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5.1 **A STUDY OF THE EFFECTS OF DIFFERENT URBAN WIND MODELS ON DISPERSION PATTERNS USING JOINT URBAN 2003 DATA**

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1. INTRODUCTION

The Quick Urban & Industrial Complex (QUIC) Dispersion Modeling System has been developed to rapidly compute the transport and dispersion of toxic agent releases in the vicinity of buildings. It is composed of a wind solver, an "urbanized" Lagrangian random-walk model, and a graphical user interface. QUIC has two different wind models- a) The QUIC-URB wind solver, an empirically-based diagnostic wind model and b) The QUIC-CFD (RANS) solver, based on the 3D Reynolds-Averaged Navier–Stokes (RANS) equations. In this paper, we discuss the effect of different wind models on dispersion patterns in dense built-up areas. The model-computed wind from the two urban wind models- QUIC-URB and QUIC-CFD are used to drive the dispersion model. The concentration fields are then compared to measurements from the Oklahoma City Joint Urban 2003 field experiment.

2. OVERVIEW OF QUIC

QUIC produces high-resolution 3-D mean wind and concentration fields around buildings, in addition to deposition on the ground and building surfaces. It has options for different release types, including point, moving point, line, area, and volumetric sources, as well as dense gas, explosive buoyant rise, multi-particle size, bio-slurry, and two-phase releases. Other features include indoor infiltration, a pressure solver, outer grid simulations, vegetative canopies, and population exposure calculations. It has been used for biological agent sensor siting in cities, vulnerability assessments for heavier-than-air chemical releases at industrial facilities, and clean-up assessments for radiological dispersal device (RDD) releases in cities (e.g., see Linger et al., 2005; Brown, 2006a, b). QUIC has also been used for dust transport studies (Bowker et al., 2007a) and for the impact of highway sound barriers on the transport and dispersion of vehicle emissions (Bowker et al., 2007b).

a) Wind Solver

(i) The QUIC-URB wind solver is an empirically-based diagnostic wind model based on the ideas of Röckle (1990). The wind solver generates a mass consistent mean wind field around buildings by using various empirical relationships based on the building height, width, and length, and the spacing between buildings to initialize the velocity fields in the regions around buildings (e.g., upwind rotor, downwind cavity and wake, street canyon vortex, and rooftop vortex). This initial flow field is then forced to satisfy mass conservation. For the 2 million grid cell downtown Oklahoma City simulation performed for this evaluation study, the wind field was generated in approximately one minute on a single processor PC. More information about the wind solver can be found in Pardyjak and Brown (2003), Singh et al. (2008), and Gowardhan et al. (2009).

(ii) The QUIC-CFD (RANS) solver is based on the 3D Reynolds-Averaged Navier–Stokes (RANS) equations for incompressible flow using a zero equation (algebraic) turbulence model based on Prandtl's mixing length theory (Gowardhan et al. 2011). The selection of zero-equation turbulence model was made so as to reduce the run time of the CFD simulation, and therefore making it more closely adapted for a fast-response application. Computational time using a zero-equation model can be reduced by 2–8 times from that using a more complex turbulence model—keeping all other computational settings such as discretization schemes and mesh size the same.

The governing RANS equations are solved explicitly in time until steady state is reached using a projection method. At each time step of the projection method, the divergence-free condition is not strictly satisfied to machine precision levels, but rather when steady state is reached incompressibility is recovered. This makes the method comparable to the artificial compressibility method (Chorin, 1967). The RANS equations are solved on a staggered mesh using a finite volume discretization scheme that is second-order accurate in space (central difference) and time (Adams–Bashforth). The law-of-the-wall was imposed at all of the solid surfaces. The pressure Poisson equation was solved using the successive over-relaxation method (SOR). A free slip condition was imposed at the top boundary and the side boundaries,

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while an outflow boundary condition is used at the outlet. For the 2 million grid cell downtown Oklahoma City simulation performed for this evaluation study, the wind field was generated in approximately 20 minutes on a single processor PC. More information on the numerical scheme and parameterizations can be found in Gowardhan et al. (2011).

b) Dispersion Model

The QUIC dispersion model is a Lagrangian random-walk code, which tracks the movement of particles as they disperse through the air. It uses the mean wind field computed by the wind solver and produces the turbulent dispersion of the airborne contaminant using random-walk equations with additional drift terms appropriate for the inhomogeneous nature of turbulence around buildings (Williams et al., 2002). The normal and shear stresses and turbulent dissipation are determined based on similarity theory, gradient transport and a non-local mixing formulation that better describes the turbulent mixing that occurs in building cavities and street canyons. Details regarding the model can be found in Williams et al. (2004).

3. FIELD EXPERIMENT DESCRIPTION

The Joint URBAN 2003 field experiment was held in Oklahoma City in July 2003 and had the goal ofobtaining measurements useful for the testing and evaluation of the next generation of urban transport and dispersion models. The experiment consisted of a large number of tracer releases at three different locations in the central business district and a network of concentration samplers and in-situ and remote sensing meteorological instrumentation placed in and around the city (Allwine et al., 2004 newer reference?).

During the experiment ten intensive operating periods (IOP's) were conducted over a roughly eight hour period. Each IOP typically consisted of three 30 minute releases of sulfur hexafluoride (SF6) and four instantaneous releases. For the thirty minute duration releases, concentration measurements were taken over a one hour period, beginning at the release start time and extending thirty minutes beyond the release end time.

Bag samplers were placed throughout the downtown area at roughly 2 m above street level and on rooftops. Sampling durations ranged from 5 minutes to 30 minutes depending on the distance from the source. For this study, the concentration measurements were averaged to 30 minutes for comparison to model output.

A suite of sonic and propeller anemometers situated in the streets in the downtown core at roughly 8 m agl were used for comparison to the QUIC model output. Thirty minute vector-averaged wind speed and wind direction measurements have been used in the evaluation.

IOP-2, release 2 (12:00 CST, July 2) and IOP-8, release 1 (CST, July 24) were chosen for this evaluation study in order to look at both a daytime and nighttime release within the downtown area. The source location, called the "Westin" release point, was at the southern edge of the high-rise district on Main St, a north-south street running through the center of the central business district.

Prevailing winds were predominately from the south-southeast during IOP 8 and the south-southwest for IOP 2.

5. MODEL SET-UP

The QUIC modeling domain covers most all of the Oklahoma City central business district (CBD) and is 1.2 km x 1.2 km in size. The horizontal grid size was set to 5 m, while the vertical resolution was set to 3 m resulting in a 240 by 240 by 60 grid cells (3.5 million total). Earlier studies with higher horizontal grid resolution indicated that the plume simulations were not sensitive to the grid size and so the simulations were performed using the 5 m grid size. The 3D building data were obtained from the Defense Threat Reduction Agency and the University of Oklahoma. Although there were trees in the downtown area, the simulations performed for this study was done without the vegetation canopy scheme turned on.

The inflow wind profile was created using a combination of wind sensors located upwind of the CBD. The closest location was about 200 meters due south (upwind) of our domain. A Dugway Proving Ground propeller anemometer was located on a tower 50 m above the ground and 15 m above the roof of a post office building. The anemometer was not operating, however, during IOP 2. Eight anemometers from Indiana University were located on several towers between 2 m and 80 m above ground level about 5 km south of our domain. For IOP2, 2 were used for the inflow profile, while for IOP8, 8 were used. A radar from the Pacific Northwest National Laboratory located about 1 km south-southwest of the CBD was used for the winds above 100 m. Different instrumentation often showed up to 20-30 degree differences in wind direction, with little consistent bias, making the specification of the inflow WD profile somewhat difficult. When available, the DPG Post Office wind measurement was considered to be most representative of the inflow wind direction since it was closest to the southern boundary of the modeling domain. 30 minute averaged wind measurements were used to drive the QUIC model over a half hour period. Table 1 shows the inflow wind profile used to drive the models:

Table 1: The inflow wind profiles used to describe different IOP cases in numerical models.

Test case: IOP2 Wind inlet profile (log) Surface roughness	U_{ref}= 5 m/s, z_{ref}=50 m, wind angle = 215; z_o= 0.6 m
Test case: IOP8 Wind inlet profile (log) Surface roughness	U_{ref}= 8.5 m/s, z_{ref}=80 m, wind angle = 165; z_o= 1 m

The atmospheric stability for the simulations was assumed to be neutral. Within the urban canopy this assumption is likely valid, but above the canopy there may be a stable layer during IOP8 and an unstable layer during IOP2. However, numerous studies have shown that a several hundred meter well-mixed neutrally-stratified layer often exists above larger-sized city centers. The downtown district of Oklahoma City is rather small, however, and thus it is not clear whether the well-mixed layer would develop so deeply.

6. MODEL EVALUATION

QUIC-URB and QUIC-CFD models were run using the exact same grid and inflow conditions. The simulations were identical in every aspect (grid resolution, building geometry, inflow direction etc.) except for the wind model used. 3D winds from these two models were used to drive the dispersion model. Again, all the parameters for the dispersion model were kept identical. The results were compared with the field data.

IOP 2 release 2:

Figure 1 shows the wind field produced by QUIC-URB and QUIC-CFD respectively. Compared to QUIC-URB, QUIC-CFD captures more of the important flow features seen in an urban area and compares well to the field data. Significant differences in street level wind speeds can also be seen. QUIC-CFD appears to better estimate channeling and strength

Figure 2 shows the scatterplot of measured and predicted velocity for both the models. It can be clearly seen that QUIC-CFD underpredicts the velocity magnitude.

Figure 3 shows the contours of vertical velocity produced by both the models. QUIC-CFD computes stronger updrafts and downdrafts around buildings

Figure 4 shows the contours of concentration (log scale) predicted by both the models. Overlaid are the field measurements. It can be observed that further than a block or two away, both models produce fairly similar concentration fields. However, near the source, the preferred plume direction is significantly different. The plume concentrations produced by QUIC-CFD better match the measurements near the source. Near the source, QUIC-URB predicts that SF_6 will exit along the east-west running street while the QUIC-CFD predicts that SF_6 will exit along the north-south running street.

IOP 8 release 1:

For IOP 8, similar effects have been observed. Near the source, QUIC-URB predicts that SF6 will exit along the north-south running street while the QUIC-CFD predicts that SF_6 will exit along the east-west running street.

7. CONCLUSION

Generally, both wind models appear to produce similar neighborhood-scale dispersion patterns. However, close to the source, significant differences in the channeling are apparent QUIC-CFD appears to predict the dispersion pattern better near the source, although there are other intermediate locations where QUIC-URB does better. Both the models are useful and the choice of wind model should be problem dependent

6. REFERENCES

Addepalli, B., M. Brown, E. Pardyjak, I. Senocak, 2007: Investigation of the flow structure around step-up, step-down, and isolated tall building configurations using wind-tunnel PIV measurements, AMS 7thSymp. Urb. Env., San Diego, CA.

Allwine, K.J., M. J. Leach, L. W. Stockham, J. S. Shinn, R. P. Hosker, J. F. Bowers, J. C. Pace, 2004: Overview of Joint Urban 2003 An Atmospheric Dispersion Study in Oklahoma City, AMS Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, 11-15 January, Seattle, WA.

Bagal, N., E. Pardyjak, and M. Brown, 2003: Improved upwind cavity parameterization for a fast response urban wind model, AMS Conf. on Urban Zone, Seattle, WA, 3 pp.

Bowker, G., R. Baldauf, V. Isakov, A. Khlystov, and W. Petersen, 2007b: The effects of roadside structures on the transport and dispersion of ultrafine particles from highways, At. Env. 41, 8128-8139.

Bowker, G., D. Gillette, G. Bergametti, B. Marticorena, and D. Heist, 2007a: Sand flux simulations at a small scale over a heterogeneous mesquite area of the northern Chihuahuan desert, J. Appl. Meteor., 46, 1410-1422.

Brown, 2007a: Radiological dispersal device (RDD) modeling in cities using the QUIC model, poster, 2007 Fall AGU Meeting, San Francisco, CA. LA-UR-07-3182, http://

Brown, 2007b: Chemical dense gas modeling around buildings using the QUIC model, poster, Fall AGU Meeting, San Francisco, CA, LA-UR-07-3182, http://

Gowardhan, A., M. Brown, M. Williams, E. Pardyjak, 2006: Evaluation of the QUIC Urban Dispersion Model using the Salt Lake City URBAN 2000 Tracer Experiment Data- IOP 10. 6th AMS Symp. Urban Env., Atlanta, GA, LA-UR-05-9017, 13 pp.

Gowardhan AA, Brown MJ, Pardyjak ER (2010) Evaluation of a fast response pressure solver for flow around an isolated cube. Environ Fluid Mech 10: 311–328. doi:10.1007/s10652-009-9152-5

Gowardhan, A., Pardyjak, E., Senocak, I., Brown, M (2011). A CFD-based wind solver for an urban fast response transport and dispersion model, Environ Fluid Mech, doi:10.1007/s10652-011-9211-6.

Leitl, B., P. Kastner-Klein, M. Rau, R. Meroney, 1997: Concentration and flow distributions in the vicinity of U-shaped buildings: wind-tunnel and computational data, J. Wind Eng. & Ind. Aerodyn., v 67-68, pp 745-755.

Linger, S., M. Brown, W.B. Daniel, A. Ivey, T. McPherson, M. Williams, and K. Omberg, 2005: Sensing threats with BioWatch, GeoIntelligence, Mar/Apr 2005, pp. 16-21, LA-UR-05-0799.

Nelson, M., B. Addepalli, F. Hornsby, A. Gowardhan, E. Pardyjak, and M. Brown: Improvements to fast-response urban wind model, 15th AMS/AWMA Met. Aspects Air Poll., LA-UR-08-0206, 6 pp.

Pardyjak, E. and M. Brown, 2001: Evaluation of a fast-response urban wind model – comparison to single-building wind-tunnel data, Int. Soc. Environ. Hydraulics, Tempe, AZ, LA-UR-01-4028, 6 pp.

Pardyjak, E.R. and M. Brown, 2003: QUIC-URB v. 1.1: Theory and User's Guide, LA-UR-07-3181, 22 pp.

Pol S., N. Bagal, B. Singh, M. Brown, and E. Pardyjak, 2006: Implementation of a rooftop recirculation parameterization into the QUIC fast response wind model, 6th AMS Urb. Env. Symp., Atlanta, GA, LA-UR-05-8631, 19 pp.

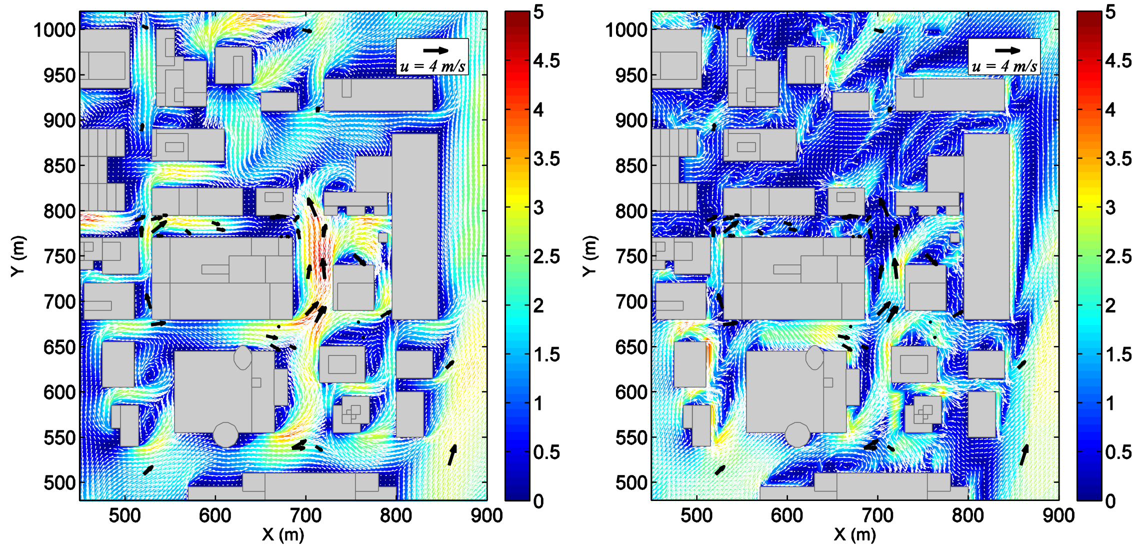
Röckle, R., 1990: Bestimmung der stomungsver-haltnisse im Bereich Komplexer Bebauugsstruk-turen. Ph.D. thesis, Vom Fachbereich Mechanik, der Technischen Hochschule Darmstadt, Germany.

Rockle, R. and C.-J. Richter, 1998: Ausbreitung von Emissionen in komplexer Bebauung – Vergleich zwischen numerischen Modellen und Windkanalmessungen, Förderkennzeichen: PEF 295002, 92 pp.

Singh, B., B. Hansen, M. Brown, E. Pardyjak, 2008: Evaluation of the QUIC-URB fast response urban wind model for a cubical building array and wide building street canyon, *Env. Fluid Mech.,* v 8, pp 281-312.

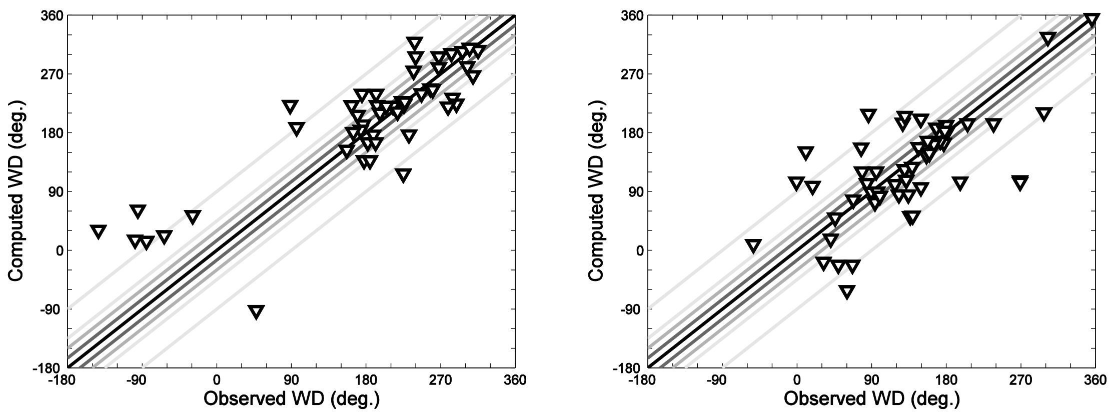
Williams, M. D., M. J. Brown, and E. R. Pardyjak, 2002: Development of a dispersion model for flow around buildings, 4th AMS Symp. Urban Env., Norfolk, VA, May 20-24 2002, LA-UR-02-0839.

Williams, M., M. Brown, B. Singh, & D. Boswell, 2004: QUIC-PLUME Theory Guide, LA-UR-04-0561, 22 pp.



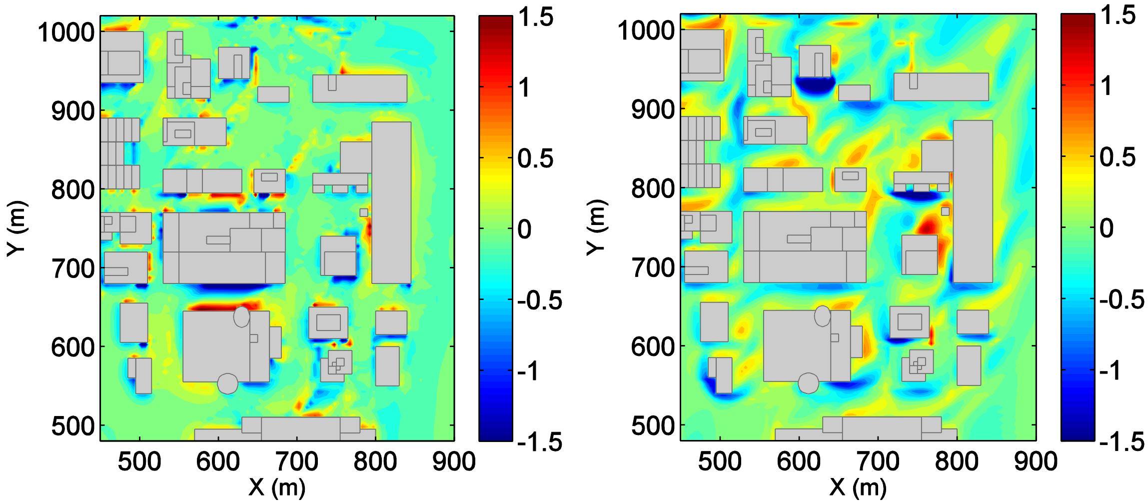
(a) (b)

Figure 1: Velocity vectors (white arrow) and contours of velocity magnitude (m/s) from (a) QUIC-URB and (b) QUIC-CFD overlaid with 30 min averaged field data (black arrow) for IOP2 during the Joint Urban 2003field experiment: horizontal slice (xy plane) at 8m AGL.



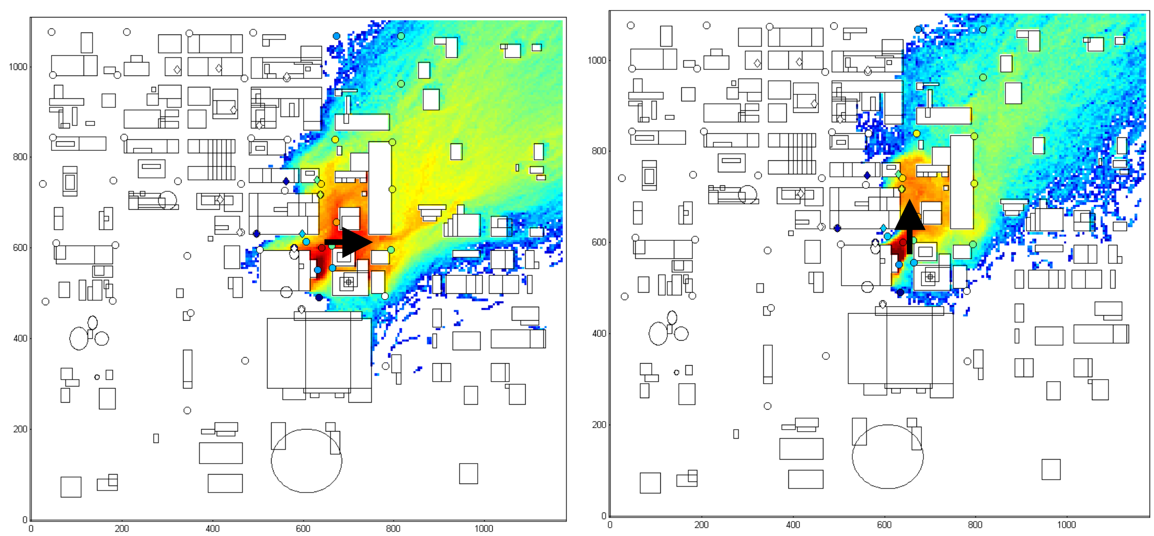
(a) (b)

Figure 2: Paired in time and space scatter plot for half hour averaged predicted and observed wind speed for IOP 2: (a) QUIC-URB and (b) QUIC-CFD.



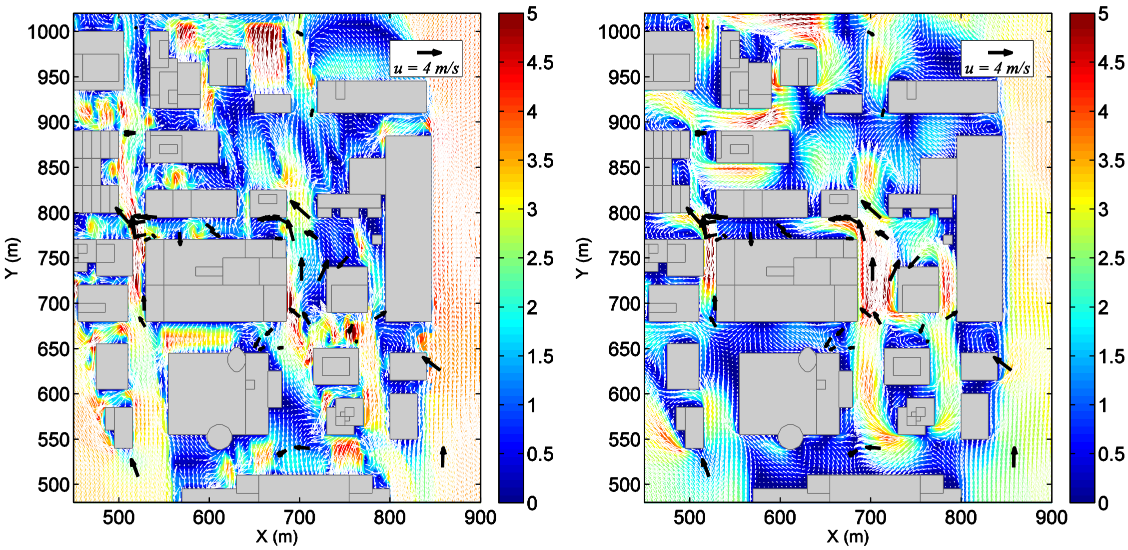
(a) (b)

Figure 3: Contours of vertical velocity (m/s) from (a) QUIC-URB and (b) QUIC-CFD during Joint Urban 2003 field experiment: horizontal slice (xy plane) at 8m AGL.



(a) (b)

Figure 4: Contours of concentration field produced using winds from (a) QUIC-URB and (b) QUIC-CFD overlaid with 30 min averaged field data (filled circles) for IOP 2 during Joint Urban 2003 field experiment: horizontal slice (xy plane) at 8m AGL.



(a) (b)

Figure 5: Velocity vectors (white arrow) and contours of velocity magnitude (m/s) from (a) QUIC-URB and (b) QUIC-CFD overlaid with 30 min averaged field data (black arrow) for IOP 8 during the Joint Urban 2003field experiment: horizontal slice (xy plane) at 8m AGL.

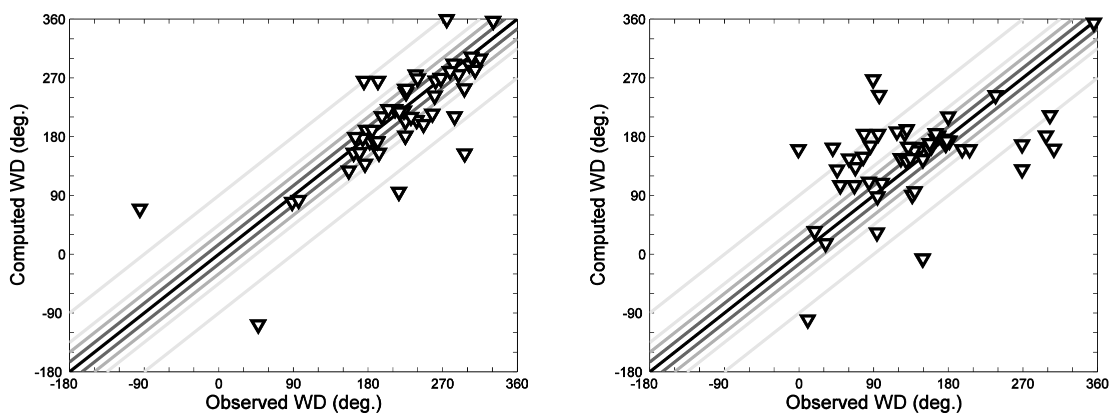


Figure 6: Paired in time and space scatter plot for half hour averaged predicted and observed wind speed for IOP 8: (a) QUIC-URB and (b) QUIC-CFD.

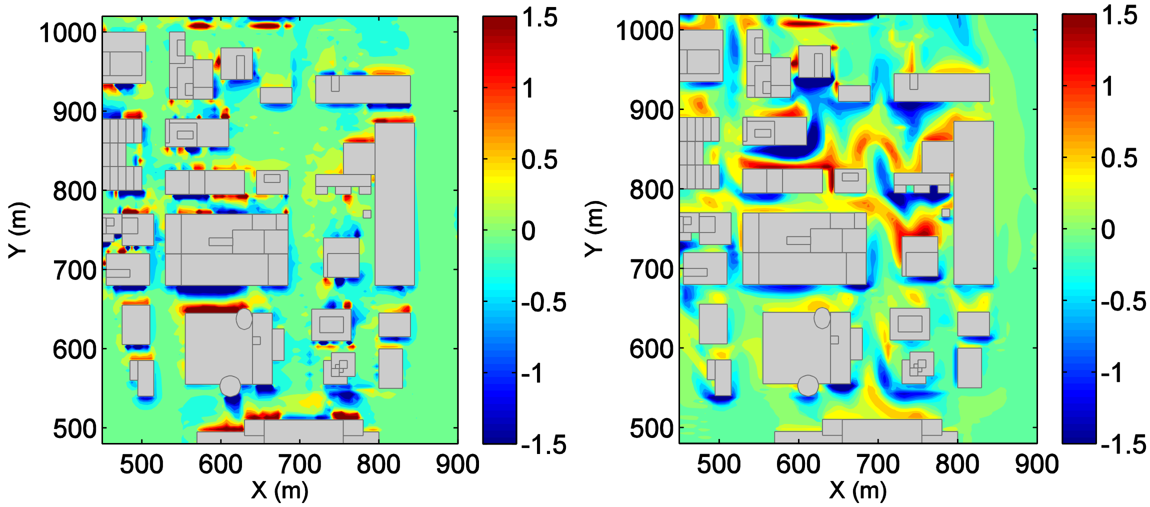


Figure 7: Contours of vertical velocity m/s from (a) QUIC-URB and (b) QUIC-CFD during Joint Urban 2003 field experiment: horizontal slice (xy plane) at 8m AGL.

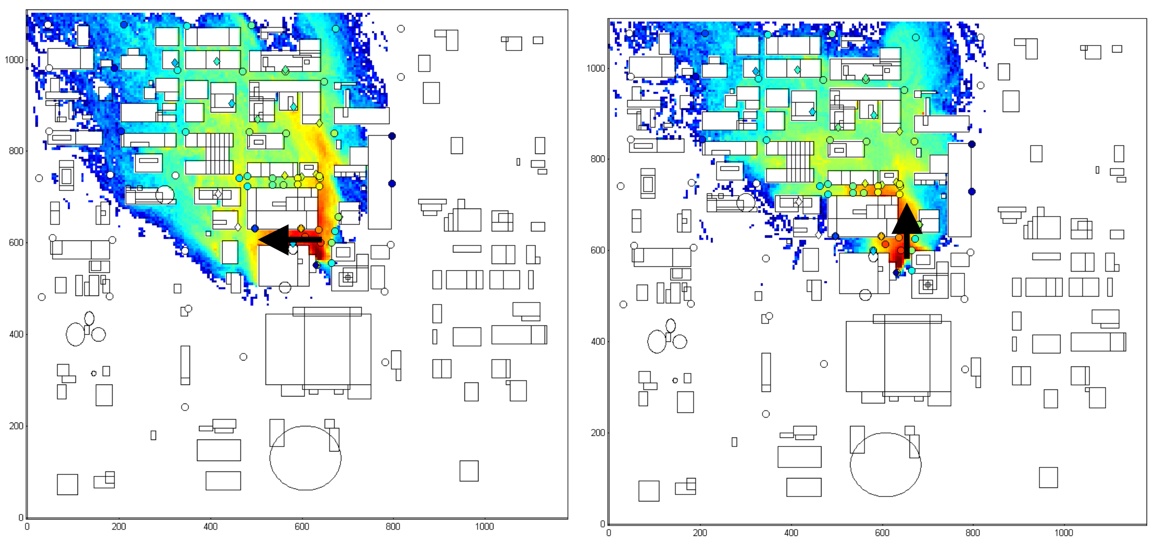


Figure 8: Contours of concentration field produced using winds from (a) QUIC-URB and (b) QUIC-CFD overlaid with 30 min averaged field data (filled circles) for IOP 8 during Joint Urban 2003 field experiment: horizontal slice (xy plane) at 8m AGL.

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