DETAILED SIMULATIONS OF ATMOSPHERIC FLOW AND DISPERSION IN DOWNTOWN MANHATTAN

An Application of Five Computational Fluid Dynamics Models

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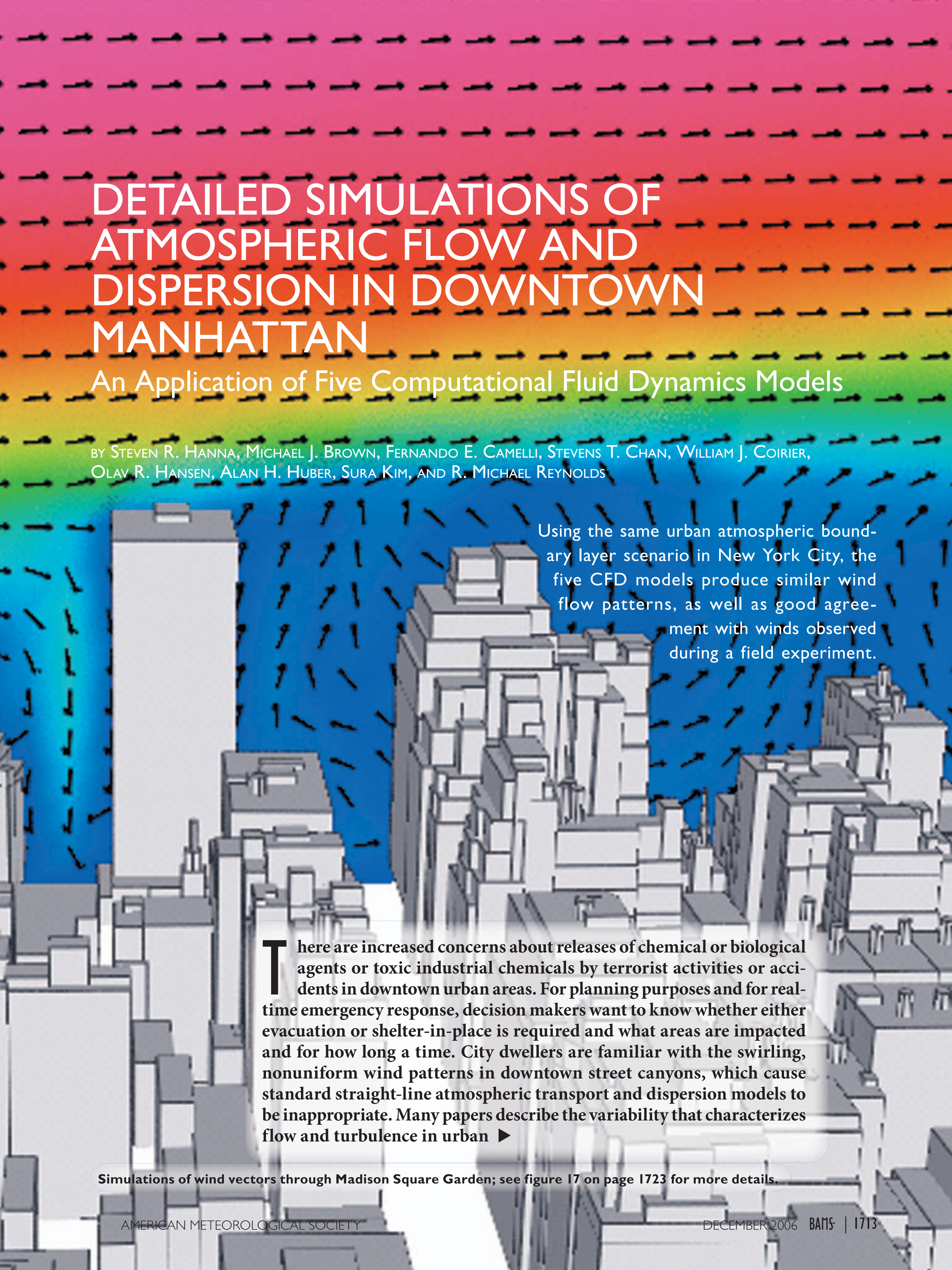
Using the same urban atmospheric boundary layer scenario in New York City, the five CFD models produce similar wind flow patterns, as well as good agreement with winds observed during a field experiment.

There are increased concerns about releases 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 whether either evacuation or shelter-in-place is required and what areas are impacted and for how long a time. City dwellers are familiar with the swirling, nonuniform wind patterns in downtown street canyons, which cause standard straight-line atmospheric transport and dispersion models to be inappropriate. Many papers describe the variability that characterizes flow and turbulence in urban ▶



Simulations of wind vectors through Madison Square Garden; see figure 17 on page 1723 for more details.

areas (e.g., Oke 1987; Rotach 1997; Roth 2000; Britter and Hanna 2003). To address this problem, 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.

New York, New York, is the focus of a set of recent field experiments sponsored by the Urban Dispersion Program of the Department of Homeland Security (DHS). The wind data from the March 2005 Madison Square Garden (MSG05) experiment are used in the current paper. 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. Others include the Salt Lake City Urban 2000 experiment (Allwine et al. 2002), the Oklahoma City Joint Urban 2003 experiment (Allwine et al. 2004; Dugway Proving Ground 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 databases provides an opportunity for further development and evaluation of many types of urban flow and dispersion models, including CFD models.

CFD MODELS. For urban applications, the CFD models solve the basic equations of motion on a high-resolution (1–10 m) three-dimensional grid system, within a domain with sides of a few kilometers at most and with typical depths from 0.5 to 1 km. Detailed three-dimensional (3D) 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. Modelers (e.g., Hanna et al. 2002) found that the CFD model-simulated turbulence was reasonable near the obstacle but, in many cases, died away too quickly once the flow passed the influence of the obstacle. Some 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. The turbulence-maintenance question and other related scientific questions were the subject of a workshop held in July 2004 at George Mason University in Fairfax, Virginia, where the current authors were in attendance and agreed to proceed with collaborative studies. A methodology for overcoming the turbulence-maintenance problem was suggested by the Environmental Protection Agency (EPA) CFD modeling group (Tang et al. 2006) at the American Meteorological Society (AMS) Annual Meeting.

One aspect of the collaborative studies discussed at the workshop was to use some standard field databases to advance the development and evaluation of the CFD models. These databases included the Kit Fox, Mock Urban Setting Test (MUST), Prairie Grass, and Evaluation of Model Uncertainty (EMU) data (e.g., Hanna et al. 2004). A key database was the classical 1955 Prairie Grass field experiment, which took place over a grassy field, allowing model performance to be tested for a scenario with no buildings or other obstacles to force the flow. Although there is not space in this paper to describe the details, some modelers were able to improve their turbulence parameterizations so as to produce good agreement with the Prairie Grass data.

Another aspect of the collaborative study was to run the CFD models as part of ongoing major studies such as the Manhattan (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 [Finite Element Model in 3D and Massively-Parallel version (FEM3MP) and FLU-

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ENT-EPA] was directly sponsored by the MSG05 lead agency (DHS) or a cosponsoring agency (the Defense Threat Reduction Agency), the Finite Element Flow-Urban (FEFLO-Urban) and FLACS runs were carried out with internal funds from George Mason University and GexCon, respectively. Thus, this scientific initiative conforms to the spirit of advancing the overall field.

A unique aspect 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,b) — W. Coirier and S. Kim, CFD Research Corporation
- FLACS (Hanna et al. 2004) — O. R. Hansen, GexCon
- FLUENT-EPA (Huber et al. 2005) — A. Huber, National Oceanic and Atmospheric Administration (NOAA)
- FEM3MP (Gresho and Chan 1998; Calhoun et al. 2005) — S. Chan, Lawrence Livermore National Laboratory
- FEFLO-Urban (Camelli et al. 2004; Camelli and Lohner 2004) — F. Camelli, George Mason University

Although these five CFD models are currently too slow 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 Quick Urban and Industrial Complex (QUIC) dispersion modeling system (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 south-southwest wind direction, which is the most probable according to historic climate data. However, the actual wind directions during MSG05 were from the north-northwest to northwest, and these wind directions are the subject of the current paper. Some comparisons for the south-southwest planning runs were presented by

Table 1. Summary of CFD model characteristics.

Characteristic	CFD-Urban	FLACS	FEM3MP	FEFLO-Urban	FLUENT-EPA
Type	RANS	RANS	RANS	LES	RANS
Mesh	Finite volume, adaptive Cartesian	Finite volume, rectangular	Finite element, hexahedrons	Unstructured tetrahedral	Finite volume, unstructured hexahedron dominant
Inflow	Fixed log profile, neutral, west-northwest, u = 5.3 m s^{-1} at z = 50 m	Fixed log profile, neutral, west-northwest, u = 5.3 m s^{-1} at z = 10 m	Fixed log profile, neutral, west-northwest, u = 5.0 m s^{-1} at z = 92 m	Fixed log profile, neutral, west-northwest u = 3.0 m s^{-1} at z = 10 m	Scaled EPA wind tunnel boundary layer, neutral, northwest u = 3.1 m s^{-1} at z = 100
Closure	k–ε	k–ε	nonlinear eddy viscosity	Smagorinski	k–ε
Domain size	3.5 km × 3.1 km × 0.6 km	Outer: 10 km × 7.5 km × 1 km, inner: 3 km × 3 km	1.75 km × 1.2 km × 0.8 km	3.3 km east–west, 2.6 km north–south, 0.6 km vertical	2 km × 2 km × 1.2 km
Resolution	3-m horizontal in MSG area, 1-m vertical stretched to 40 m at 600 m	10-m horizontal and 5-m vertical in inner area	5-m horizontal, 2–8-m vertical	2 m at street	1–2 m near buildings, expansion away from buildings
Grid points, elements	2.1 M	2.7 M grid cells	12.7 M	4.4 M points, 25.2 M elements	19 M grid cells

M. Brown at the 2006 AMS Annual Meeting (Camelli et al. 2006), and a brief comparison of FEM3MP with observations for the MSG05 west-northwest case was presented by M. 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 observations from south-southwest wind directions to aid in the evaluations.

Summaries of the CFD model characteristics and assumptions for the current MSG05 exercise (for the west-northwest wind directions observed during the field experiment) are given in Table 1. Readers interested in more details can consult the references. All models except for FEFLO-Urban were run in Reynolds-averaged Navier–Stokes (RANS) mode. The RANS models' outputs have 3D variability but represent an average over time and are therefore steady state. FEFLO-Urban was run in large-eddy simulation (LES) mode, which requires more computer time but produces time-variable flow fields.

All CFD models used the three-dimensional building database 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, because buildings in large cities such as New York are razed and rebuilt with surprising frequency, it is necessary to update the 3D file for applications at any particular time.

To allow for comparisons with the observed winds at street level, the CFD model simulations were made for average rooftop wind conditions observed during

Table 2. Summary of wind observations during two MSG05 experiment days (10 and 14 Mar 2005).

Site label	Name	z (m) AGL	10 March wind speed (m s^{-1})	10 March wind direction (°)	14 March wind speed (m s^{-1})	14 March wind direction (°)	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 building
CCNY*	City College of New York	58	5.2	266	5.2	309	Open rooftop
SIT*	Stevens Institute of Technology	52	5.7	297	6.9	335	Open rooftop
EML*	Environmental Monitor Laboratory	82	3.3	286	4.3	323	Open rooftop
LBR*	Lehmann Bros. Building	160	4.7	286	3.6	308	Open rooftop
JFK*	Airport	3.4	6.2	290	6.5	320	Flat airport
S1	Northwest MSG	3.0	3.0	212	2.7	187	See figure
S2	Southwest MSG	3.0	1.7	27 steady	1.2	80 variable	See figure
S3	Southeast MSG	3.0	3.3	76 steady	2.6	Variable west–east	See figure
S4	Northeast MSG	3.0	1.6	Variable, north-northwest to south-southeast	3.6	165 steady	See figure
S5	Northwest One Penn Plaza	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 Side of MSG	3.0	1.2	17	2.0	28	Channeled

*These sites are outside of the MSG area shown in Fig. 1.

the two time periods (from 0900 to 1400 LST 10 and 14 March 2005) during which time the MSG05 field experiment took place. These two days were both characterized by fairly steady moderate west-northwest to northwest wind flows, well-mixed near-neutral conditions, and cold temperatures (near 0°C). Hanna et al. (2006) provide an overview of the MSG05 field experiment and a summary of the wind and turbulence observations. As seen in Table 1, the five CFD models assumed similar inflow conditions, based on averaged wind observations at rooftop and other exposed sites on 10 March, as listed in Table 2. Although the five models used slightly different assumptions for inflow (upwind) wind speeds, 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.

To illustrate the magnitudes and variability of the observed wind speeds and directions, Table 2 (prepared by Hanna et al. 2006) contains average observed winds during the five-hour (0900–1400 LST) experiment periods on 10 and 14 March. Data are given for the anemometers shown on Fig. 1, as well as for anemometers from other Manhattan building tops, from John F.

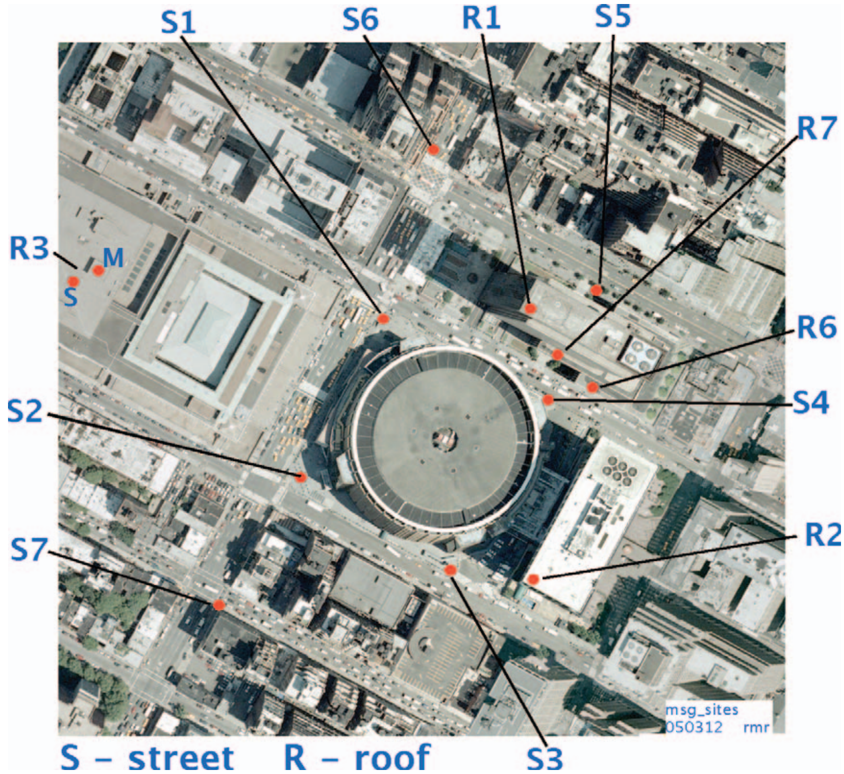

Fig. 1. Aerial photograph of area (of approximate dimensions 500 m × 500 m) around MSG in Manhattan, where MSG is the round building and has 130-m diameter and 50-m height. The 229-m-tall One Penn Plaza building is to the northeast of MSG and the 153-m-tall Two Penn Plaza building is to the east-southeast of MSG. At the R3 site (on the Farley Post Office), M refers to the fixed anemometer and S refers to the sodar.

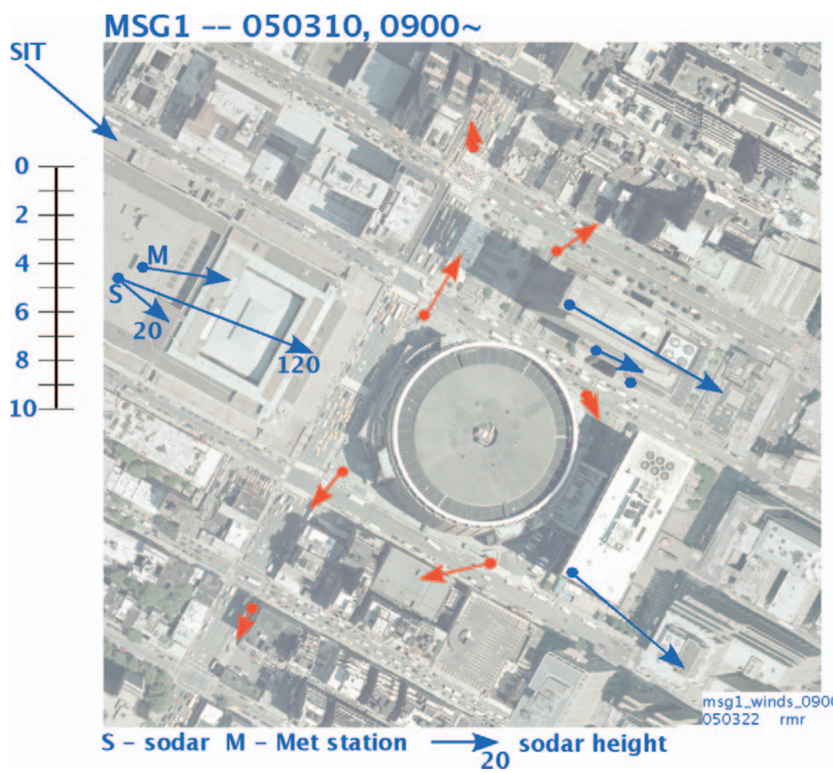

Fig. 2. Observed wind vectors (red near street level and blue at rooftop) at 0900 LST 10 Mar 2005. At the "S" site on the Post office, the sodar wind vectors at z = 20 and 120 m above the roof are shown.

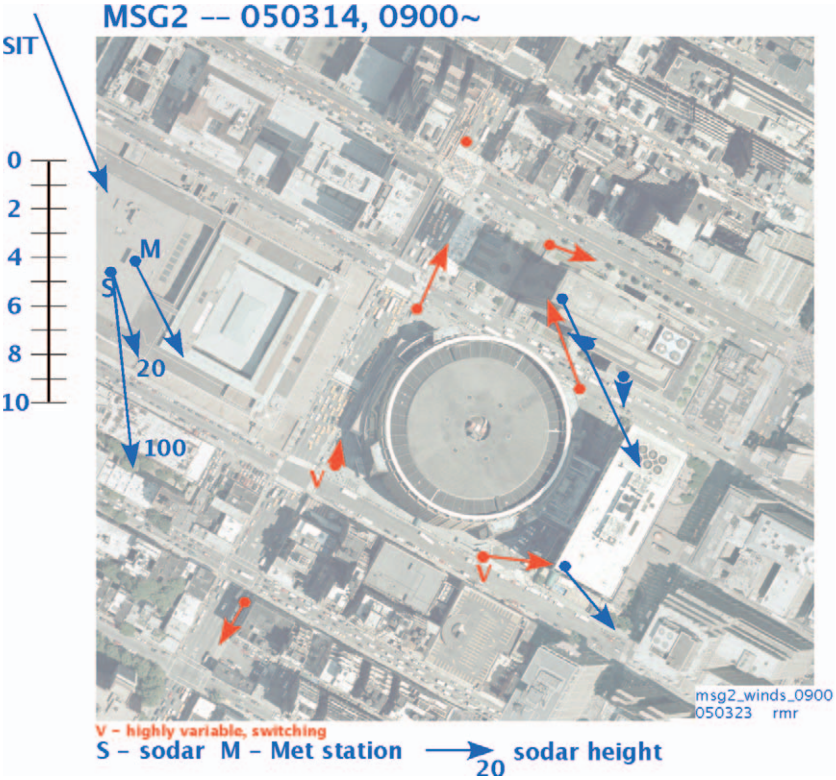

FIG. 3. Observed wind vectors (red near street level and blue at rooftop) at 0900 LST 14 Mar 2005. At the "S" site on the Post office, the sodar wind vectors at z = 20 and 120 m above the roof are shown.

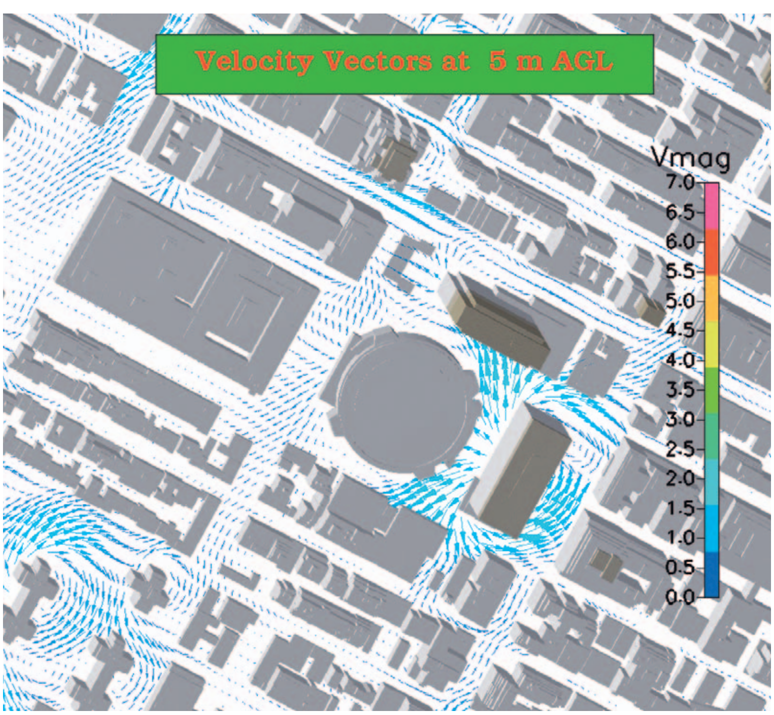

FIG. 4. Simulations of horizontal wind vectors (m s^{-1}) at z = 5 m by CFD-Urban model for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

Kennedy International (JFK) Airport, and from the top of a building on the Stevens Institute of Technology (SIT) campus in Hoboken, New Jersey, on the west bank of the Hudson River.

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 Madison Square Garden (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 use the same geographic domain and include, as an example, the observed 30-minute-averaged wind vectors from 0900 to 0930 LST 10 March and 14 March, respectively.

The observed rooftop winds have speeds of about 6 m s^{-1} and are from the west-northwest direction on 10 March and the northwest direction on 14 March, while the observed street-level winds (with an average scalar speed of about 2 m s^{-1}) 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 south-southwest wind direction used in the CFD planning runs (Camelli et al. 2006) and the west-northwest wind directions observed during the field experiment and used in the current comparisons. Because the broad side of One Penn Plaza faces the south-southwest, it dominates the flow for the south-southwest wind direction. And because the broad side of Two Penn Plaza faces the west-northwest, it dominates for the west-northwest 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 the southwest and northwest.

Although the MSG05 CFD model comparison exercise is nearly finished, these same CFD models are being run for the August 2005 Midtown field experiment (MID05) in Manhattan. MID05 was the second experiment in the series begun by MSG05 and involved more experiment days (six instead of two) and many more meteorological and sampling instruments. Wind speeds were lighter, by a factor of 3, in MID05 than in MSG05. The MID05 CFD comparisons are being planned to be more quantitative than the current qualitative comparisons for MSG05.

There are 19 figures presented that illustrate the degree of agreement (or disagreement) among the five models for MSG05. The first set of figures presents the horizontal wind vectors near the ground. The second set of figures presents the vertical velocities near the ground. The third set of figures shows along-wind (x–z) cross sections of wind vectors. The final set of figures shows some predicted normalized concentration patterns for the tracer-release locations around MSG. With much more planning and support, we perhaps could have produced the figures in the same format and color scheme for each model. However, because several of the modelers are participating on a volunteer basis, we were satisfied once the domains, inputs, heights of outputs, and other details were reasonably close for each model. Per-

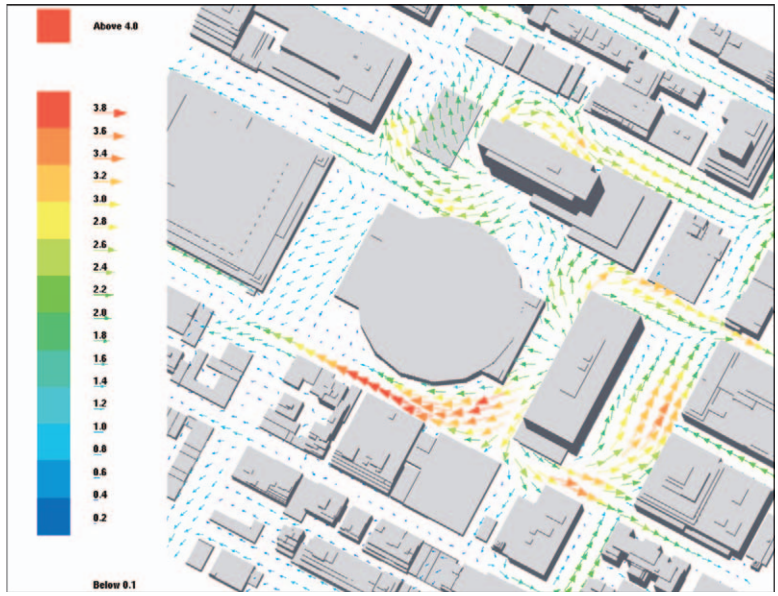

Fig. 5. Simulations of horizontal wind vectors (m s^{-1}) at z = 5 m by FLACS model for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

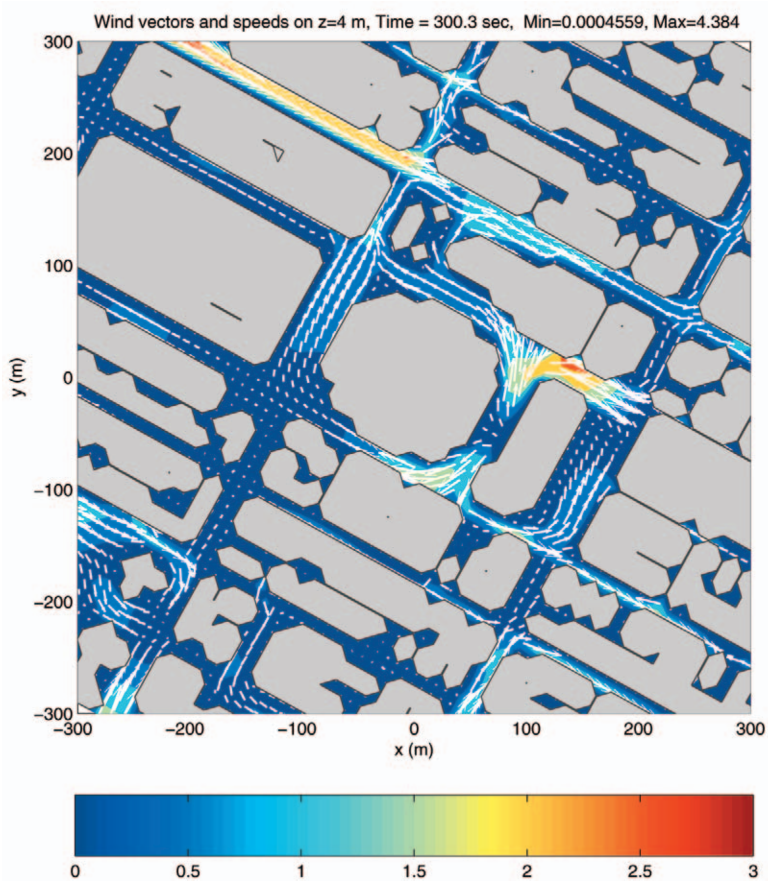

Fig. 6. Simulations of horizontal wind vectors (m s^{-1}) at z = 4 m by the FEM3MP model for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

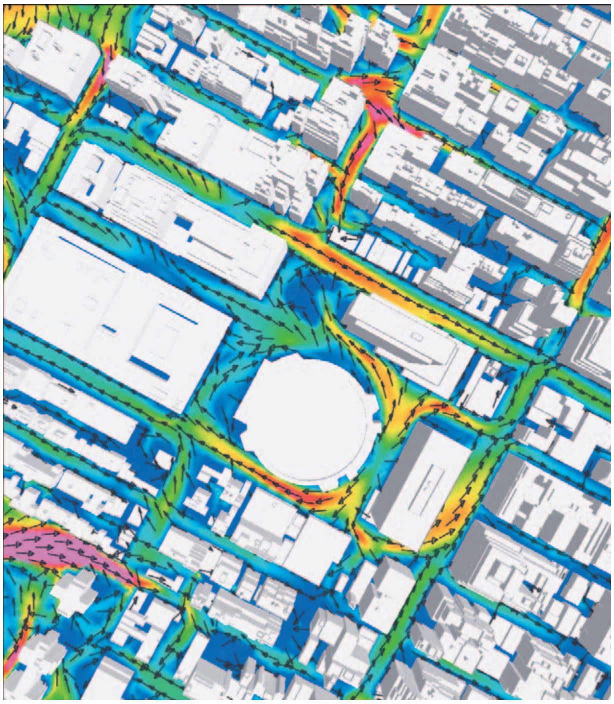

Fig. 7. Simulations of horizontal wind vectors (m s^{-1}) at z = 5 m by FEFLO-Urban model for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

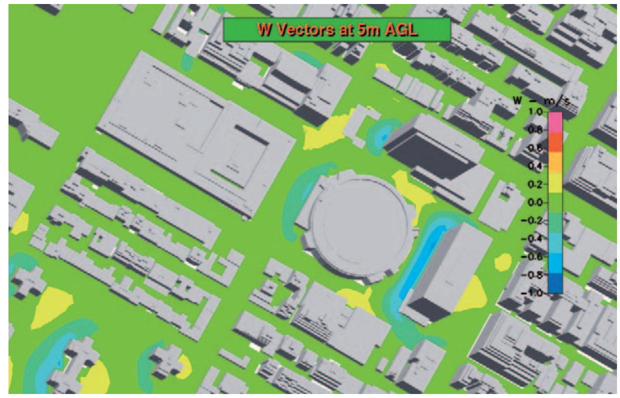

Fig. 9. Simulations of vertical velocity *w* (m s^{-1}) at z = 5 m, by CFD-Urban for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

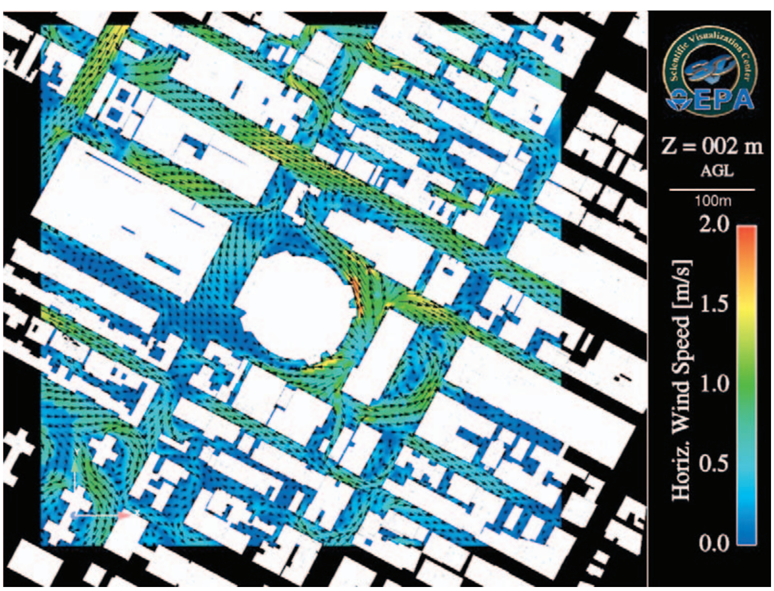

Fig. 8. Simulations of horizontal wind vectors (m s^{-1}) at z = 2 m by FLUENT-EPA model for 10 Mar 2005 upstream wind inputs (flow from the northwest).

haps future comparison studies could impose precise criteria for these details beforehand.

RESULTS. Examples of simulated wind vectors near street level, at 0900 LST 10 March of the MSG05 field experiment, are given in Figs. 4 through 8 for the five CFD models (CFD-Urban, FLACS, FEM3MP, FEFLO-Urban, and FLUENT-EPA, respectively). Side-by-side comparisons with the 30-minute-averaged observed wind vectors (in Fig. 2) show reasonable agreement in speed (within a factor of 2) and direction (within about 30°) for most street-level sites. For example, the models capture the diverging flow toward the upwind and crosswind directions on the windward side of MSG and Two Penn Plaza (just east of MSG).

In the planning run comparisons for the south-southwest 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 Figs. 4 through 8 reveal similar discrepancies in certain parts of the domain.

The CFD model outputs and the observations are compared qualitatively in the current paper. The CFD team is proceeding with limited quantitative comparisons for the MSG05 experiment, and more extensive comparisons for the MID05 experiment, and 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, the results show the strong influence on the near-surface wind flow of the tallest buildings, which bring down momentum from aloft on their windward sides and have an upward-directed "chimney effect" on their leeward sides. These vertical velocity patterns on a horizontal plane near the ground are seen in Figs. 9–13 for the five CFD models (CFD-Urban, FLACS, FEM3MP, FEFLO-Urban, and FLUENT-EPA, respectively). The typical magnitudes of the vertical velocities are a few tenths of a meter per second, although larger values (as much as 5 m s^{-1}) are sometimes simulated close to tall buildings. These vertical motions are associated 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 vertical (x-z) cross sections, as shown in Figs. 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 the west–northwest to east–southeast. This direction is approximately aligned with the inflow wind direction. In particular, the downdraft on the windward side of Two Penn Plaza (just east of MSG) is clearly seen in the figures, as well as the street canyon eddy on the windward side of MSG. Slightly different orientations have been used for the five models; for example, in Fig. 16 (for FEM3MP), the absence of buildings to the right side (to the south-southeast) of the Two Penn Plaza building

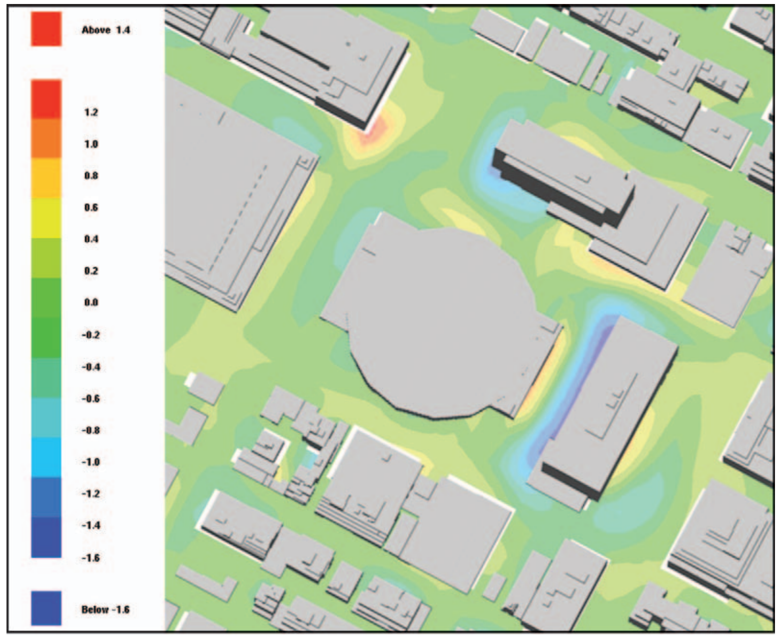

FIG. 10. Simulations of vertical velocity *w* (m s^{-1}) at z = 5 m, by FLACS for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

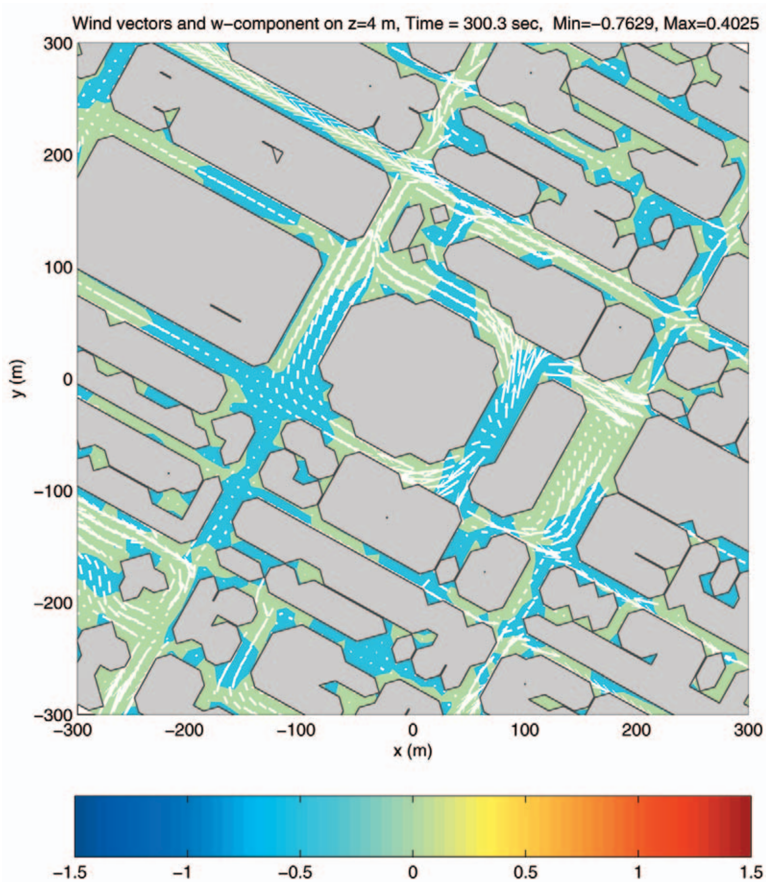

FIG. 11. Simulations of vertical velocity *w* (m s^{-1}) at z = 5 m, by FEM3MP for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

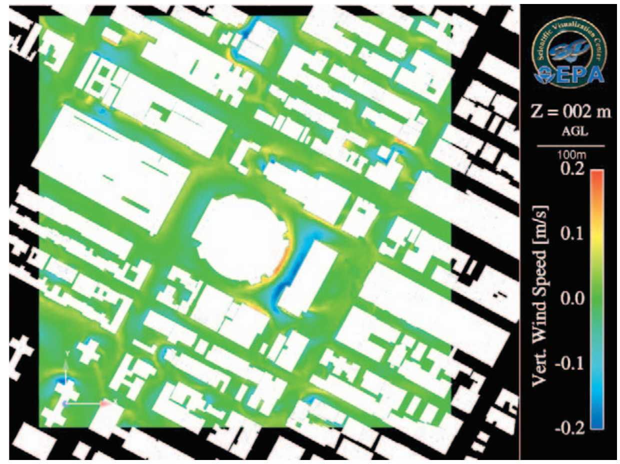

Fig. 13 (above). Simulations of vertical velocity *w* (m s^{-1}) at *z* = 2 m, by FLUENT-EPA for 10 Mar 2005 upstream wind inputs (flow from the northwest).

Fig. 12 (left). Simulations of vertical velocity *w* (m s^{-1}) at *z* = 5 m, by FEFLO-Urban for 10 Mar 2005 upstream wind inputs (flow from the west-northwest).

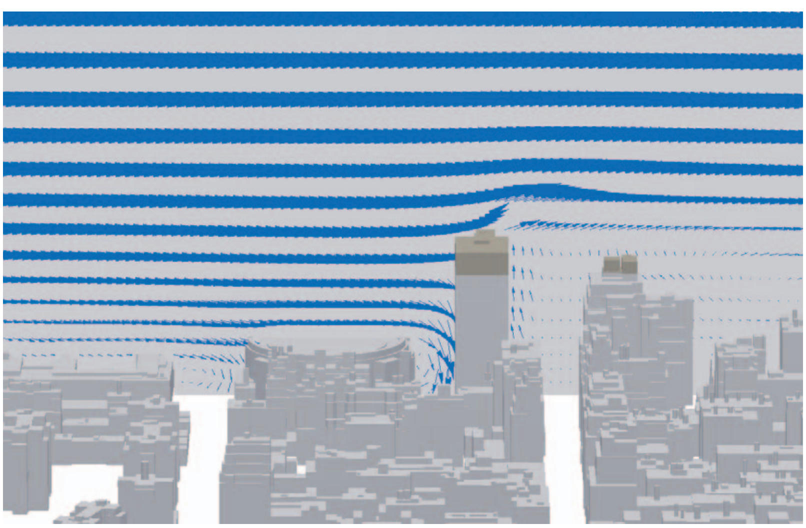

Fig. 14. Simulations of wind vectors (m s^{-1}) on *x–z* cross section through MSG for the west-northwest direction, for CFD-Urban. The view is toward the north-northeast.

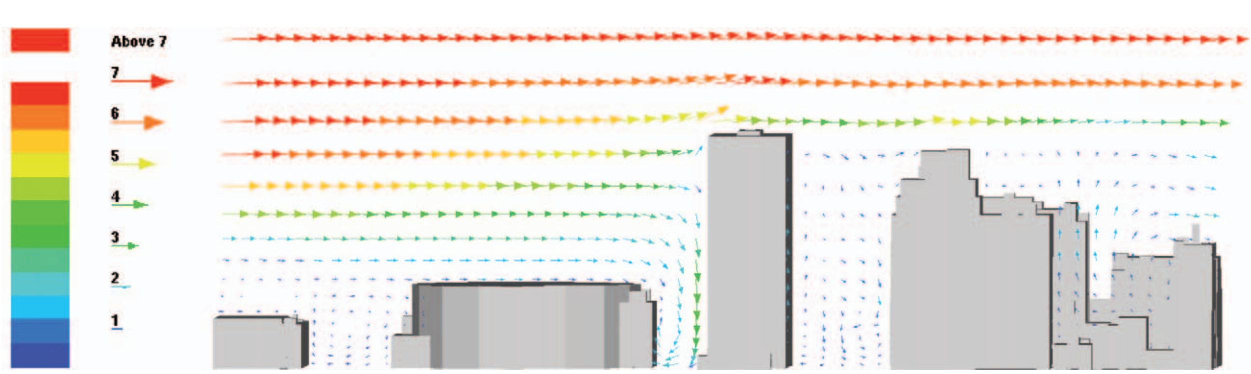

Fig. 15. Simulations of wind vectors (m s^{-1}) on *x–z* cross section through MSG for the west-northwest direction, for FLACS. The view is toward the north-northeast.

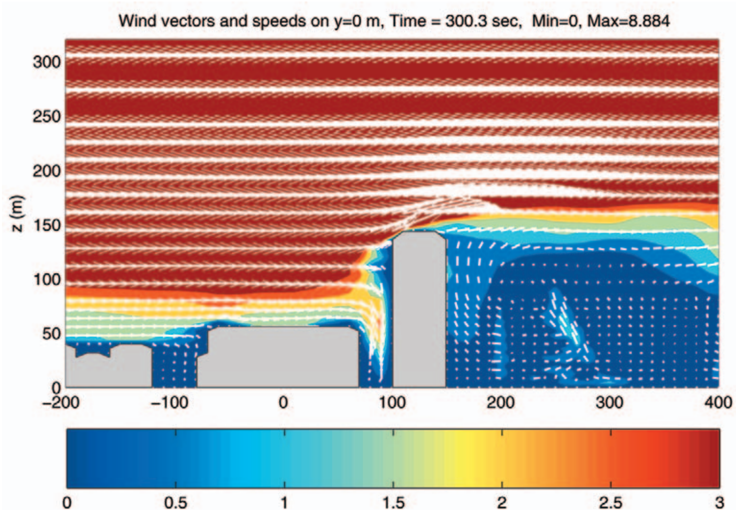

Fig. 16. Simulations of wind vectors (m s^{-1}) on *x–z* cross section through MSG for the west-northwest direction, for FEM3MP. The view is toward the north-northeast.

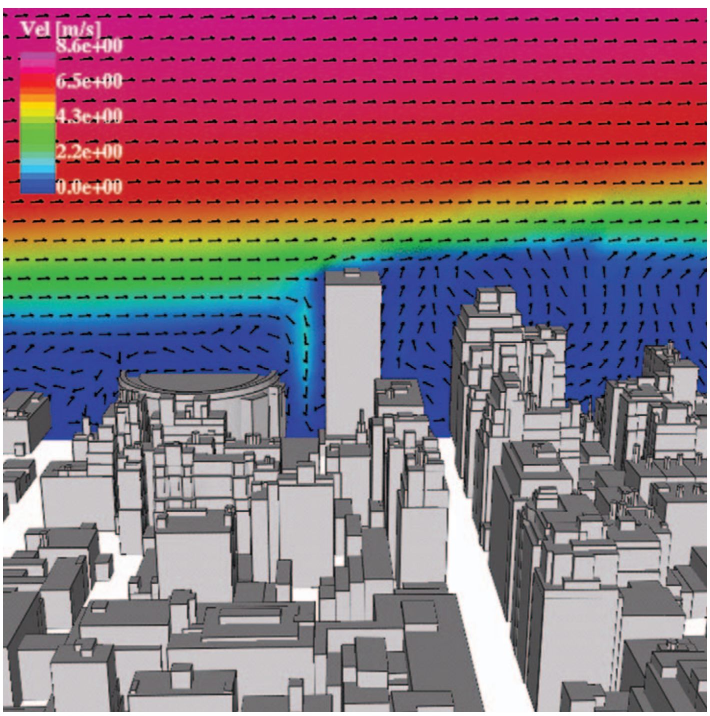

Fig. 17. Simulations of wind vectors (m s^{-1}) on *x–z* cross section through MSG for the west-northwest direction, for FEFLO-Urban. The view is toward the north-northeast.

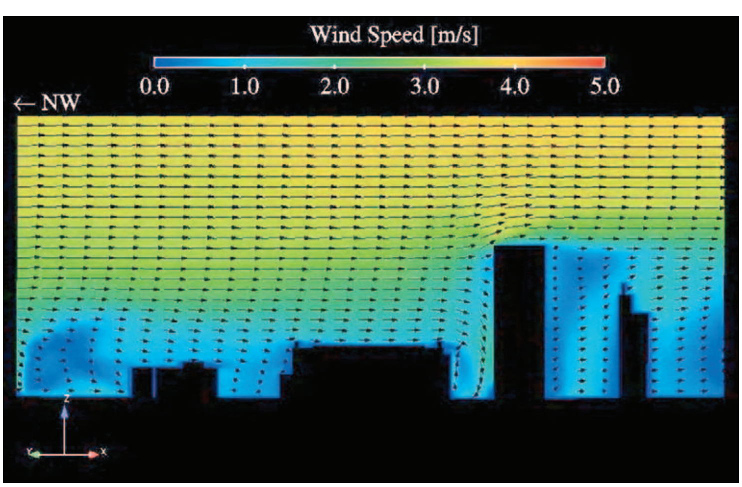

Fig. 18. Simulations of wind vectors on *x–z* cross section through MSG for the northwest direction, for FLUENT-EPA. The view is toward the north-northeast.

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

Fig. 20. FLACS simulation of tracer gas dispersion for a point release near street level on the southwest side of MSG for the west-northwest wind direction. This is one of the five source locations used during the MSG05 field experiment. The figure is for 900 s after the release was initiated.

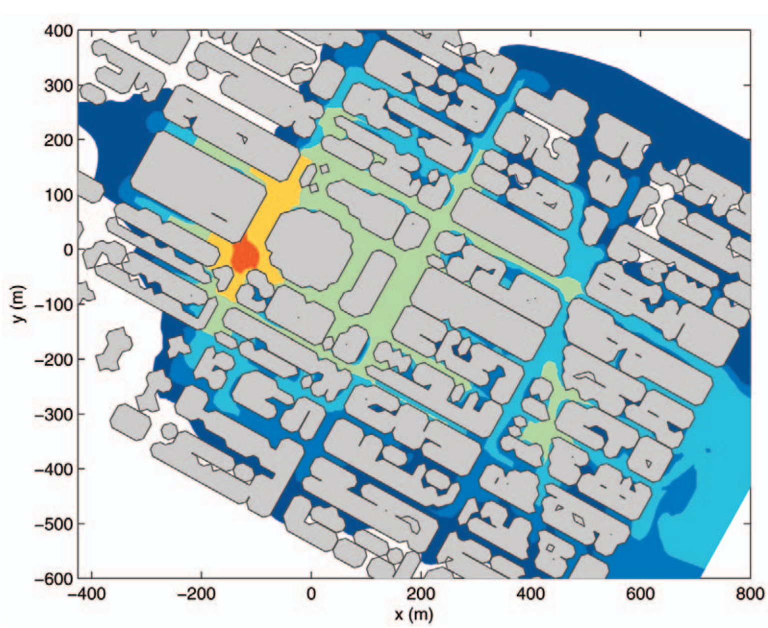

Fig. 21. FEM3MP simulation of tracer gas dispersion for the west-northwest wind direction and a point release near street level on the southwest side of MSG. This is one of the five source locations used during the MSG05 field experiment.

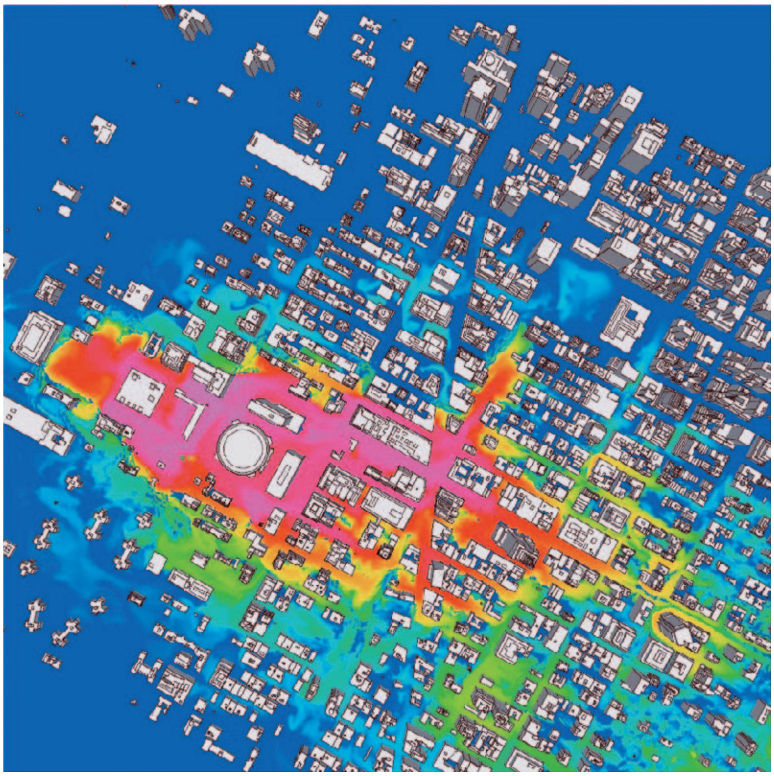

FIG. 22. FEFLO-Urban simulations of tracer gas dispersion for a west-northwest wind direction. There is a continuous release from five point sources near street level (on sidewalk off four corners of MSG and on sidewalk north of One Penn Plaza) as used during MSG05. The figure presents the plume concentrations at a time of 1000 s after the release is initiated.

is because the *x–z* cross section passes through the middle of a narrow street.

Four of the models were also used to simulate tracer dispersion patterns for eventual 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 from the release positions around MSG are shown in Figs. 19–22 for CFD-Urban, FLACS, FEM3MP, and FEFLO-Urban, respectively. The simulations are presented in normalized mode, and comparisons are not given with the actual observations because of security reasons.

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.

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