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# Detailed Simulations of Atmospheric Flow and Dispersion in Urban Downtown Areas by Computational Fluid Dynamics (CFD) Models – An Application of Five CFD Models to Manhattan

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**Abstract** - Computational Fluid Dynamics (CFD) model simulations of urban boundary layers have improved so that they are useful in many types of flow and dispersion analyses. The study described here is intended to assist in planning emergency response activities related to releases of chemical or biological agents into the atmosphere in large cities such as New York City. Five CFD models (CFD-Urban, FLACS, FEM3MP, FEFLO-Urban, and Fluent-Urban) have been applied by five independent groups to the

same 3-D building data and geographic domain in Manhattan, using approximately the same wind input conditions. Wind flow observations are available from the Madison Square Garden March 2005 (MSG05) field experiment. It is seen from the many side-by-side comparison plots that the CFD models' simulations of near-surface wind fields generally agree with each other and with field observations, within typical atmospheric uncertainties of a factor of two. The qualitative results shown here suggest, for example, that transport of a release at street level in a large city could reach a few blocks in the upwind and crosswind directions. There are still key differences seen among the models for certain parts of the domain. Further quantitative examinations of differences among the models and the observations are necessary to understand causal relationships.

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**Key Words:** Urban boundary layers, CFD models, Madison Square Garden 2005 field experiment, urban dispersion, emergency response models.

**One Sentence Summary** – Five Computational Fluid Dynamics (CFD) models are compared, using the same urban atmospheric boundary layer scenario in Manhattan and are shown to produce similar wind flow patterns, as well as good agreement with observed winds during a field experiment.

## 1. Background

There are increased concerns about air quality in large urban areas, which are growing in size across the globe. The current paper is concerned about a specific problem – the possible release of chemical or biological agents or toxic industrial chemicals by terrorist activities or accidents in downtown urban areas. For planning purposes and for real-time emergency response, decision-makers want to know where to safely send emergency responders, whether evacuation or shelter-in-place of the public is required, and which specific areas of the city are impacted and for how long a time. City-dwellers are familiar with the swirling, non-uniform wind patterns in downtown street canyons, which cause standard straight-line atmospheric transport and dispersion models to be inappropriate within a few blocks of the release. Many papers describe the variability that characterizes flow and turbulence in urban areas (e.g., Oke 1987, Rotach 1996, Roth 2000, and Britter and Hanna 2003). To help provide some guidance to emergency responders, a group of scientists and engineers has been using Computational Fluid Dynamics (CFD) models to estimate airflow and dispersion patterns in the street canyons of large cities.

Manhattan is the focus of a set of recent field experiments sponsored by the Urban Dispersion Program (UDP) of the Department of Homeland Security (DHS). The wind data from the March 2005 Madison Square Garden experiment are used in the current paper (Hanna et al., 2006). In addition, a second field experiment took place in August 2005 in the Midtown area. The Manhattan experiments are part of a sequence of

intensive urban field experiments that have taken place over the past five years, sponsored collaboratively by a number of agencies. Other field experiments include the Salt Lake City Urban 2000 experiment (Allwine et al., 2002), the Oklahoma City Joint Urban 2003 experiment (Allwine et al., 2004; DPG, 2005), and the London Dispersion of Air Pollutants and their Penetration into the Local Environment (DAPPLE) experiment (Britter, 2005). These experiments make use of dense networks of fast-response sonic anemometers sited at street level and on building tops, as well as remote sounders such as minisodars. The experiments also include tracer gas releases and sampling at many locations. The availability of these extensive urban data bases provides an opportunity for further development and evaluation of many types of urban flow and dispersion models, including CFD models.

## 2. CFD Models and Input Assumptions

For urban applications, the CFD models solve the basic equations of motion on a high resolution (1 to 10 m) three-dimensional grid system, within a domain with sides of a few km at most and with typical depth of 0.5 to 1 km. Detailed three-dimensional (3-D) building data are also needed for the simulations. Now that computers are faster and have more storage, it has become possible to run CFD models on an urban domain within a reasonable time frame (say less than a few hours). Multiple sensitivity studies are now possible. However, most early applications were to scenarios that were strongly forced by obstacles, such as a single cube, and only the near-field results were analyzed. Most modelers (e.g., Hanna et al., 2002) found that the CFD model-simulated turbulence was

realistic near the obstacle but died away too quickly once the flow passed the influence of the obstacle. The models had a difficult time maintaining sufficient turbulence over, say, a uniform grassy field. The atmosphere is naturally quite turbulent, with turbulence intensities of 0.1 or more. This dilemma was the subject of a workshop in July 2004 at George Mason University in Fairfax, VA., where the current authors were in attendance and agreed to proceed with collaborative studies to attempt to resolve the problem. For example, a methodology for overcoming the turbulence problem was suggested by Tang et al. (2006) at the AMS Annual Meeting.

One aspect of the collaborative study discussed at the workshop was to use some standard field data bases to advance the development and evaluation of the CFD models. These data bases included the Kit Fox, MUST, Prairie Grass, and EMU data (e.g., Hanna et al., 2004). A key data base was the classical 1956 Prairie Grass field experiment, which took place over a grassy field. Although there is not space in this paper to describe the details, the modelers improved their turbulence parameterizations so as to produce good agreement with the Prairie Grass data.

Another aspect of the collaborative study was to run several CFD models as part of ongoing major studies such as the Manhattan Madison Square Garden 2005 (MSG05) study. The models were used to plan the experiment and are now being used to analyze the results, as discussed in the current paper. It should be mentioned that, while some of the CFD work (FEM3MP and Fluent-Urban) was directly sponsored by the MSG05 lead agency (DHS) or a cosponsoring agency (the Defense Threat Reduction Agency, who

supported the CFD-Urban runs), the FEFLO-Urban and FLACS runs were carried out with internal funds from George Mason University and GexCon, respectively. Also, the Fluent-Urban runs were cosponsored by the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA). Thus this scientific initiative conforms to the spirit of advancing the overall field.

A unique characteristic of the current paper is that this is the first time that several CFD models have been applied to the same urban boundary layer scenario to enable model comparisons. Identical three-dimensional building data files and similar input meteorology were used. The CFD models, their references, and the persons running the models for the current study are listed below.

| | |
|---|---|
| CFD-Urban (Coirier et al., 2005; Coirier and Kim, 2006a and 2006b) | (William Coirier and Sura Kim of CFD Research Corporation) |
| FLACS (Hanna et al., 2004) | (Olav R. Hansen of GexCon) |
| FEM3MP (Gresho and Chan, 1998; Calhoun et al., 2005) | (Stevens Chan of Lawrence Livermore National Laboratory) |
| FEFLO-Urban (Camelli et al., 2004; Camelli and Lohner, 2004) | (Fernando Camelli of George Mason University) |

Fluent-Urban (Huber et al., 2005) (Alan Huber of NOAA)

Although these five CFD models are not sufficiently fast to be used for real-time emergency response, they can be used for planning purposes and to guide parameterizations in simpler, real-time wind flow models. An example of a fast-running real-time wind flow and dispersion model that is parameterized based on the CFD results is QUIC (Williams et al., 2004).

Four of these same CFD models (all but FEM3MP) were used to plan the MSG05 experiment. Those runs used the expected SSW wind direction, which has the highest probability according to historic climate data. However, the actual wind directions during MSG05 were from the WNW to NNW, which are the subject of the current paper. Some comparisons for the SSW planning runs were presented by Michael Brown at the AMS 2006 Annual Meeting (Camelli et al., 2006) and a brief comparison of FEM3MP with observations for the MSG05 WNW case was presented by Martin Leach at the same meeting (Leach et al., 2006). The conclusions by Camelli et al. (2006) concerning model-to-model comparisons were similar to what is found here (i.e., good agreement concerning general flow patterns), although there were no on-site observations from SSW wind directions to aid in the evaluations.

Summaries of the CFD model characteristics and assumptions for the MSG05 exercise (for the WNW wind directions observed during the field experiment on 10 March 2005)

are given in Table 1. Readers interested in more details can consult the references. All models except FEFLO-Urban were run in Reynolds-Averaged Navier Stokes (RANS) mode. FEFLO-Urban was run in Large Eddy Simulation (LES) mode, which requires more computer time but which produces time variable flow fields that "look like" real 3-D time dependent turbulence. The RANS models outputs have 3-D variability but represent an average over time and are therefore steady-state.

All CFD models used the three-dimensional building data base for Manhattan licensed by the Vexcel Corporation. These licensed building data have a resolution of about 1 m, and support visualizations that look like "real" photographs. However, we point out that, since buildings in large cities such as New York City are razed and rebuilt with surprising frequency, it is necessary to update the 3-D file for applications at any particular time.

To allow comparisons with the observed winds, the CFD model simulations were made for the first MSG05 experiment time period (from 9 am to 2 pm on 10 March 2005). Both days of MSG05 (10 and 14 March) were characterized by fairly steady moderate wind flows, well-mixed nearly-neutral conditions, and cold temperatures (near 0 C). As seen in Table 2, the wind directions were slightly different during the two days – WNW on 10 March and NW to NNW on 14 March (Hanna et al., 2006). In this paper, a wind direction close to WNW is assumed for all models, in order to simulate the 10 March period.

Although Table 1 shows that the five CFD models used slightly different assumptions for inflow (upwind) wind speeds and directions, the results are expected to be relatively unaffected because the buildings have such a strong effect on the wind patterns and the incoming flow has a few blocks to adjust to the underlying built-up urban area.

The sonic anemometers listed in Table 2 measured winds at eight locations near street level and on several rooftops, such as the One Penn Plaza (229 m) and Two Penn Plaza (153 m) buildings, which are adjacent to MSG. Figure 1 shows the MSG domain and buildings, and gives the positions of the anemometers at street level (S) and at rooftop (R). Figures 2 and 3 employ the same geographic domain and include, as examples, the observed 30-minute averaged wind vectors from 9:00 to 9:30 am on 10 March and 14 March, respectively. The observed rooftop winds have speeds of about 6 m/s and are from the WNW direction on March 10 (see Figure 2) and from the NW direction on 14 March (see Figure 3), while the observed street-level winds (with an average scalar speed of about 2 m/s) have many directions, depending on nearby buildings. The figures show that, with the exception of the two sonic anemometers close to the windward (east) side of Two Penn Plaza, the observed street-level wind patterns do roughly agree on the two days.

As intuition would suggest, the relative influence of the One Penn Plaza (229 m) and Two Penn Plaza (153 m) buildings switches for the SSW wind direction used in the CFD planning runs (Camelli et al., 2006) and the WNW wind directions observed during the field experiment. Since the broad side of One Penn Plaza faces the SSW, it dominates

the street-level flow for the SSW wind direction. And since the broad side of Two Penn Plaza faces the WNW, it dominates the street-level flow for the WNW wind direction, as seen in the results in the figures. Although we did not carry out any CFD model runs for light winds with variable directions, it is obvious that the flow patterns would flip back and forth from being dominated by one building or the other if the wind directions are varying back and forth between SW to NW.

## 3. Results of CFD Model Runs

Examples of simulated wind vectors near street level, at 9 am on 10 March of the MSG05 field experiment, are given in Figures 4 through 8 for the five CFD models (CFD-Urban, FLACS, FEM3MP, FEFLO-Urban, and Fluent-Urban, respectively). To aid the visual comparisons of the figures, the domain size and orientation is approximately the same for all models. Side-by-side comparisons with the observed wind vectors (in Figure 2) show reasonable agreement in speed (within a factor of two) and direction (within about 30°) for most street-level sites. For example, the models capture the diverging flow towards the upwind and crosswind directions on the windward side of MSG and of Two Penn Plaza (just east of MSG).

In the planning run comparisons for the SSW wind direction, Camelli et al. (2006) show that there are a few locations on the domain that show significant differences among the models, and these warrant further investigations. Usually the differences occur where the wakes of two adjacent buildings are "battling" each other for dominance.

Careful comparisons of Figures 4 through 8 reveal similar discrepancies in certain parts of the domain. The CFD team is proceeding with quantitative comparisons of the simulated winds in the figures in this paper, and those results will be shown in a future paper. For example, the 30 minute averaged wind speed and direction simulated by the five models at each anemometer location will be compared using standard statistics. Vertical profiles and cross-sections of model outputs such as turbulent kinetic energy (TKE) will be tabulated and analyzed.

As another qualitative conclusion from Figures 4 - 8, the results show the strong influence of the tallest buildings on the near-surface wind flow. The tall buildings bring down momentum from aloft on their windward sides, and have an upward directed "chimney effect" on their leeward sides. The simulated vertical velocity patterns are seen in Figures 9 - 13 for the five CFD models (CFD-Urban, FLACS, FEM3MP, FEFLO-Urban, and Fluent-Urban, respectively). The typical magnitudes of the vertical velocities are a few tenths of meters per second, although larger values (as much as 1 m/s) are sometimes simulated close to tall buildings. These vertical motions are consistent with the diverging and converging flow patterns at street level, which can extend a block or two out from the base of the building. The lateral extent of the outflow and inflow patterns is approximately equal to one or two building heights.

The vortices in street canyons and behind buildings can also be seen when the results of the simulations are plotted as along-wind and vertical (x-z) cross-sections, as in Figures 14 – 18 for the five CFD models. The x-z cross-section is through the middle of

MSG and directed parallel to the streets (e.g., 33rd Street), which are oriented from WNW to ESE. This direction is approximately aligned with the inflow wind direction. Note that the wind vectors are plotted as the x-z component in Figures 14 - 17, for CFD-Urban, FLACS, FEM3MP, and FEFLO-Urban, respectively. But the wind vectors are plotted as only the x component in Figure 18, for Fluent-Urban. Many circulations can be seen on the x-z cross-sections. For example, the downdraft on the windward side of Two Penn Plaza (just east of MSG) is clearly seen in Figures 14 - 17, as well as the street canyon eddy on the windward side of MSG. The horizontal vectors shown in Figure 18, for Fluent-Urban, also show the reversal in near-surface wind flow upwind of MSG.

Four of the models also were used to simulate tracer dispersion patterns, for comparison with observations during MSG05. Although the tracer studies are not the main emphasis of the current paper, it is found that the models agree that the tracer initially spreads a block or two upwind and laterally while it is still near street level, and then spreads downwind as a broad plume after it mixes vertically to the building tops. Examples of CFD model simulations of tracer dispersion are shown in Figures 19 - 22 for CFD-Urban, FLACS, FEM3MP and FEFLO-Urban, respectively. The tracer source locations were on the four corners of MSG and on the north side of One Penn Plaza.

When time series of CFD model concentration plots are studied, they show the "hold-up" of tracer material in recirculating zones behind buildings or in blocked regions with very low velocities. These zones are very important for emergency response decisions,

and further analysis of the CFD model outputs and the tracer data should aid in devising decision strategies.

It is seen from these example figures that the simulations by the five models are qualitatively similar. They agree fairly well with each other and with the MSG05 flow observations, at least concerning general patterns and flow magnitudes. Although more analysis is clearly needed, these preliminary CFD results suggest that they hold promise for aiding in increasing our understanding of wind flow and tracer dispersion in urban areas. Clearly the extensive recent CFD model enhancements to account for the relatively large turbulence intensities in the atmosphere have led to much more accurate simulations, especially in large built-up urban areas.

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**References:**

Allwine, K.J., J.H. Shinn, G.E. Streit, K.L. Clawson, M. Brown, 2002: Overview of Urban 2000. *Bull. Am. Meteorol. Soc.*, **83** (4), 521-536.

Allwine K.J., M. Leach, L. Stockham, J. Shinn, R. Hosker, J. Bowers, and J. Pace, 2004: *Overview of Joint Urban 2003 – An atmospheric dispersion study in Oklahoma City*. Preprints, Symposium on Planning, Nowcasting and Forecasting in the Urban Zone. American Meteorological Society, January 11-15, 2004, Seattle, Washington. Available on CD from AMS, 45 Beacon St., Boston, MA 02215.

Britter, R.E., 2005: DAPPLE: Dispersion of Air Pollutants and their Penetration into the Local Environment. http://www.dapple.org.uk

Britter, R.E. and S.R. Hanna, 2003: Flow and dispersion in urban areas. *Annu. Rev. Fluid Mech.*, **35**, 469-496.

Calhoun, R., F. Gouveia, J. Shinn, S. Chan, D. Stevens, R. Lee and J. Leone, 2005: Flow around a complex building: Experimental and large-eddy simulation comparisons. *J. Appl. Meteorol.*, **44**, 571-590.

Camelli, F.E., W.J. Coirier, A.H. Huber, O.R. Hansen, S. Kim, S.R. Hanna and M.J. Brown, 2006: An intercomparison of four CFD models: Transport and dispersion around

Madison Square Garden. Paper J2.6 at 14th Conference on Air Pollution Modeling, Atlanta, GA. American Meteorological Society. Available on-line at www.ametsoc.org and on CD from AMS, 45 Beacon St., Boston, MA 02215.

Camelli, F., S. R. Hanna, and R. Löhner, 2004: Simulation of the MUST field experiment using the FEFLO-Urban CFD model. *Fifth Symposium on the Urban Environment*, Vancouver, Canada, AMS.

Camelli, F. E. and R. Löhner, 2004: *Engin. Comput.*, **21**, 748.

Coirier, W. J., D. M. Fricker, M. Furmaczyk and S. Kim, 2005: A computational fluid dynamics approach for urban area transport and dispersion. *Environ. Fluid Mech*. **15.**

Coirier, W. J. and S. Kim, 2006a: CFD modeling for urban area contaminant transport and dispersion: model description and data requirements, Paper JP2.11 at *6th Symposium on the Urban Environment*, American Meteorological Society. Available on-line at www.ametsoc.org and on CD from AMS, 45 Beacon St., Boston, MA 02215.

Coirier, W. J. and S. Kim, 2006b: Summary of CFD-Urban results in support of the Madison Square Garden and Urban Dispersion Program field tests, Paper J5.5 at *6th Symposium on the Urban Environment*, American Meteorological Society. Available on-line at www.ametsoc.org and on CD from AMS, 45 Beacon St., Boston, MA 02215.

Dugway Proving Ground, 2005: Data Archive for JU2003. https://ju2003-dpg.dpg.army.mil

Gresho, P.M and S. T. Chan, 1998: Projection 2 goes turbulent – and fully implicit. *Int. J. of Comp. Fluid Dyn.* **9,** 249-272.

Hanna, S. R., O. R. Hansen and S. Dharmavaram, 2004: FLACS air quality CFD model performance evaluation with Kit Fox, MUST, Prairie Grass, and EMU observations. *Atmos. Environ.*, **38**, 4675-4687.

Hanna, S. R, S. Tehranian, B. Carissimo, R. W. Macdonald and R. Lohner, 2002: Comparisons of model simulations with observations of mean flow and turbulence within simple obstacle arrays. *Atmos Environ.* **36**, 5067-5079.

Hanna, S. R., J. White, Y. Zhou and A Kosheleva, 2006: Analysis of JU2003 and MSG05 meteorological and tracer data. Paper J7.1 at 6th Symposium on the Urban Environment, Atlanta, GA. American Meteorological Society. Available on-line at www.ametsoc.org and on CD from AMS, 45 Beacon St., Boston, MA 02215.

.

Huber, A., M. Freeman, R. Spencer, B. Bell, K. Kuehlert and W. Schwarz, 2005: Applications of CFD simulations of pollutant transport and dispersion within ambient urban building environments: Including homeland security. Paper 1241 at AWMA 98th Annual Conf., June 21-23, www.awma.org/OnlineLibrary.

Leach, M. J., S. T. Chan and J. K. Lundquist, 2006: High-resolution CFD simulation of airflow and tracer dispersion in New York City. Paper J5.6 at AMS 6th Symposium on the Urban Environment, Atlanta, GA. American Meteorological Society. Available on-line at www.ametsoc.org and on CD from AMS, 45 Beacon St., Boston, MA 02215.

Oke, T.R., 1987: *Boundary Layer Climates*, Routledge, London.

Rotach, M.W., 1996: The turbulence structure in the urban roughness sublayer. *Flow and Dispersion Through Groups of Obstacles*, (ed. R. J. Perkins and S. E. Belcher), Clarendon Press, Oxford.

Roth, M., 2000: Review of atmospheric turbulence over cities. *Quart. J. Roy. Meteorol. Soc.,* **126**, 941-990.

Tang, W. A. Huber, B. Bell and W. Schwartz, 2006: Application of CFD simulations for short-range atmospheric dispersion over open fields and within arrays of buildings. 14th Joint Conf. on the Appl. of Air Poll. Meteorol. with the AWMA, Atlanta, GA. American Meteorological Society. Available on-line at www.ametsoc.org and on CD from AMS, 45 Beacon St., Boston, MA 02215.

Williams, M.D., M. Brown, D. Boswell, B. Singh and E. Pardyjak, 2004: Testing of the QUIC-PLUME model with wind-tunnel measurements for a high-rise building. Paper

J5.3 at AMS Urban Environment Conference, Vancouver, August. Available at AMS web site (www.ametsoc.org) and on CD from AMS, 45 Beacon St., Boston, MA 02215.

## Table and Figure Captions

Table 1. Summary of CFD model characteristics.

Table 2. Summary of wind observations during two MSG05 experiment days.

Figure 1 – Aerial photograph of area (of approximate dimensions 500 m by 500 m) around Madison Square Garden (MSG) in Manhattan, where MSG is the round building and has diameter 130 m and height 50 m. The 229 m tall One Penn Plaza building is to the NE of MSG and the 153 m tall Two Penn Plaza building is to the ESE of MSG. At the R3 site (on the Farley Post Office), M refers to the fixed anemometer and S refers to the sodar.

Figure 2 – Observed wind vectors (red near street level and blue at rooftop) at 9 am on 10 March 2005. At the "S" site on the Post Office, the sodar wind vectors at z = 20 and 120 m above the roof are shown.

Figure 3 – Observed wind vectors (red near street level and blue at rooftop) at 9 am on 14 March 2005. At the "S" site on the Post Office, the sodar wind vectors at z = 20 and 120 m above the roof are shown.

Figure 4. Simulations of horizontal wind vectors (m/s) at z = 5 m by CFD-Urban model for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 5. Simulations of horizontal wind vectors (m/s) at z = 5 m by FLACS model for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 6. Simulations of horizontal wind vectors (m/s) at z = 4 m by FEM3MP model for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 7. Simulations of horizontal wind vectors (m/s) at z = 5 m by FEFLO-Urban model for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 8. Simulations of horizontal wind vectors (m/s) at z = 2 m by Fluent-Urban model for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 9. Simulations of vertical velocity, w (m/s), at z = 5 m, by CFD-Urban for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 10. Simulations of vertical velocity, w (m/s), at z = 5 m, by FLACS for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 11. Simulations of vertical velocity, w (m/s), at z = 5 m, by FEM3MP for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 12. Simulations of vertical velocity, w (m/s), at z = 5 m, by FEFLO-Urban for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 13. Simulations of vertical velocity, w (m/s), at z = 2 m, by Fluent-Urban for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 14. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for CFD-Urban. The view is towards the NNE.

Figure 15. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for FLACS. The view is towards the NNE.

Figure 16. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for FEM3MP. The view is towards the NNE.

Figure 17. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for FEFLO-Urban. The view is towards the NNE.

Figure 18. Simulations of horizontal wind vectors on x-z cross section through MSG for WNW direction, for Fluent-Urban. The view is towards the NNE.

Figure 19. CFD-Urban simulation of tracer gas dispersion for a point release near street level on the SW side of MSG, for the WNW wind direction. This is one of the five source locations used during the MSG05 field experiment.

Figure 20. FLACS simulation of tracer gas dispersion for a point release near street level on the SW side of MSG for the WNW wind direction. This is one of the five source locations used during the MSG05 field experiment. The figure is for 900 seconds after the release was initiated.

Figure 21. FEM3MP simulation of tracer gas dispersion for WNW wind direction and a point release near street level on the SW side of MSG. This is one of the five source locations used during the MSG05 field experiment.

Figure 22. FEFLO-Urban simulations for WNW wind direction. There is a continuous release from five point sources near street level (on sidewalk off four corners of MSG and on sidewalk north of One Penn Plaza) as used during MSG05. The three panels present the plume concentrations at times of 10, 500 and 1000 seconds after the release is initiated. In these figures north is 28 degrees to left of the direction towards the top of the page; therefore a wind direction from the left side of the figure is close to an actual WNW wind direction.

Table 1. Summary of CFD model characteristics.

| Characteristic | CFD-Urban | FLACS | FEM3MP | FEFLO-Urban | Fluent-Urban |
|---|---|---|---|---|---|
| **Type** | RANS | RANS | RANS | LES | RANS |
| **Mesh** | Finite volume adaptive Cartesian | Finite volume rectangular | Finite element hexahedrons | Unstructured tetrahedral | Finite volume, adaptive |
| **Inflow** | Fixed log profile, neutral , WNW, u = 5.3 m/s at z = 50 m | Fixed log profile, neutral , WNW, u = 5.3 m/s at z = 10 m | Fixed log profile, neutral , WNW, u = 5.0 m/s at z = 92 m | Fixed log profile, neutral , WNW, u = 3.0 m/s at z = 10 m | Matched EPA wind tunnel profile, u = 3.1 m/s at z = 100 m |
| **Closure** | k-ε | k-ε | Non-Linear Eddy Viscosity (NEV) | Smagorinsky | k-ε |
| **Domain size** | 3.5 km by 3.1 km by 0.6 km | Outer 10 km by 7.5 km by 1 km; Inner 3 km by 3 km | 1.75 km by 1.2 km by 0.8 km | 3.3 km EW<br>2.6 km NS<br>0.6 km vert | 2 km by 2 km by 1.2 km |
| **Resolution** | 3 m hor in MSG area, 1 m vert stretched to 40 m at 600m | 10 m hor and 5 m vert in inner area | 5 m horiz,<br>2 to 8 m vert | 2 m at street | 1 to 2 m near bldgs, expansion away from bldgs |
| **Grid points/ elements** | 2.1M | 2.7M grid cells | 12.7M | 4.4M points<br>25.2 M elem | 19 M grid cells |

Table 2. Summary of wind observations during two MSG05 experiment days.

| Site Label | Name | z (m) agl | 3/10 Wind Speed m/s | 3/10 Wind Dir deg | 3/14 Wind Speed m/s | 3/14 Wind Dir deg | Comment |
|---|---|---|---|---|---|---|---|
| R1 | One Penn Plaza | 229 | 7.3 | 286 | 7.0 | 327 | Tall rooftop |
| R2 | Two Penn Plaza | 153 | 5.8 | 306 | 3.8 | 318 | Tall rooftop |
| R3 | Farley Post Office | 34 | 3.6 | 281 | 3.9 | 269 | On broad flat bldg |
| CCNY | City College of New York | 58 | 5.2 | 266 | 5.2 | 309 | Open rooftop |
| SIT | Stevens Inst of Tech | 52 | 5.7 | 297 | 6.9 | 335 | Open rooftop |
| EML | Environ Monitor Lab | 82 | 3.3 | 286 | 4.3 | 323 | Open rooftop |
| LBR | Lehmann Bros Bldg | 160 | 4.7 | 286 | 3.6 | 308 | Open rooftop |
| JFK | Airport | 3.4 | 6.2 | 290 | 6.5 | 320 | Flat airport |
| S1 | NW MSG | 3.0 | 3.0 | 212 | 2.7 | 187 | See figure |
| S2 | SW MSG | 3.0 | 1.7 | 27 steady | 1.2 | 80 variable | See figure |
| S3 | SE MSG | 3.0 | 3.3 | 76 steady | 2.6 | Var W-E | See figure |
| S4 | NE MSG | 3.0 | 1.6 | Variable NNW-SSE | 3.6 | 165 steady | See figure |
| S5 | NW OPP | 3.0 | 2.6 | 238 | 1.7 | 292 | See figure |
| S6 | Front of New Yorker Hotel | 5.0 | 1.2 | 162 | --- | --- | Channeled |
| S7 | 8th Ave S of MSG | 3.0 | 1.2 | 17 | 2.0 | 28 | Channeled |

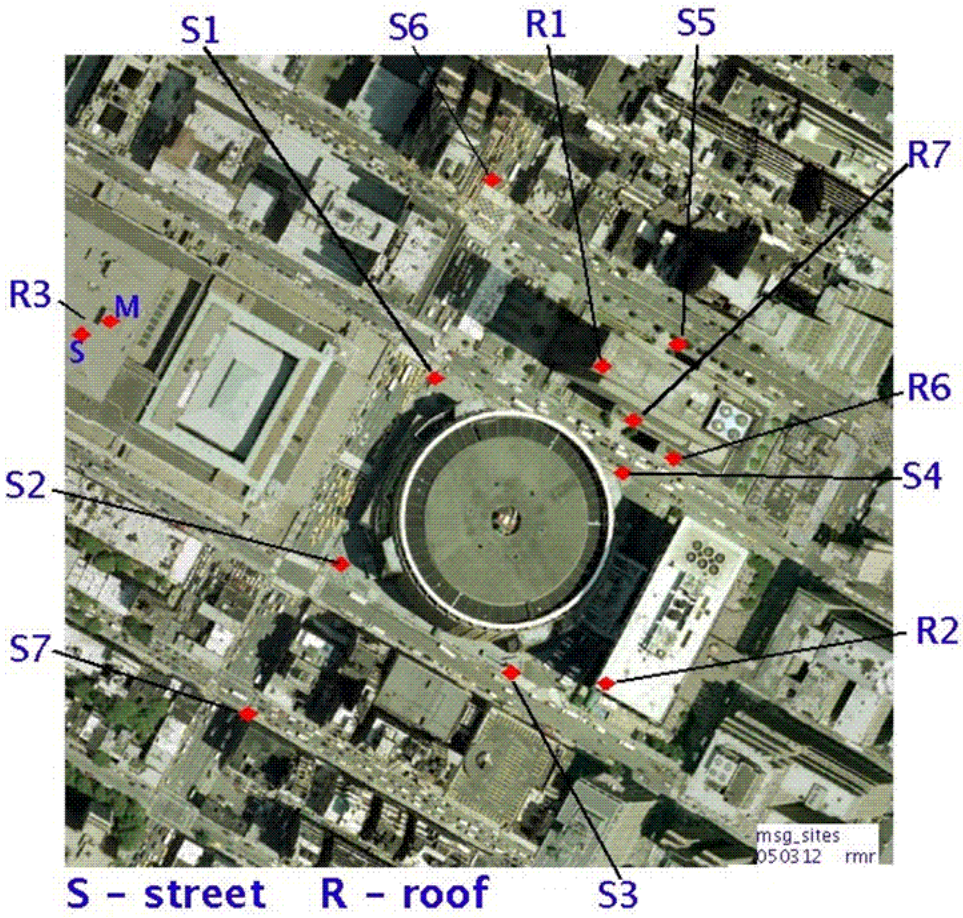



Figure 1 – Aerial photograph of area (of approximate dimensions 500 m by 500 m) around Madison Square Garden (MSG) in Manhattan, where MSG is the round building and has diameter 130 m and height 50 m. The 229 m tall One Penn Plaza building is to the NE of MSG and the 153 m tall Two Penn Plaza building is to the ESE of MSG. At the R3 site (on the Farley Post Office), M refers to the fixed anemometer and S refers to the sodar.

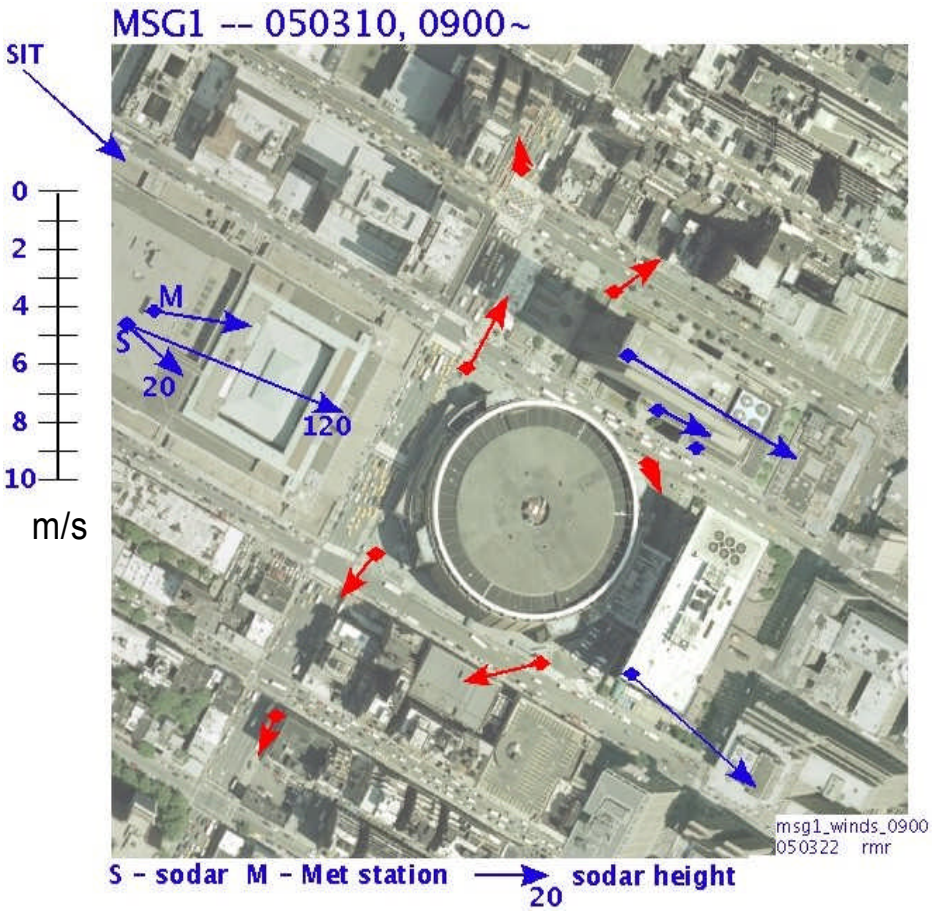



Figure 2 – Observed wind vectors (red near street level and blue at rooftop) at 9 am on 10 March 2005. At the "S" site on the Post Office, the sodar wind vectors at z = 20 and 120 m above the roof are shown.

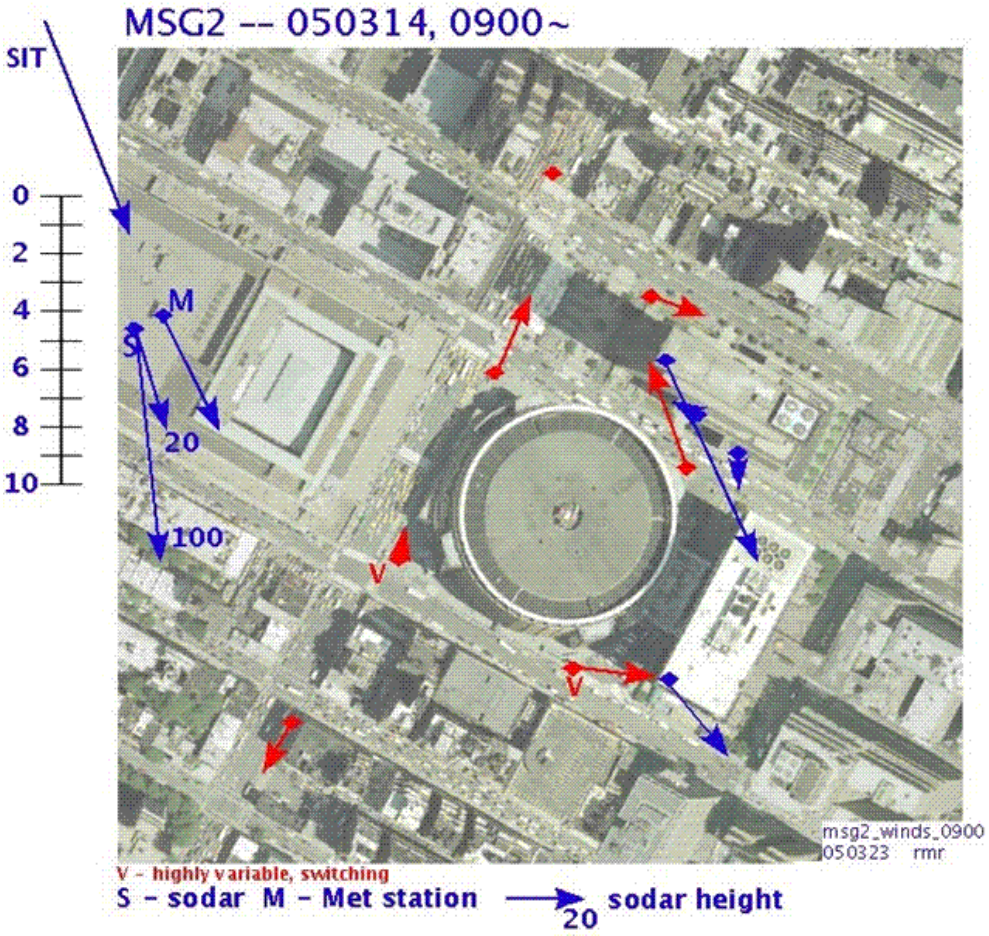



Figure 3 – Observed wind vectors (red near street level and blue at rooftop) at 9 am on 14 March 2005. At the "S" site on the Post Office, the sodar wind vectors at z = 20 and 120 m above the roof are shown.

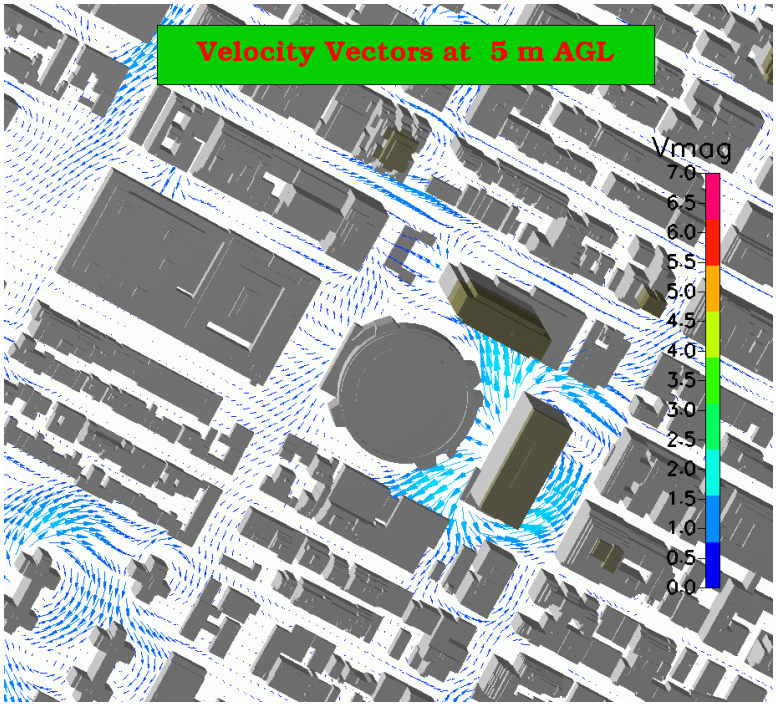



Figure 4. Simulations of horizontal wind vectors (m/s) at z = 5 m by CFD-Urban model for 10 March 2005 upstream wind inputs (flow from WNW).

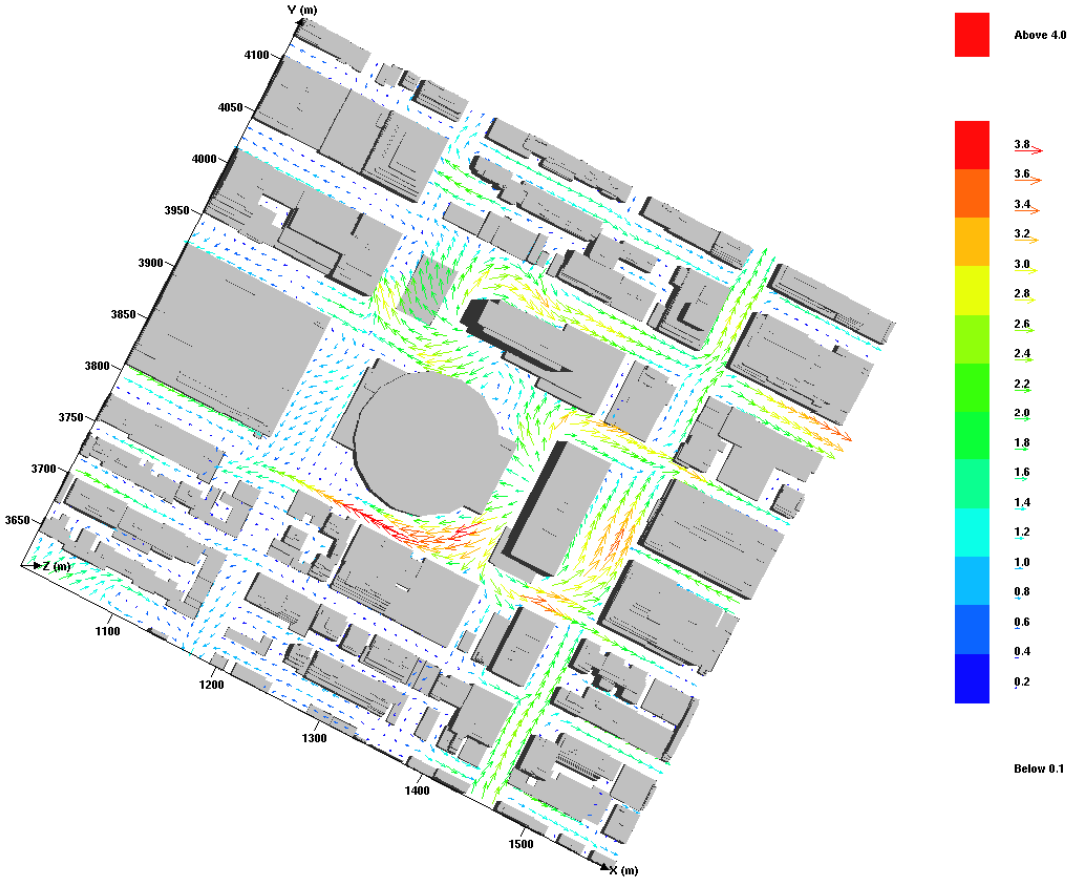



Figure 5. Simulations of horizontal wind vectors (m/s) at z = 5 m by FLACS model for 10 March 2005 upstream wind inputs (flow from WNW).

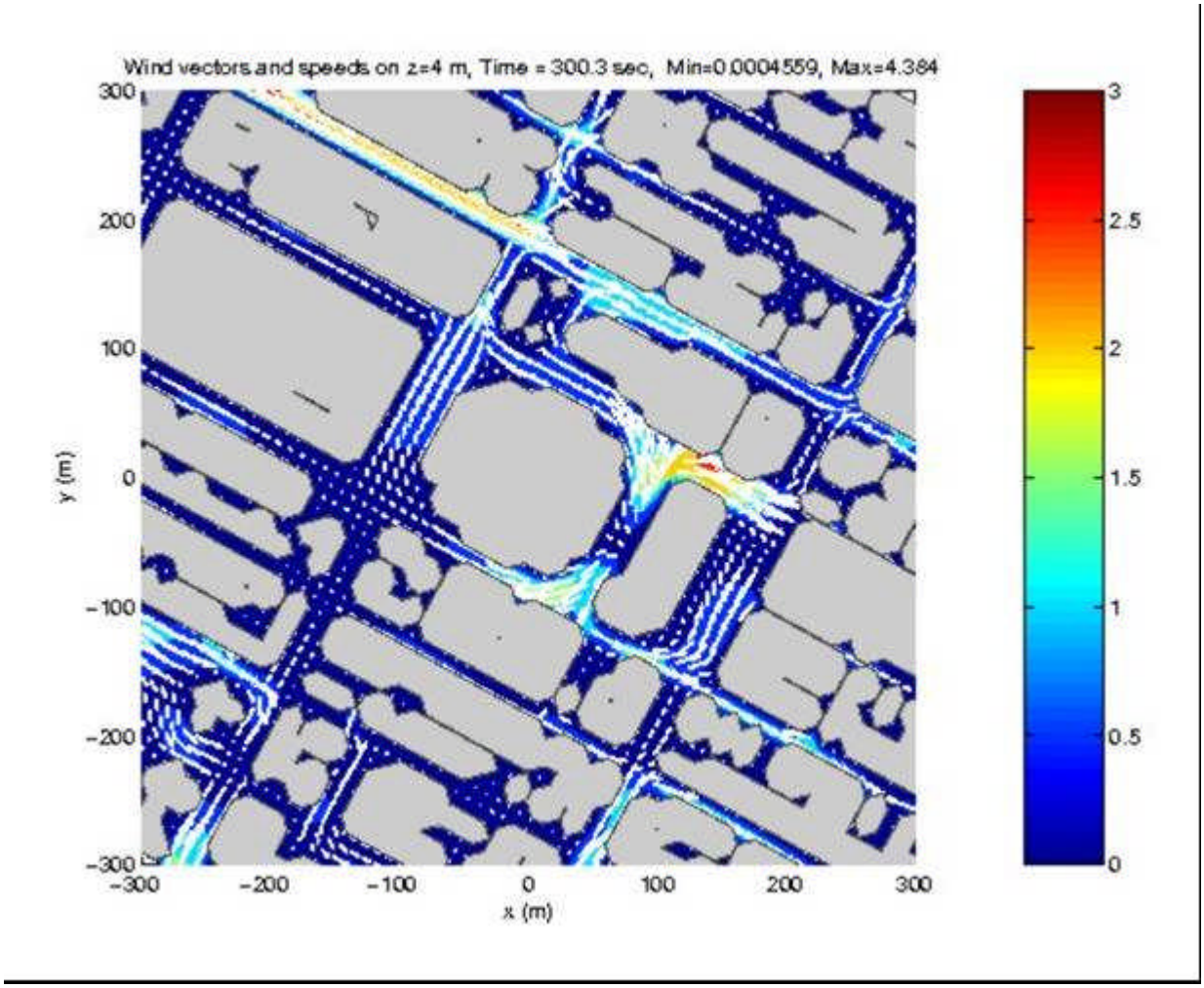



Figure 6. Simulations of horizontal wind vectors (m/s) at z = 4 m by FEM3MP model for 10 March 2005 upstream wind inputs (flow from WNW).

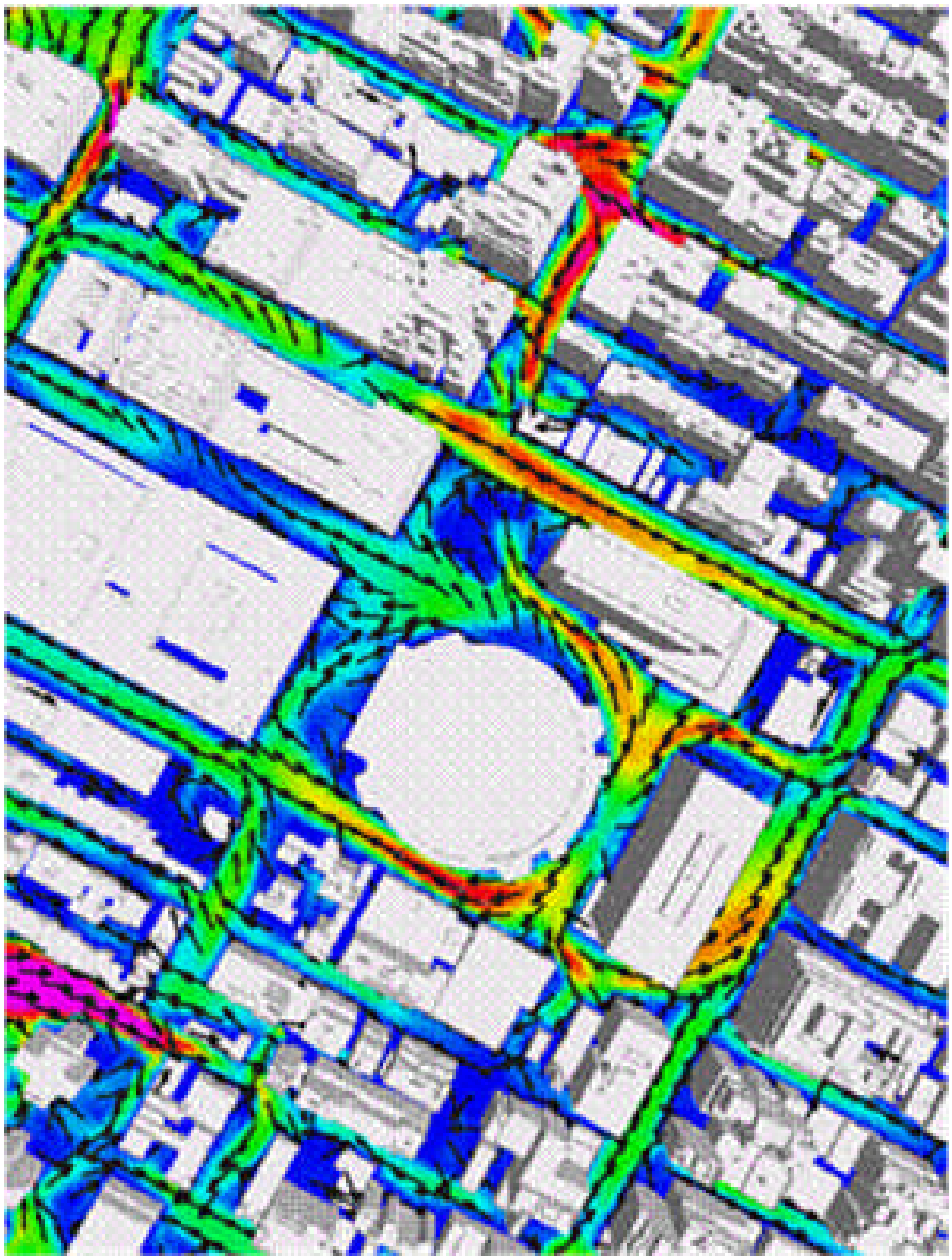


Figure 7. Simulations of horizontal wind vectors (m/s) at z = 5 m by FEFLO-Urban model for 10 March 2005 upstream wind inputs (flow from WNW).

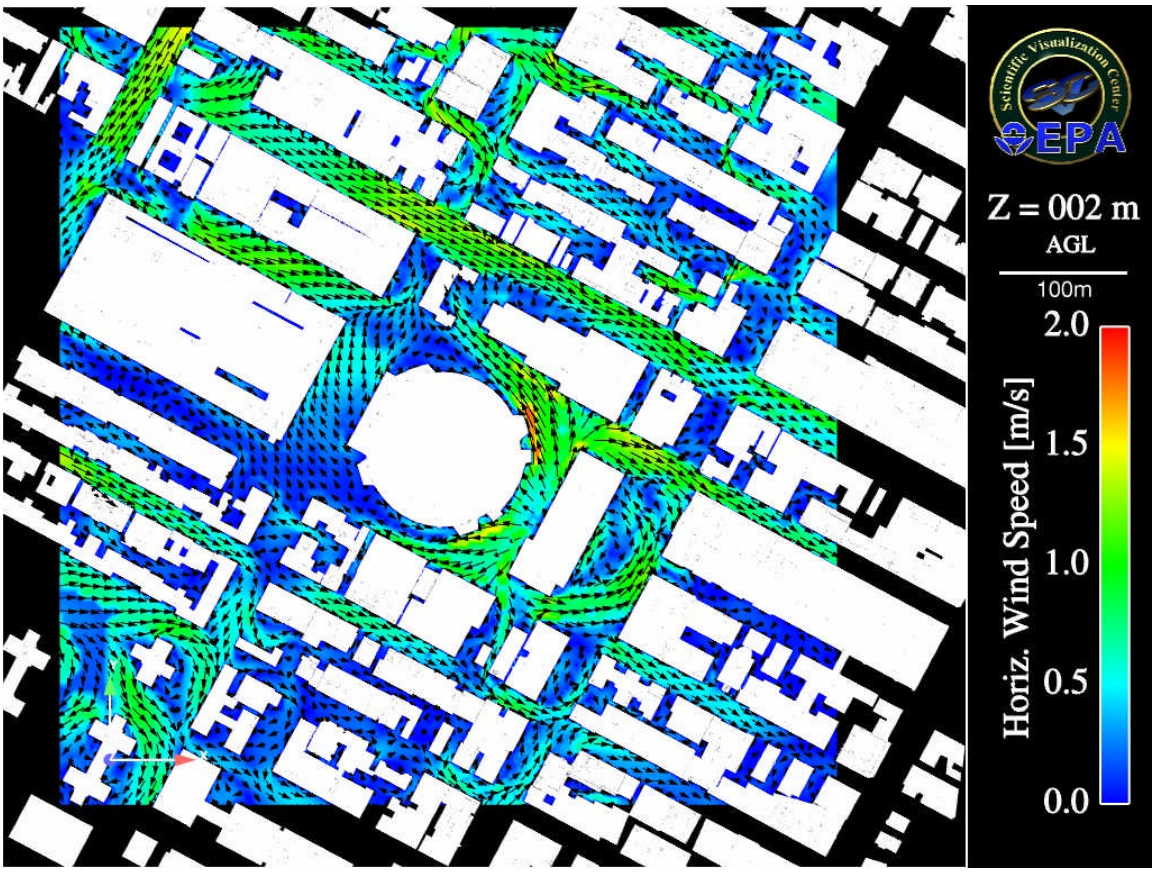



Figure 8. Simulations of horizontal wind vectors (m/s) at z = 2 m by Fluent-Urban model for 10 March 2005 upstream wind inputs (flow from WNW).

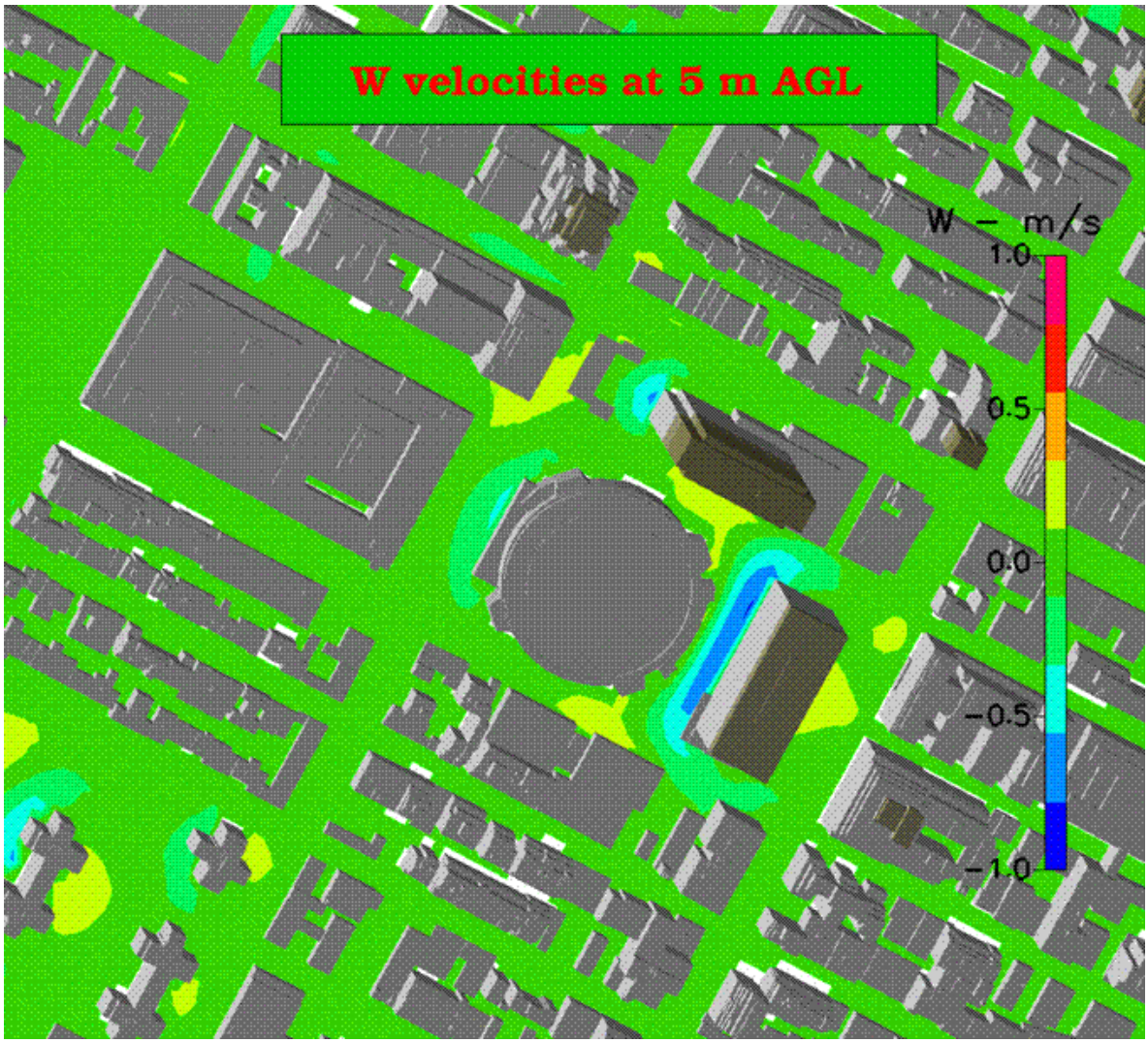



Figure 9. Simulations of vertical velocity, w (m/s), at z = 5 m by CFD-Urban model for 10 March 2005 upstream wind inputs (flow from WNW).

Figure 10. Simulations of vertical velocity, w (m/s), at z = 5 m by FLACS model for 10 March 2005 upstream wind inputs (flow from WNW).

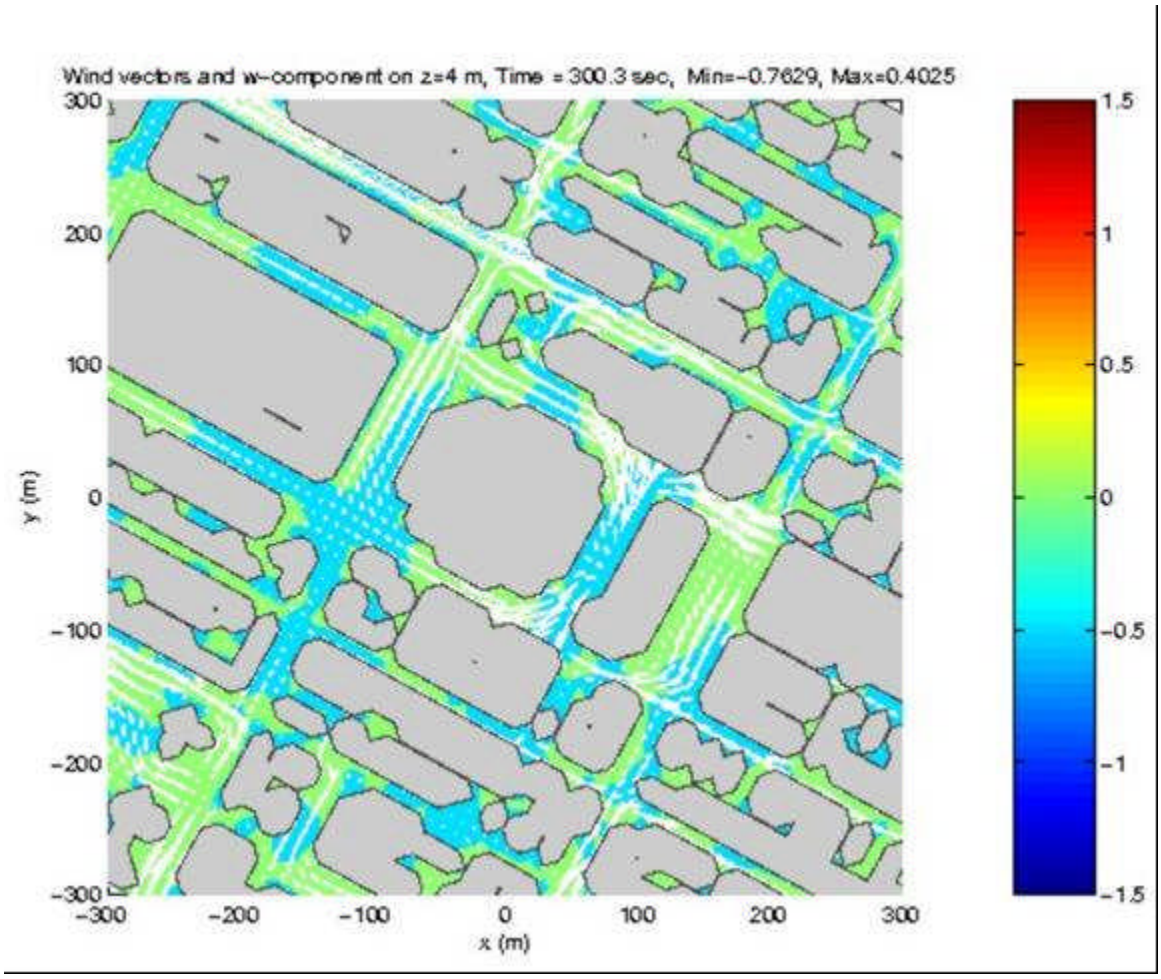



Figure 11. Simulations of vertical velocity, w (m/s), at z = 5 m by FEM3MP for 10 March 2005 upstream wind inputs (flow from WNW).

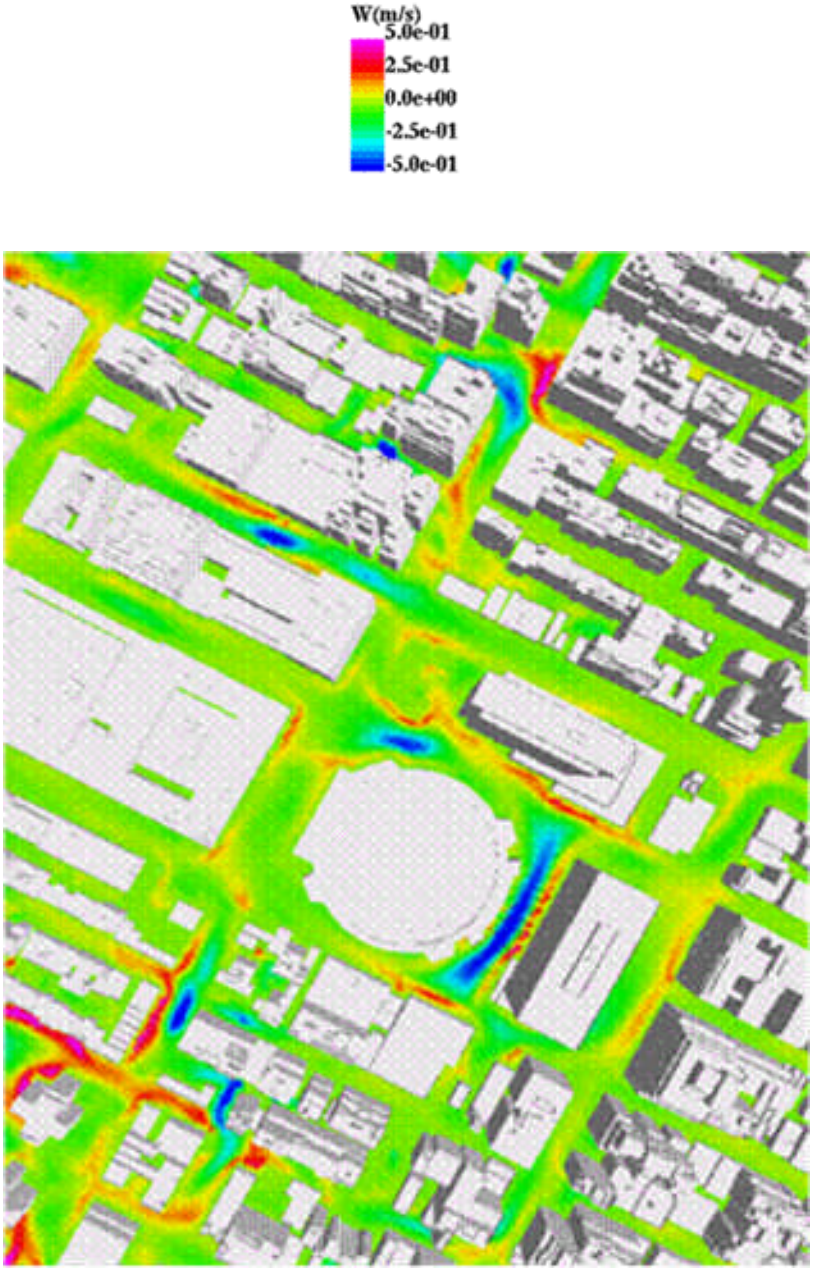



Figure 12. Simulations of vertical velocity, w (m/s), at z = 5 m by FEFLO-Urban for 10 March 2005 upstream wind inputs (flow from WNW).

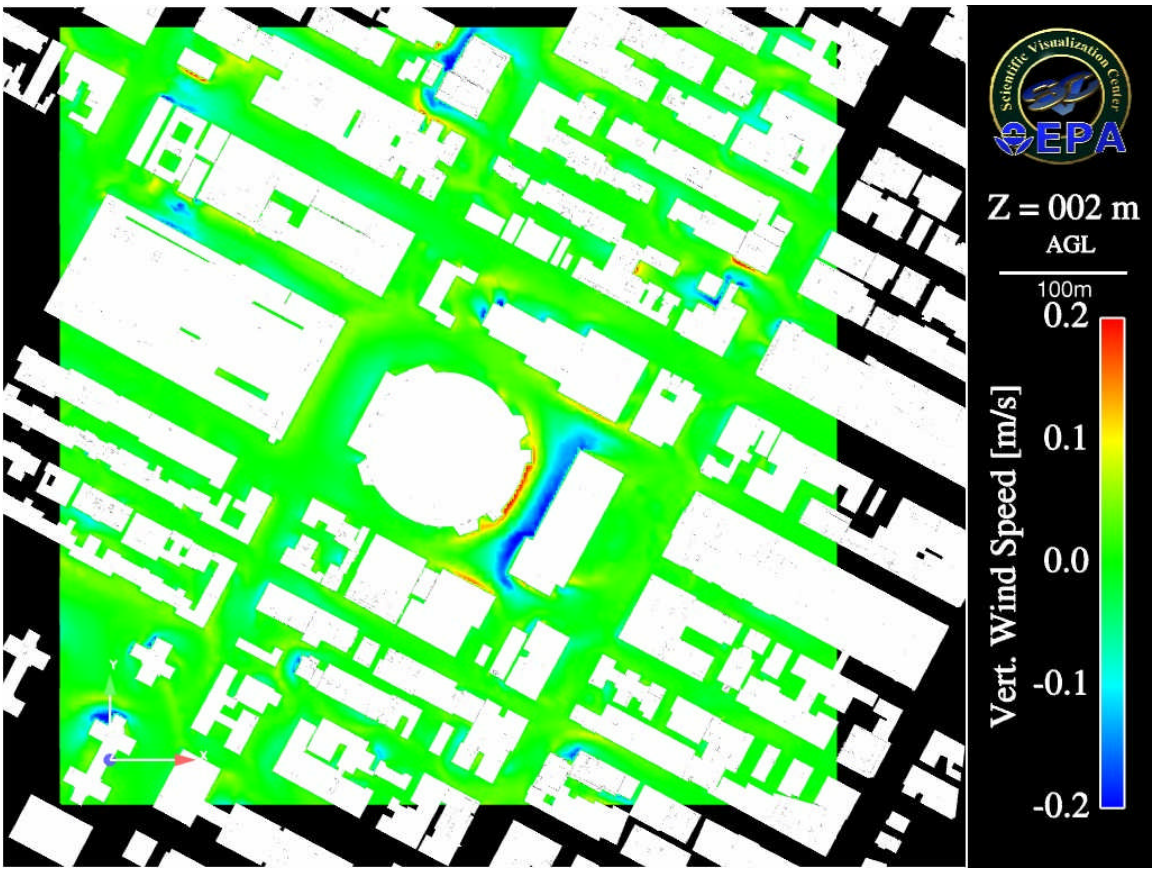



Figure 13. Simulations of vertical velocity, w (m/s), at z = 2 m by Fluent-Urban for 10 March 2005 upstream wind inputs (flow from WNW).

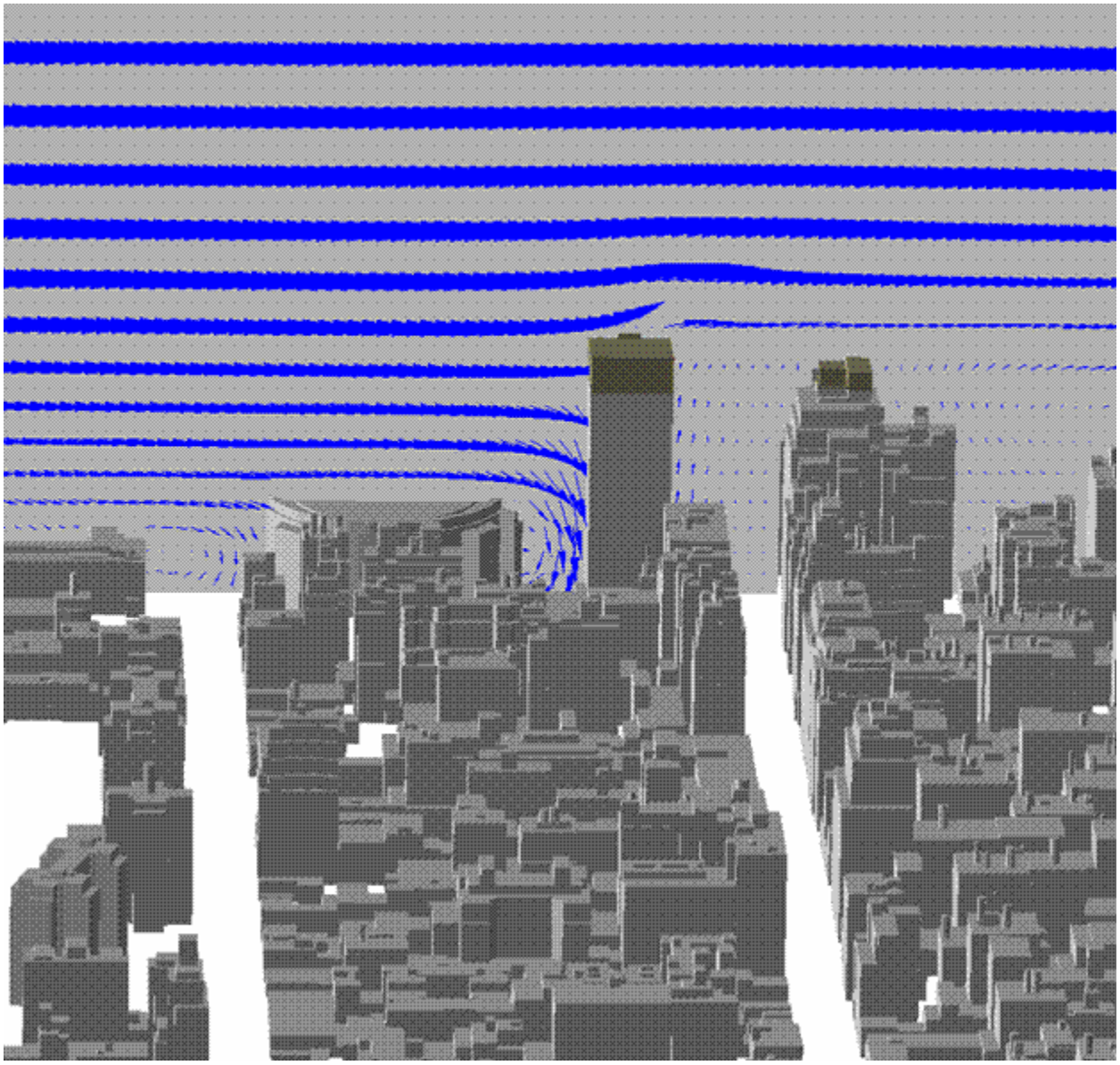


Figure 14. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for CFD-Urban. The view is towards the NNE.

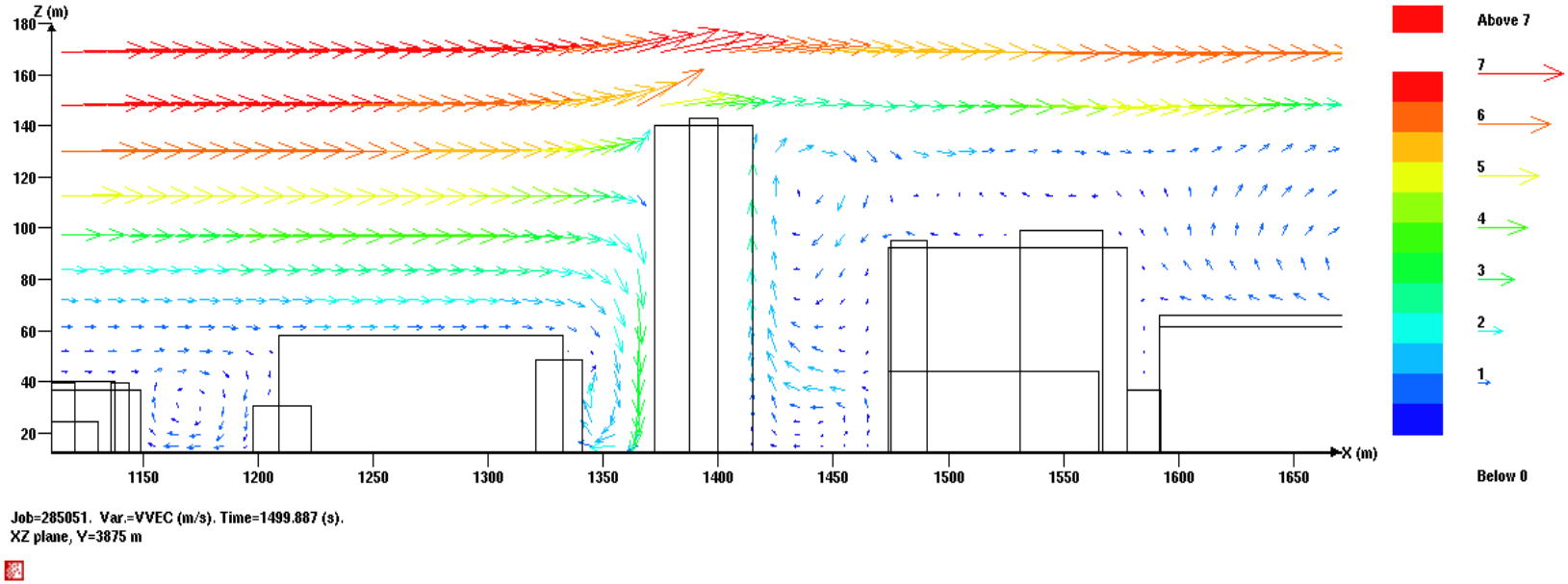



Figure 15. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for FLACS. The view is towards the NNE.

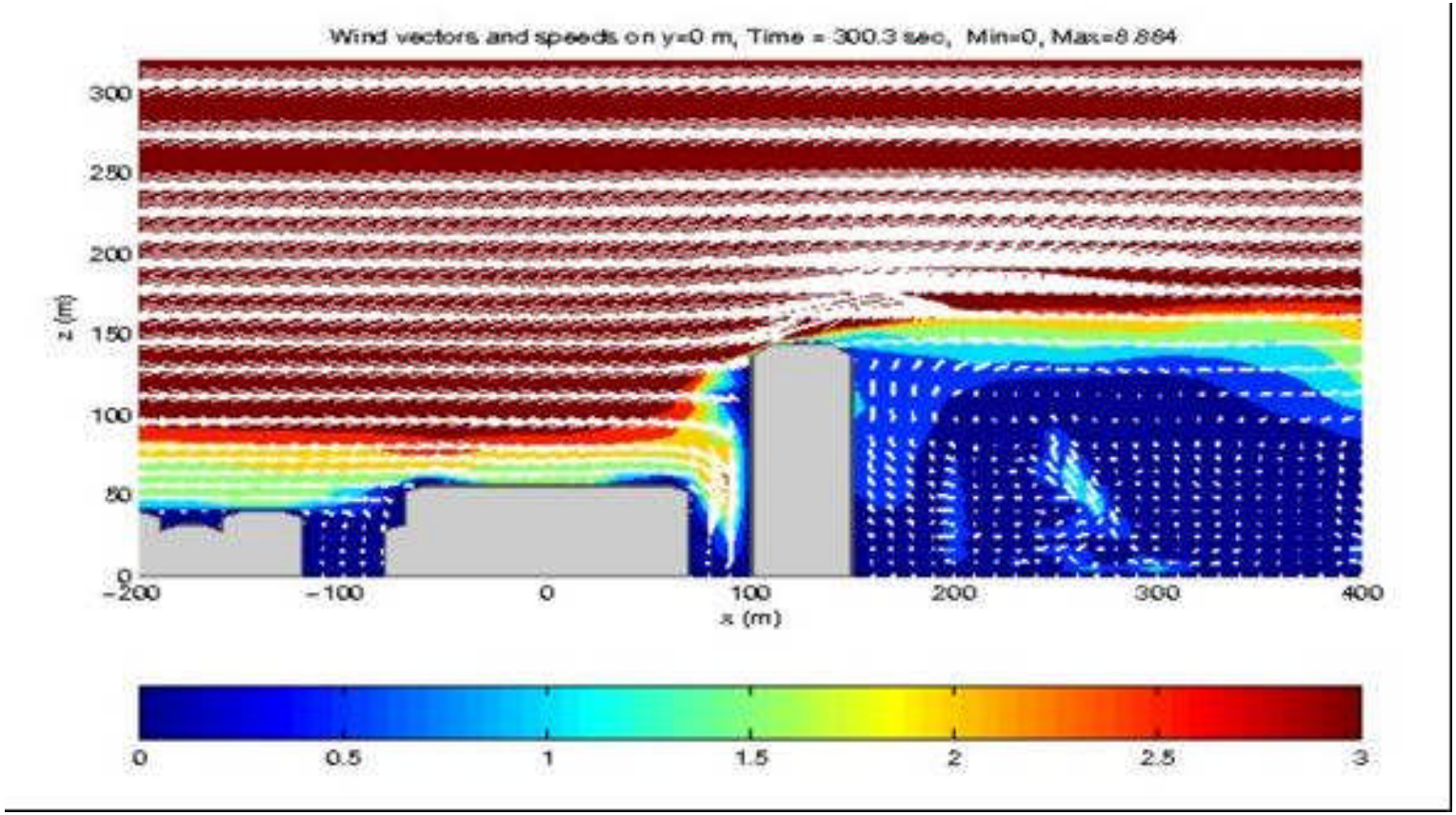
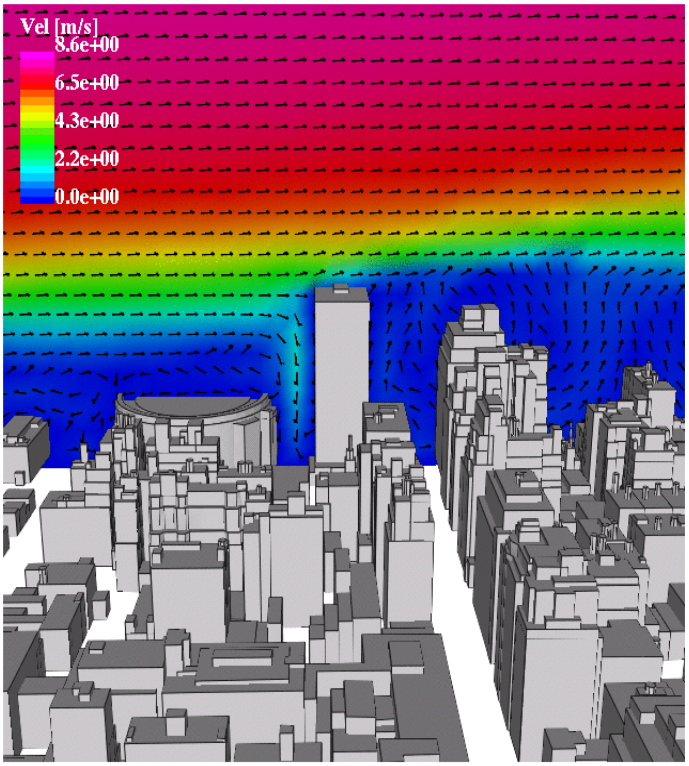



Figure 16. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for FEM3MP. The view is towards the NNE.

Figure 17. Simulations of wind vectors (m/s) on x-z cross section through MSG for WNW direction, for FEFLO-Urban. The view is towards the NNE.



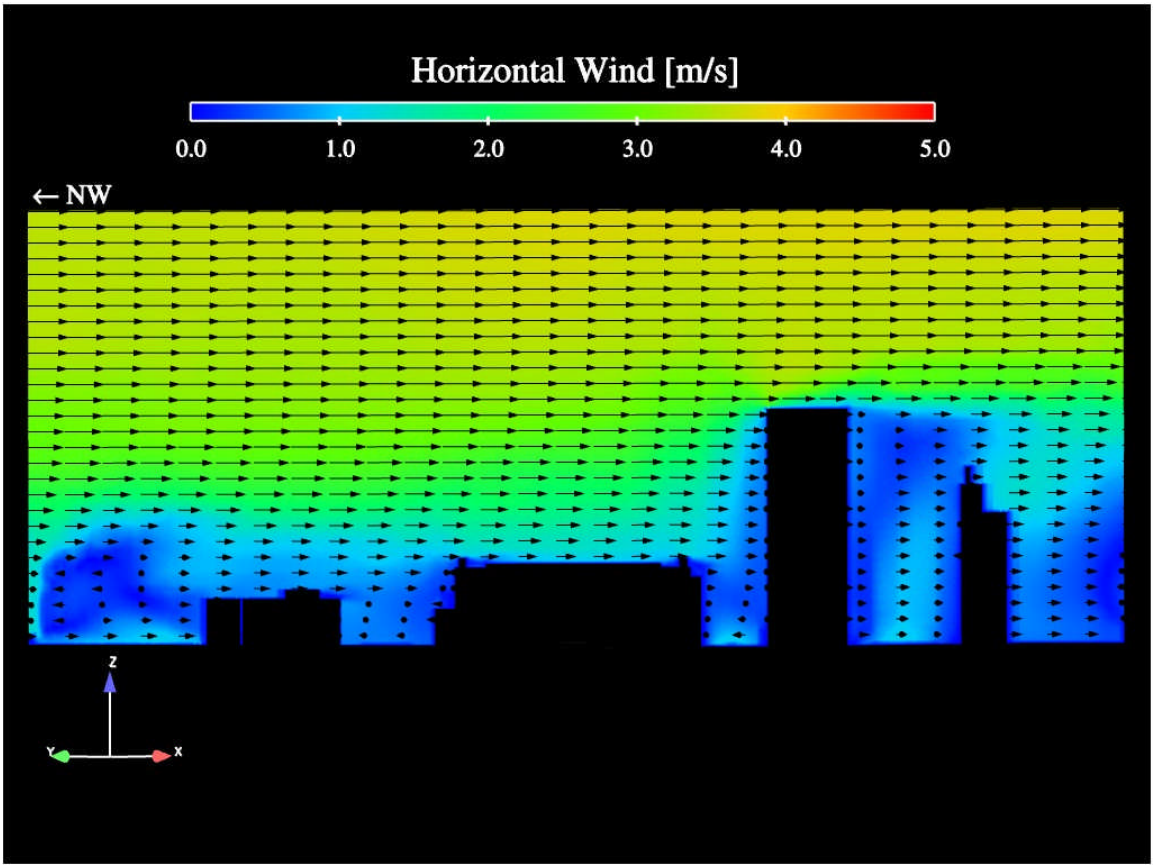



Figure 18. Simulations of horizontal wind vectors (m/s) on x-z cross section through MSG for WNW direction, for Fluent-Urban. The view is towards the NNE.

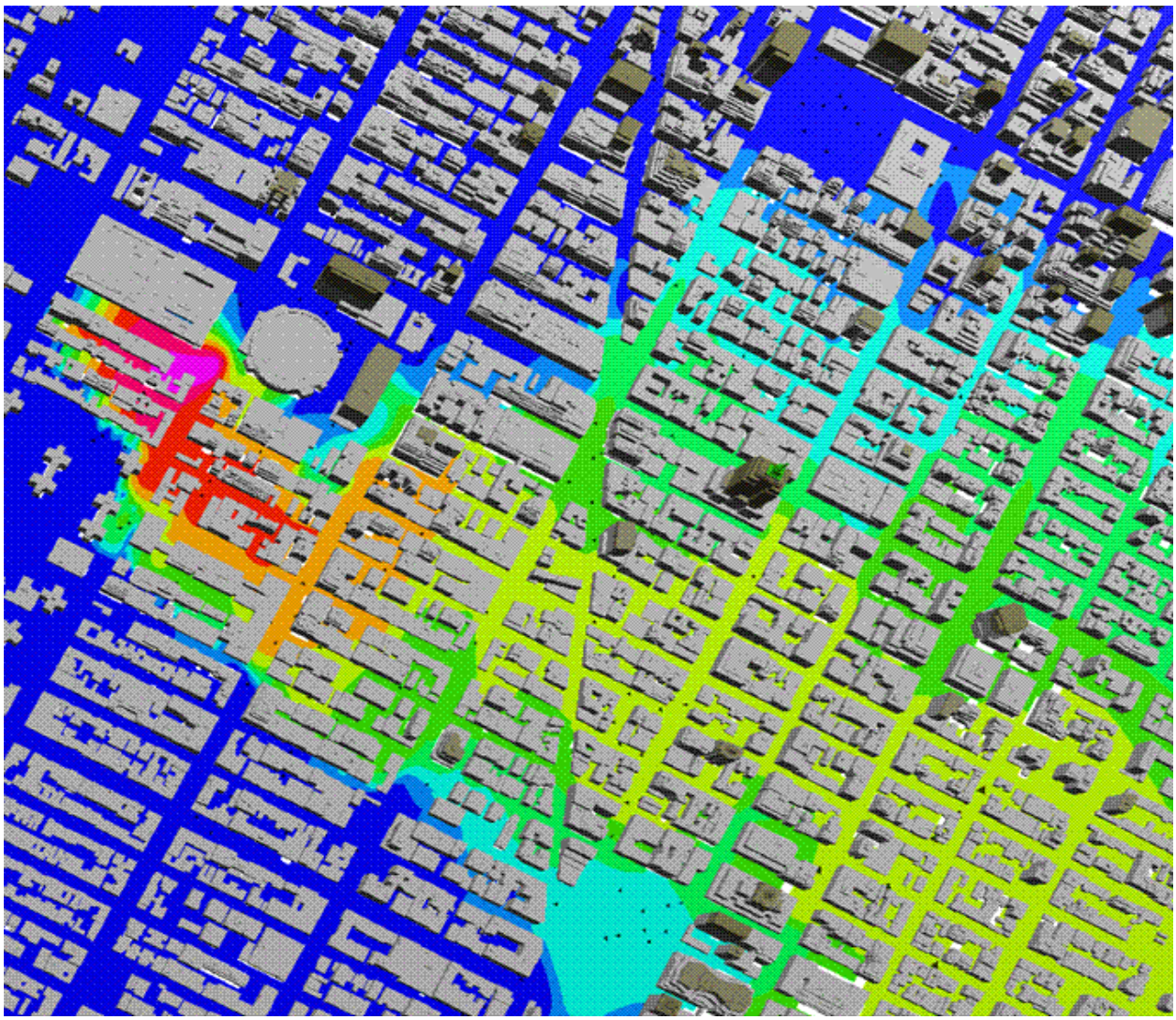


Figure 19. CFD-Urban simulation of tracer gas dispersion for a point release near street level on the SW side of MSG, for the WNW wind direction. This is one of the five source locations used during the MSG05 field experiment.

Figure 20. FLACS simulation of tracer gas dispersion for a point release near street level on the SW side of MSG, for the WNW wind direction. This is one of the five source locations used during the MSG05 field experiment. The figure is for 900 seconds after the release was initiated.

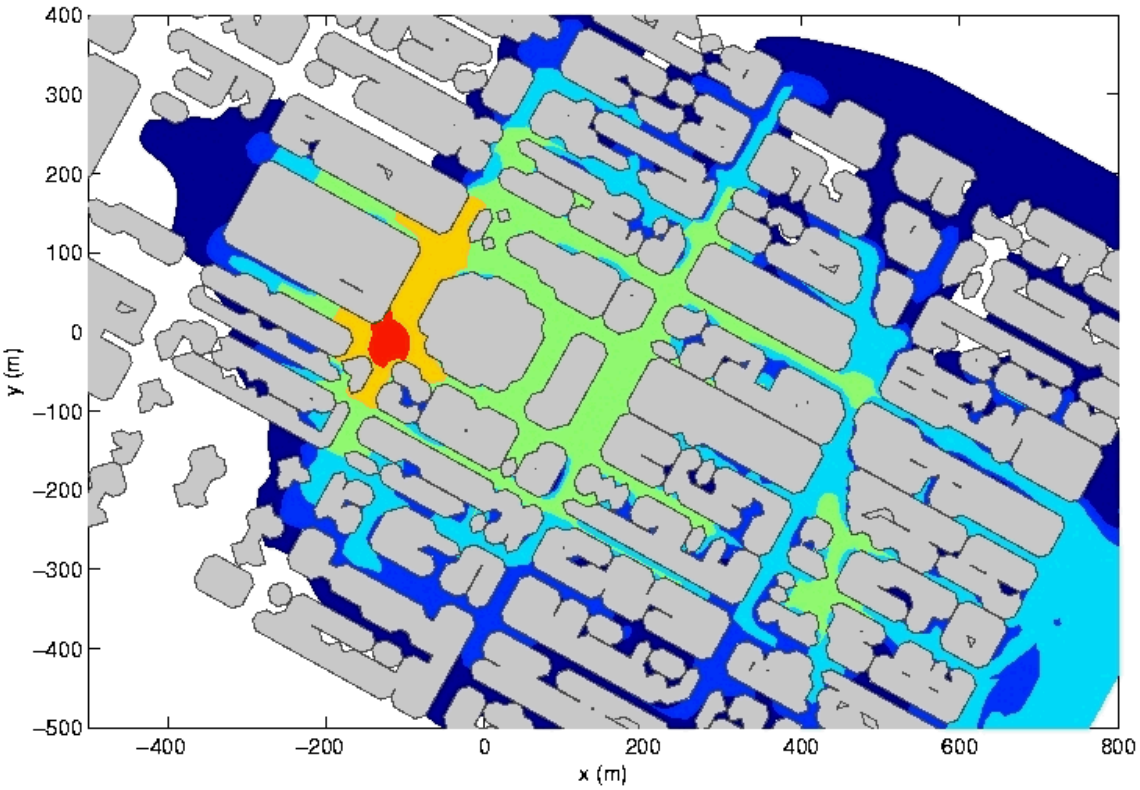



Figure 21. FEM3MP simulation of tracer gas dispersion for WNW wind direction and a point release near street level on the SW side of MSG. This is one of the five source locations used during the MSG05 field experiment.

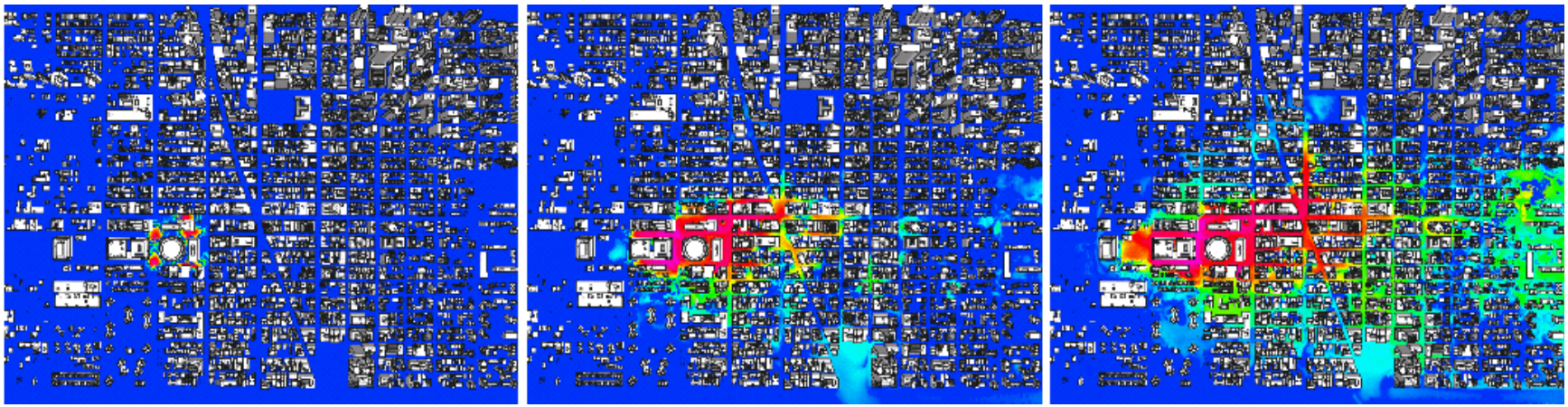


Figure 22. FEFLO-Urban simulations for WNW wind direction. There is a continuous release from five point sources near street level (on sidewalk off four corners of MSG and on sidewalk north of One Penn Plaza) as used during MSG05. The three panels present the plume concentrations at times of 10, 500 and 1000 seconds after the release is initiated. In these figures north is 28 degrees to left of the direction towards the top of the page; therefore a wind direction from the left side of the figure is close to an actual WNW wind direction.