8 m near the top boundary. All the buildings were treated as virtual buildings (drag elements). Fig. 1 is a 3-D view of the buildings modeled within the computational domain, with MSG located in the middle of the domain.

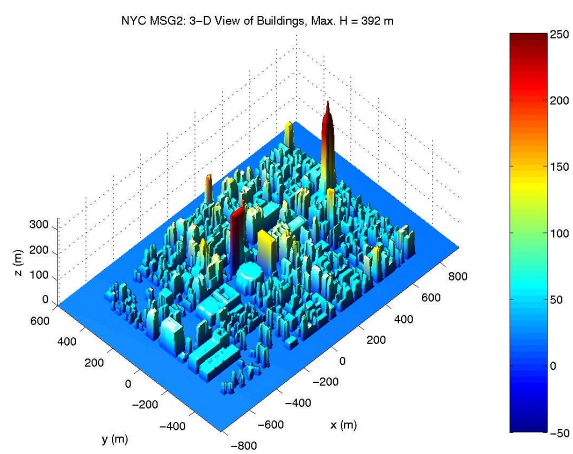


Fig. 1. A three-dimensional view of the computational domain and modeled buildings used in the simulation of airflow and dispersion near Madison Square Garden. MSG is in the middle of the computational domain.

In the simulation, an inlet velocity profile with urban effects suggested by Steve Hanna (private communication) was employed. Also considered in the profile is the meteorological data measured at the Stevenson Institute of Technology (SIT) and provided to us by Michael Reynolds of Brookhaven National Laboratory (private communication). The measured wind speed was 5 m/s and at 292$^{o}$ at 92 m above ground level. Shown in Fig. 2 is the constructed “urban” wind profile, together with a logarithmic profile for comparison. The “urban” wind profile was assumed to be steady in time and imposed on the west and south boundary as inflow boundary conditions.

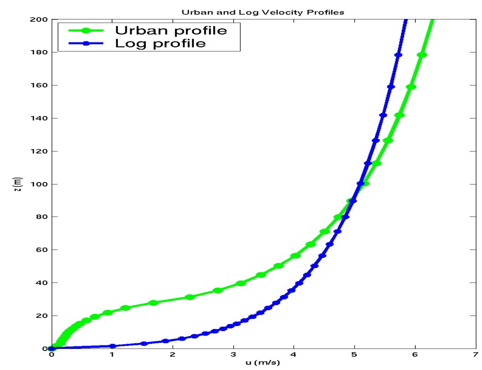


Fig. 2. Urban wind profile used as inflow boundary conditions on the west and south boundary. Also shown is a logarithmic profile for comparison.

A quasi steady state flow field was established after ~5 minutes of simulated time. The RANS approach with a non-linear eddy viscosity (NEV) turbulence model (Gresho and Chan, 1998) was used and neutral atmospheric stability was assumed in the simulation.

In the following, some preliminary results from the flow simulation are presented and briefly compared with observed data. More results for the flow field and also dispersion results will be presented at the conference.

Fig. 3 is a close-up view of the predicted wind vectors near MSG at z=4 m and Fig. 4 shows the observed wind vectors near street level and at various rooftops around MSG. As seen in the figure, our model is able to capture the diverging flow towards the upwind and crosswind directions on the windward side of MSG and of Two Penn Plaza (to the east of MSG in the figure). Compared against the measured data at street level, our model predictions appear to agree reasonably well with the observed data. Besides the complexity of the flow near MSG, another interesting feature of the flow is that noticeable reverse flow occurs along a couple of streets to the lower west corner of MSG. Unfortunately there is no field measurements available for comparison.

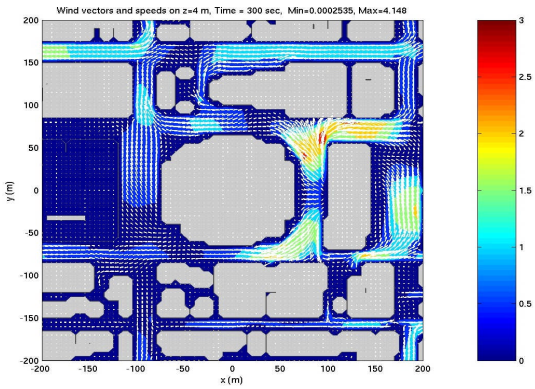


Fig. 3. Predicted horizontal wind vectors and horizontal wind speeds (color contours) near Madison Square Garden on z =4 m plane.

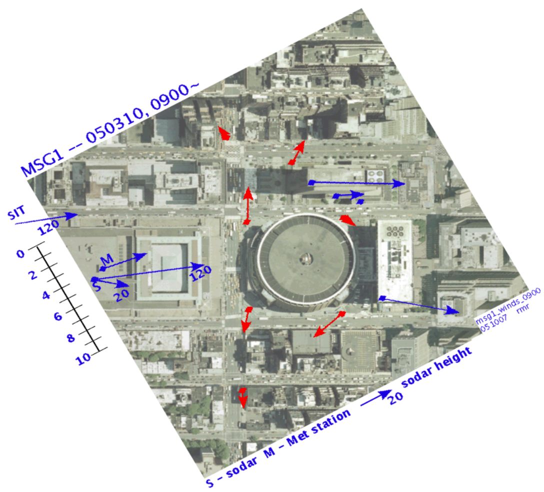


Fig. 4. Observed wind vectors (red near street level and blue at rooftop) at 9 am on March 10, 2005. The wind vector measured at SIT has a speed of 5 m/s and wind direction of 292$^{o}$ at 92 m AGL. One Penn Plaza building is to the north and Two Penn Plaza building is to the east of Madison Square Garden in the picture. Courtesy of Michael Reynolds, BNL.

In Fig. 5, predicted wind vectors and wind speeds (color contours) on the z=50 m plane are depicted. The results show the strong influence on the wind flow by tall buildings such as One Penn Plaza and Two Penn Plaza. There are, among others, significant downdrafts on the windward sides and updrafts on the leeward sides of these buildings. In particular, due to the almost direct impingement of the incoming flow, the magnitude of updrafts and downdrafts around Two Penn Plaza gets considerably higher than 1 m/s.

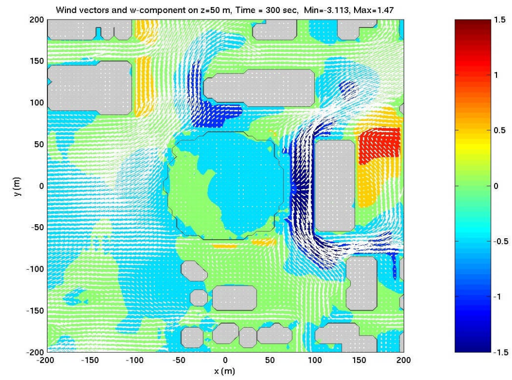


Fig. 5. Predicted horizontal wind vectors and vertical wind speeds (color contours) near Madison Square Garden on z=50 m plane, illustrating significant downdrafts and updrafts generated by tall buildings.

In Fig. 6, predicted wind vectors and wind speeds (color contours) on the east-west vertical plane (y=0) passing through MSG are shown. The variations and intensity of downdrafts and updrafts around Two Penn Plaza can be clearly seen. Also shown in the figure are two (clockwise) rotating vortices adjacent to MSG.

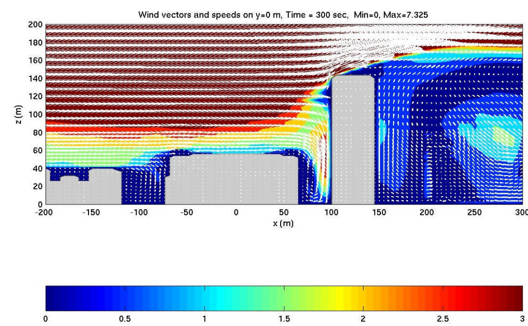


Fig. 6. Predicted horizontal wind vectors and horizontal wind speeds on the east-west vertical plane (y=0) passing through MSG.

## 4. CONCLUSIONS

In this paper, the FEM3MP model has been used to model the wind flow around Madison Square Garden. Our model predictions for the surface winds are generally very consistent with field observations.

In particular, our model is able to capture the diverging flow towards the upwind and crosswind directions on the windward side of MSG and Two Penn Plaza.

Besides revealing the complex flow features near MSG, our model results also indicate that noticeable reverse flow occurs along a couple of the east-west running streets upwind of MSG. These results suggest that transport of a street level release in NYC could extend for a few blocks in both upwind and crosswind directions relative to the prevailing wind direction above rooftops.

Our model predictions of significant downdrafts and updrafts around tall buildings and the existence of rotating vortices in the street canyons adjacent to MSG could also have significant implications for the transport of the released materials. The materials could be brought down or up around tall buildings, depending on the local wind being a downdraft or updraft. Once trapped in the vortices of the street canyons near MSG, the released materials could linger for much longer than expected.

We will perform a dispersion simulation, using the calculated wind field, and continue to compare our model predictions against the observed wind and concentration in more details. More results and findings will be reported at the conference.

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