J6.3 Evaluation of the QUIC Urban Dispersion Model using the Salt Lake City URBAN 2000 Tracer Experiment Data – IOP 10

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1. INTRODUCTION

Computational fluid dynamics (CFD) models hold great promise for simulating transport and dispersion in cities. Comparisons to field and laboratory measurements show that these models work fairly well in many cases (e.g., DeCroix and Brown 2002, Camelli et al. 2004). At the present time, however, CFD models are computationally very intensive and because turn around time is very important for some applications, faster alternatives are being developed which will generate flow fields in less time. Diagnostic-empirical models are one such option; they attempt to account for the dominant building-induced circulations through empirical algorithms (e.g., Röckle 1990, Kaplan and Dinar 1996).

Our team has developed the Quick Urban and Industrial Complex (QUIC) dispersion modeling system with a wind solver based on the Röckle approach. These types of models have been fairly well evaluated for simple building arrangements (Williams et al. 2004). However, for more complex building arrangements, such as those that exist in real cities, less model testing has been reported. In this paper, we compare QUIC model-produced concentration fields with tracer measurements obtained from one of the intensive operating periods (IOP 10) in the Salt Lake City URBAN 2000 field experiment (Allwine et al. 2002). We will focus on the near-source concentration field in the immediate vicinity of the buildings and within several blocks of the release area and highlight similarities and differences between the model computations and experimental measurements.

2. MODEL DESCRIPTION

The QUIC fast response dispersion modeling system produces high-resolution wind and concentration fields in cities. It consists of an urban wind model QUIC-URB, a Lagrangian dispersion model QUIC-PLUME, and a graphical user interface QUIC-GUI. Such models, which can quickly produce the required velocity and concentration field, have many applications. Some of the applications are as follows:

1. Vulnerability assessments (where many simulations must be performed).
2. Training, table top exercises (where feedback or interaction is desired).
3. Emergency response.
4. Sensor sitting & source inversion tools.

a) QUIC-URB

QUIC–URB is based on the dissertation of Röckle (1990) in which a mass consistent diagnostic wind model for computing the 3D flow field around building obstacles was developed. In this model, an initial wind field is prescribed based on an incident flow and superimposed on this are various time-averaged flow effects associated with buildings. QUIC-URB utilizes empirical algorithms for determining initial wind fields in the rooftop and upstream recirculation zones (Bagal et al. 2004), the downwind cavity and wake for a single building (Singh et al. 2006) and in the street canyon between buildings. A mass consistent wind field is produced similar to the traditional diagnostic wind model (e.g., Sherman, 1978), but special treatment of the boundary conditions are needed at the building walls (Pardyjak and Brown 2003).

b) QUIC-PLUME

The QUIC-PLUME dispersion model is a Lagrangian random-walk model which tracks the movement of particles as they disperse through the air. QUIC-PLUME uses the mean wind field computed by QUIC-URB 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. 2004). The normal and shear stresses and turbulent dissipation are determined based on gradient transport and similarity theory. QUIC-PLUME also includes a non-local mixing formulation that better describes the turbulent mixing that occurs in building wakes or cavities (Williams et al. 2004b).

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3. EXPERIMENTAL DESCRIPTION

The URBAN 2000 meteorological and tracer field campaign was conducted in downtown Salt Lake City during October 2000 (Allwine et al., 2002). The experiments were designed as multi-scale experiments with three scales investigated: building, downtown, and urban scales. Sulfur hexafluoride (SF_6) was released at ground level from a parking lot location in downtown Salt Lake City near the intersection of 400 South and 200 East streets (Fig. 1) during each of seven nighttime intensive operating periods (IOP's). The release location was surrounded by medium height buildings (~10-35m). Directly north of the release point is the Heber-Wells building and directly south is the L-shaped City Centre building. For this study, we have focused on IOP 10 because the wind direction varied slowly over each trial and that allowed us to test our new time-varying version of QUIC. During IOP 10, SF_6 was released as a point source at 1 g/s for three 1-hour time periods from 00-01, 02-03, and 04-05 MST.

A sparse array of meteorological measurements was deployed in URBAN 2000, both in the downtown area and in the suburban area. Figure 1 depicts the six square block downtown area, showing the tracer bag samplers and meteorological instrument locations. Samplers near the source were located 1 m AGL, while all other surface samplers were at 3 m AGL. Figure 2 shows the location of the bag samplers that were used in our evaluation study and their associated collecting times which ranged from 5 minutes to 1 hour.

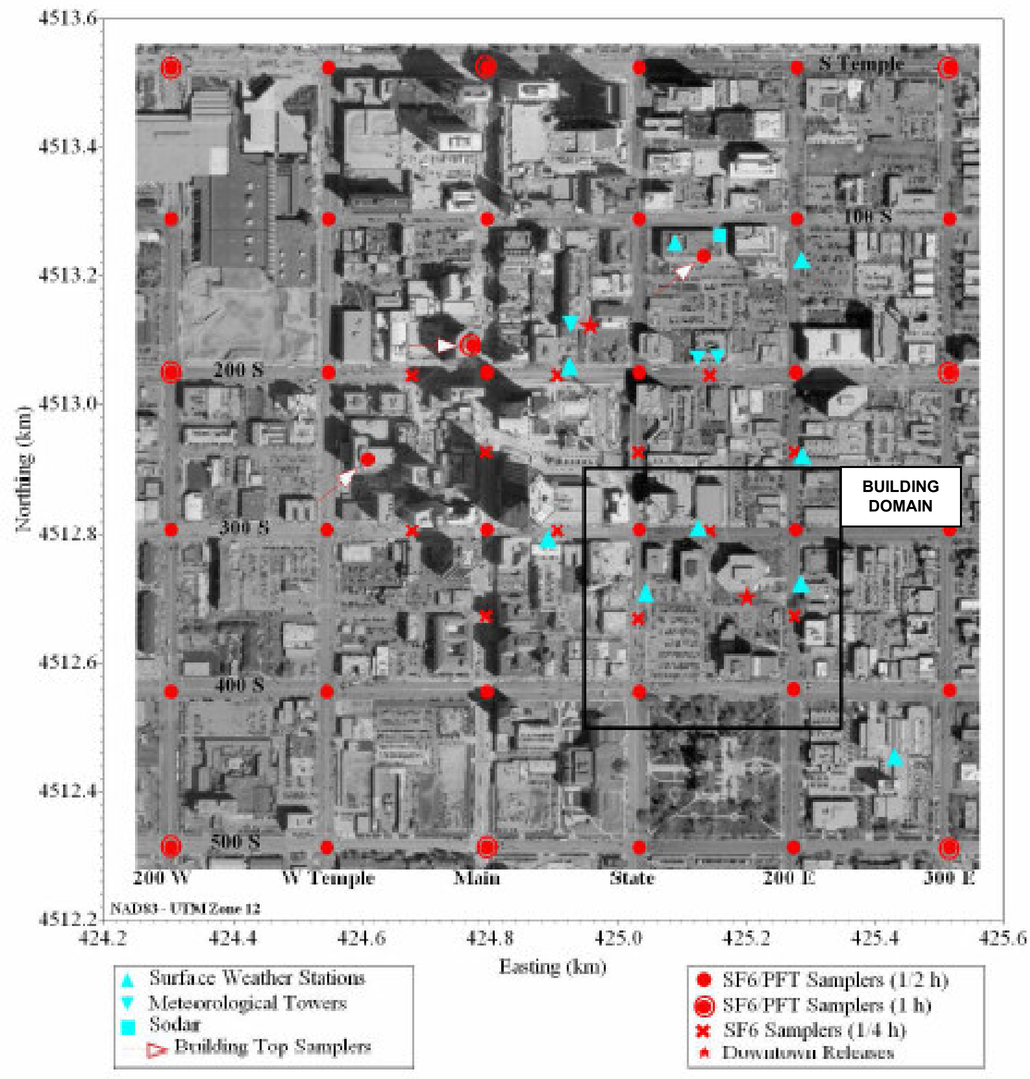


Fig. 1: The location of meteorological stations and tracer gas bag samplers for the URBAN2000 field program in the downtown Salt Lake City area (from Allwine et al. 2002).

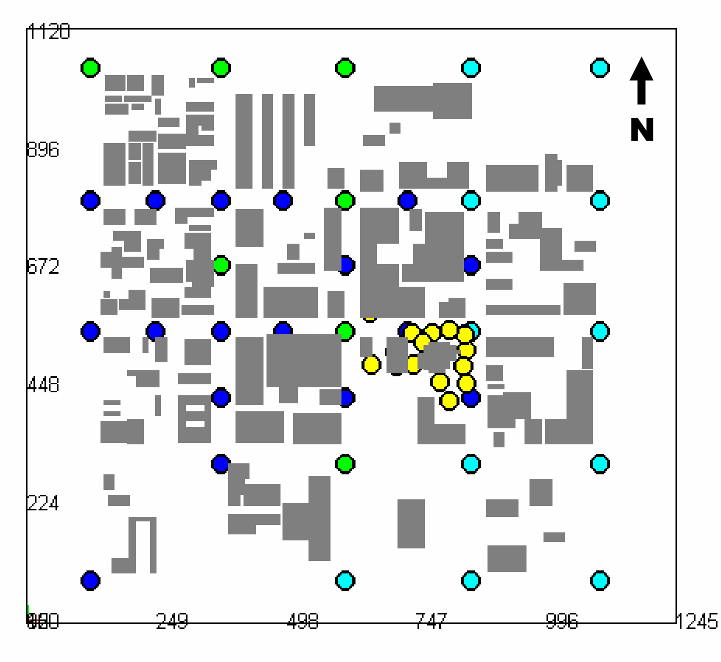


Fig. 2: Location of bag samplers colored according to their averaging times: 1 Hour ( ), 30 minutes ( ), 15 minutes ( ) and 5 minutes ( ).

4. MODEL SET-UP

a) Domain Parameters

The QUIC-URB simulations were performed on a domain of 1250m x 1120m x 180m at 5 m resolution (2,016,000 grid cells). A building data set obtained from Urban Data Solutions was used to specify the footprints and heights of the buildings. The buildings were constructed using a beta version of the City Builder tool (Gowardhan and Brown 2005). Trees and vehicles were not accounted for in the simulation and the underlying terrain was assumed to be flat. The QUIC-PLUME concentration grid was set to 62 x 55 x 24 grid cells with 20m resolution in the horizontal and 5 m in the vertical.

b) Inflow Parameters

One of the most important inputs to the QUIC dispersion modeling system is the mean wind inflow profile. It determines the prevailing wind direction and therefore the bulk movement of the plume. Unfortunately, a nearby upwind vertical profile of mean wind was not measured during the URBAN 2000 experiment.

For many of the prevailing wind directions, many of the meteorological instrument locations in the downtown domain were not free from building effects. The Raging Waters site, where a profiler, sodar, and met tower were co-located approximately 5 km southwest of the downtown area, was determined to have winds that were not representative of the flow in the downtown region due to the complex mountain-valley influences in the region (e.g., DeCroix, 2002). For southeasterly prevailing winds, DeCroix and Brown (2002) concluded that that sonics located on a snorkel lift a few blocks to the southeast of the release point at 7 m and 11 m AGL (known as the “Blue Goose” sonics) could be combined with the Dugway Proving Ground (DPG) sodar located on the rooftop of the Federal Building to obtain a reasonably representative inflow profile for the downtown area (see Fig. 3). Although the sodar is about 3 blocks north of the release site, the assumption is that at higher elevations above the influence of individual buildings the winds measured there are representative of a larger horizontal area.

The inflow profiles for the QUIC-URB wind model shown in Fig. 4 were constructed using 10 min. averaged winds due to the significant variation in the wind-direction during any single trial (1 hour duration). Note that for several cases, there was significant uncertainty in how to specify the mean wind direction between 11 m and 55 m AGL. Note also that the measurements appear to show significant directional wind shear with height.

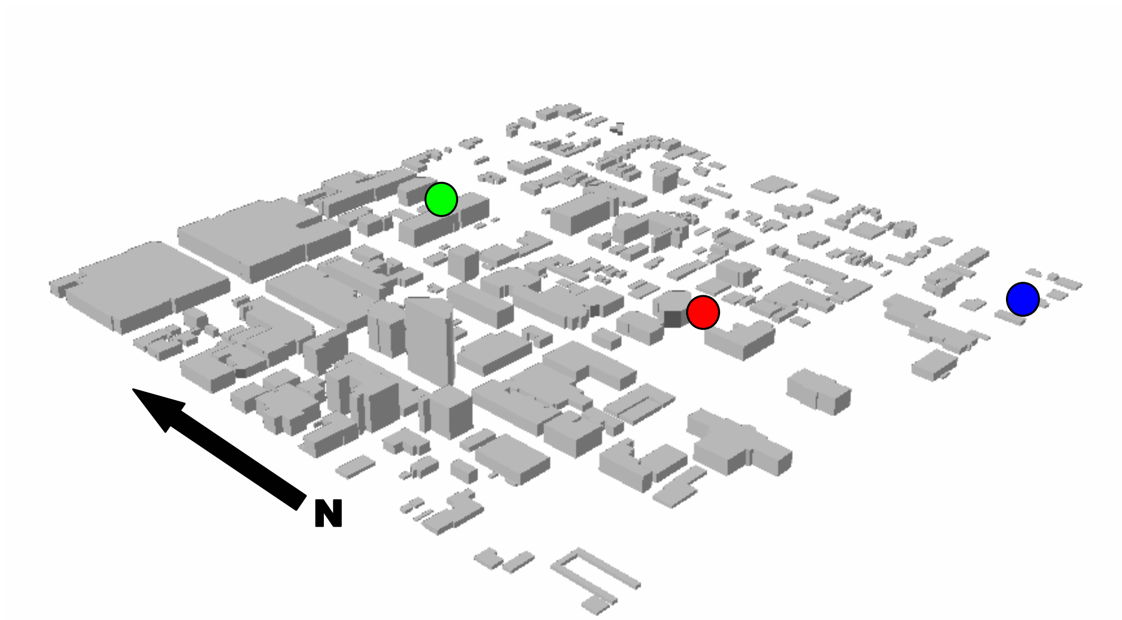
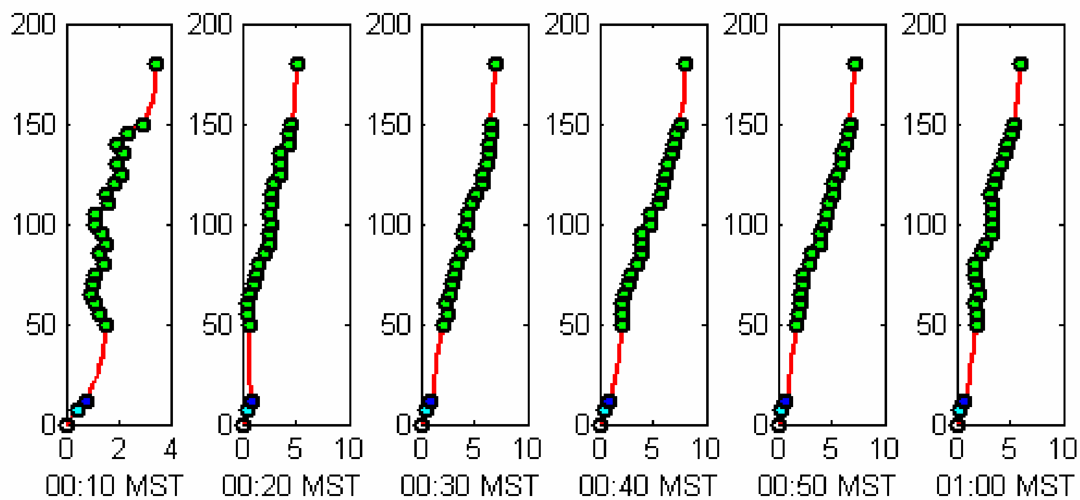


Fig. 3: 3D image of the Salt Lake City domain (UDS data) showing the release location ( ), location of the Blue Goose sonics ( ) and location of the DPG Sodar ( ).



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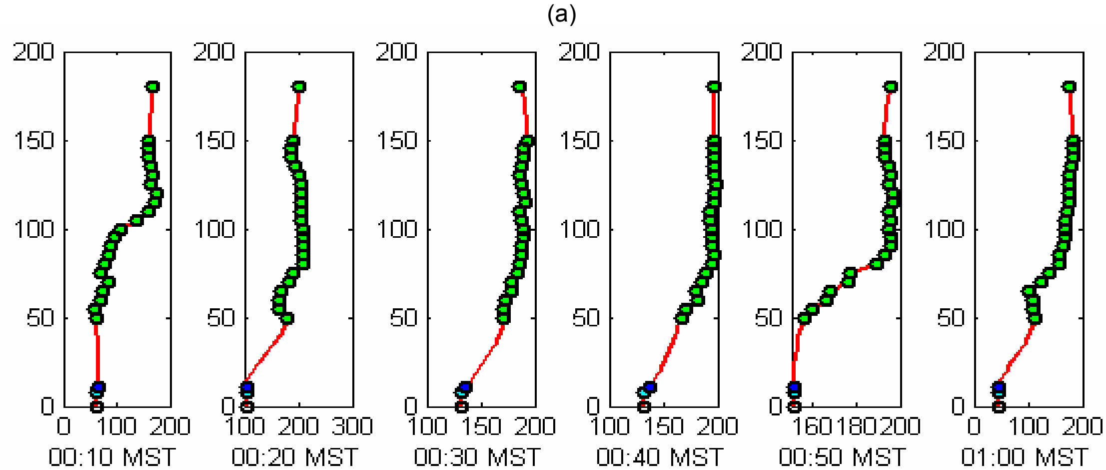
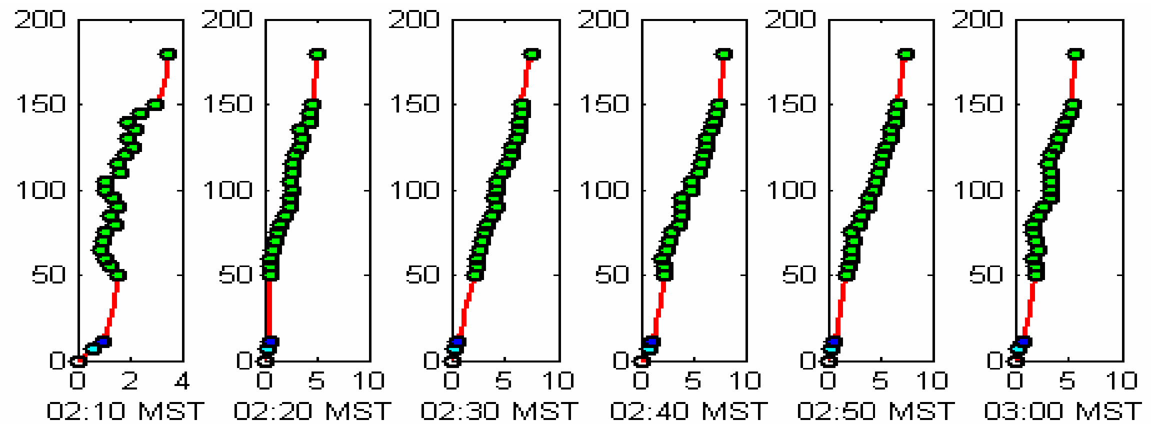


(b)

Fig. 4: 10 minute averaged inflow profile (--) constructed from the "Blue Goose" sonic measurements at 7.3 m ( ) and 11 m ( ) and the DPG Sodar ( ) for (a) wind speed (m/s) and (b) wind direction (degrees) versus height (m) for IOP 10, trial 1.



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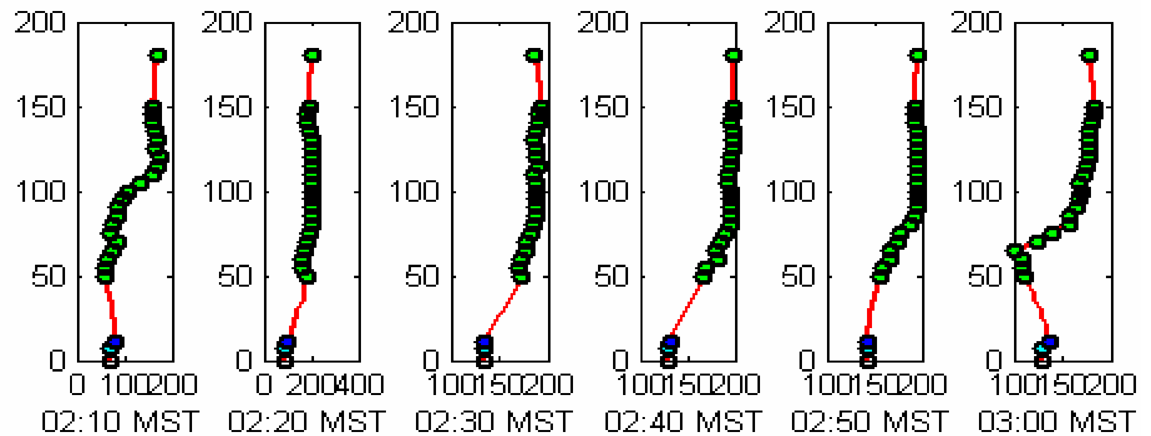
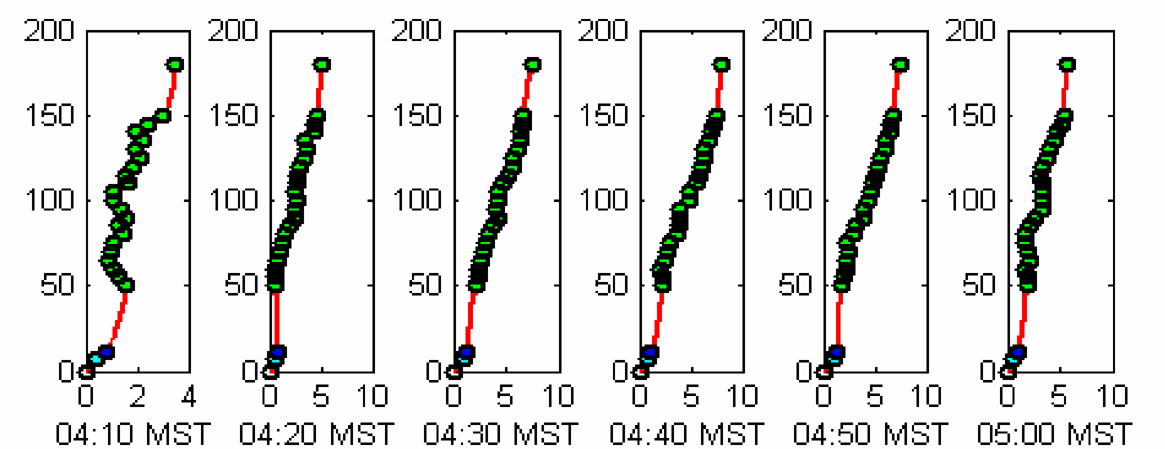


(b)

Fig. 5: 10 minute averaged inflow profile (--) constructed from the "Blue Goose" sonic measurements at 7.3 m ( ) and 11 m ( ) and the DPG Sodar ( ) for (a) wind speed (m/s) and (b) wind direction (degrees) versus height (m) for IOP 10, trial 2.



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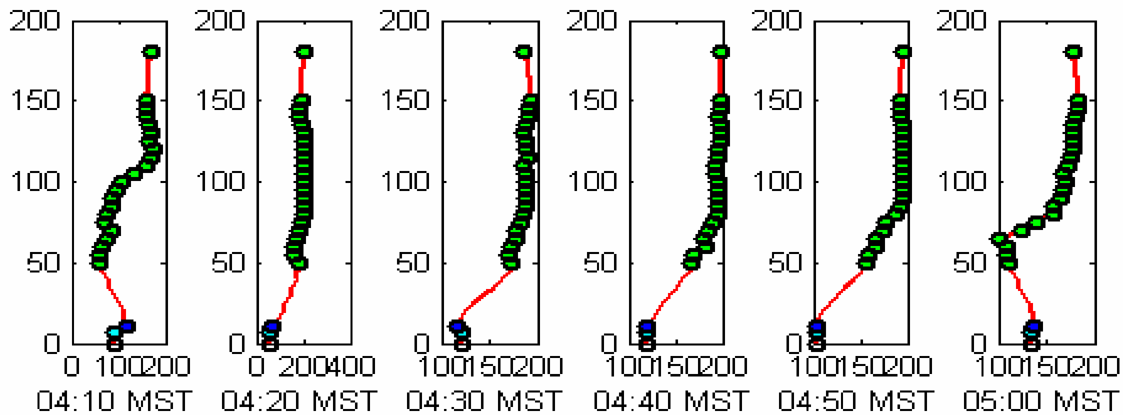


(b)

Fig. 6: 10 minute averaged inflow profile (--) constructed from the "Blue Goose" sonic measurements at 7.3 m (◯) and 11 m (◯) and the DPG Sodar (◯) for (a) wind speed (m/s) and (b) wind direction (degrees) versus height (m) for IOP 10, trial 3.

c) Model Parameters

QUIC-URB: The QUIC-URB simulations were performed using the original Röckle street canyon parameterization, no upwind parameterization, and the logarithmic rooftop parameterization. QUIC-URB version 4.0 with time-varying inflow capabilities was utilized for this study.

QUIC-PLUME: For the QUIC-PLUME simulations, 100,000 neutrally buoyant particles were released continuously at a rate of 1 g/s for IOP 10 for a time period of 3600 sec. The averaging time used to calculate the concentration was 600 s and the maximum time step allowed for the simulations was 4 s. Note that the QUIC-PLUME code adjusts the time step accordingly to satisfy the Courant condition and the Lagrangian timescale constraint. A spherical source of radius 2.5 m was used and its center was placed 2.5 m above ground level.

5. RESULTS

The winds in the downtown region during most of the URBAN 2000 experiments were extremely light. As shown in Fig. 8, the average wind speed observed at the "Blue Goose" sonic location at 7.3 m AGL varied between 0.2 and 1.0 m/s and may be partially due to this sonic being below the "urban" forest canopy height. The "Blue Goose" sonic at 11 m AGL reported nearly double the wind speed at most times (not shown here). During each trial, the wind direction varied significantly over the hour, as expected under light wind conditions (Fig. 7). During Trial 1, the winds varied nearly 100 degrees, from E-NE to S-SE. During Trial 2, the winds varied about 60 degrees over the hour, from E to SE. During Trial 3, the winds varied about 70 degrees, from NE to SE. But a prop-vane anemometer (denoted PWIDS HW) located at surface meteorological station HW, which was mounted on a light pole several meters AGL a half-block east of the release location (yellow dot on Fig. 11) shows winds that are slightly more southerly as compared to "Blue Goose" during the 1st trial. During the 2nd trial, the measurements show much greater variation in wind direction ranging from 40 to 200 degrees and during the 3rd trial the data shows wind varying from SE to SW.

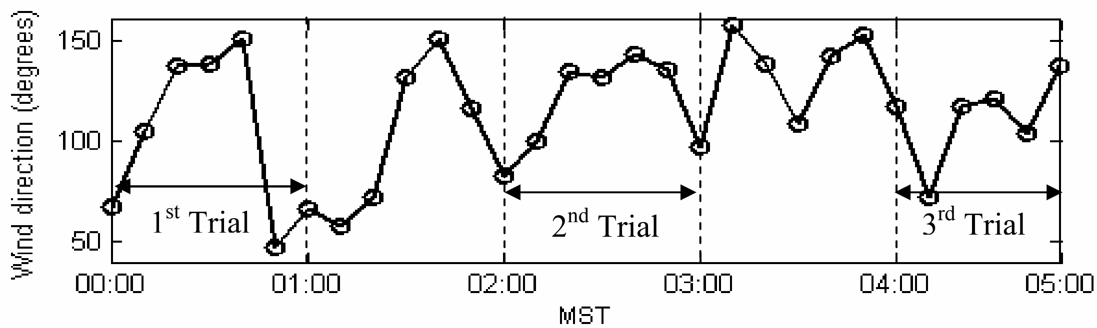


Fig. 7: Time series of surface wind direction ("Blue Goose" sonic at 7.3 m) from 00:00 MST to 05:00 MST during IOP 10.

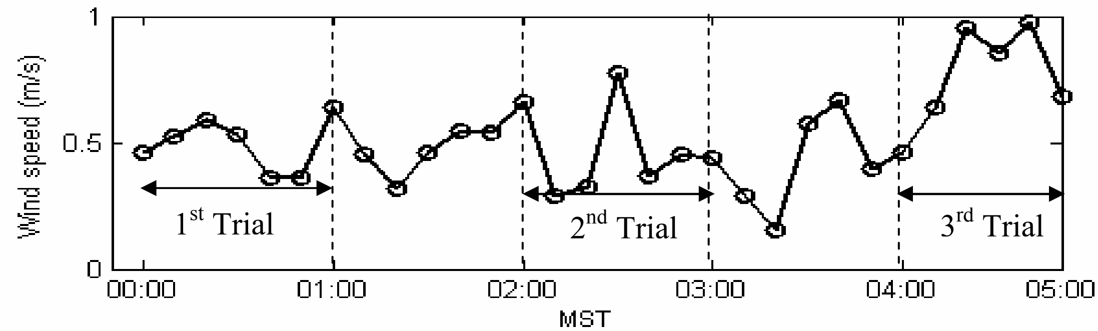


Fig. 8: Time series of surface wind speed ("Blue Goose" sonic at 7.3 m) from 00:00 MST to 05:00 MST during IOP 10.

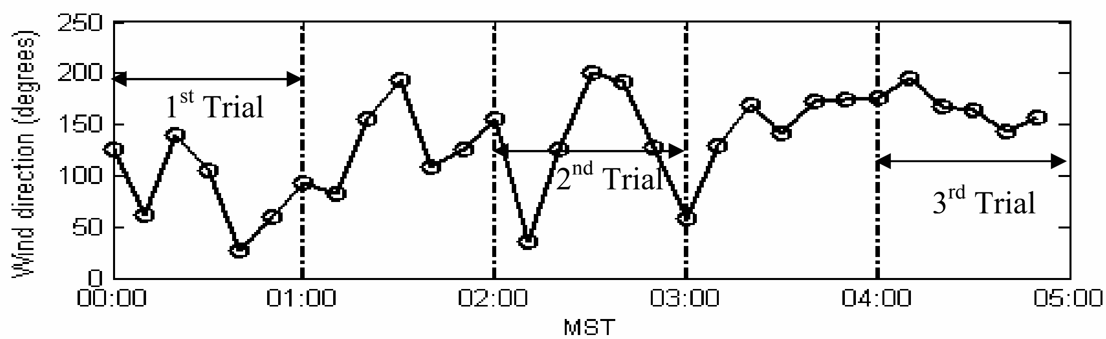


Fig. 9: Time series of surface wind direction at PWIDS HW from 00:00 MST to 05:00 MST during IOP 10.

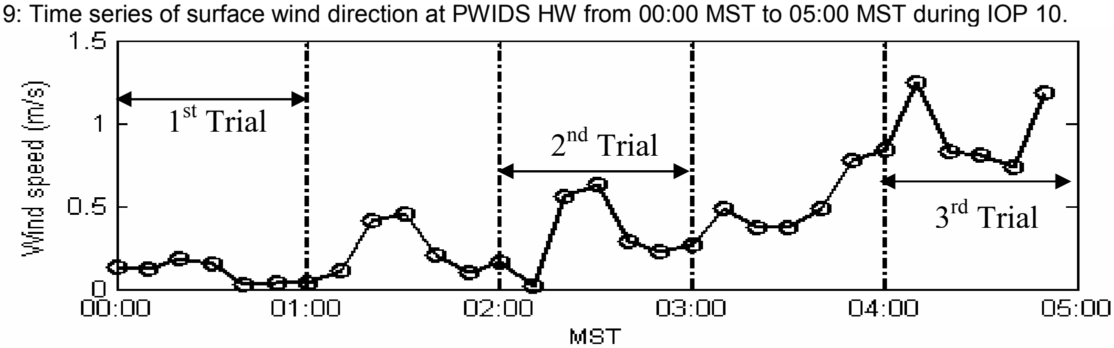


Fig. 10: Time series of surface wind speed at PWIDS HW from 00:00 MST to 05:00 MST during IOP 10.

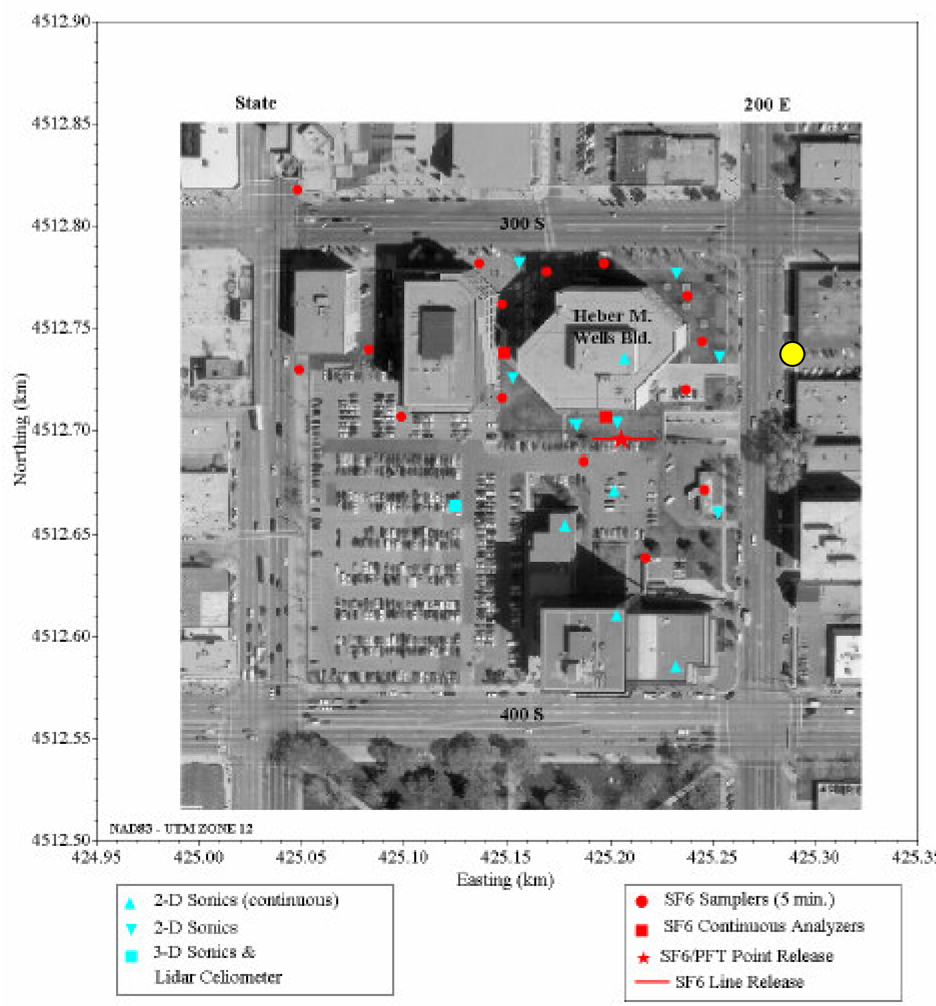


Fig. 11: The location of meteorological stations and tracer gas bag samplers for the URBAN2000 field program in the building domain (from Allwine et al. 2002) (( ) "HW" PWIDS surface met station).

5.1. Trial 1:

Figure 12a shows that the direction and expanse of plume predicted by QUIC for the 1st trial is in fairly good agreement with the observed data. Near the source, the model shows the bulk of the plume traveling due west, perhaps underestimating the amount of transport due north around the Heber-Wells building. There are a few locations along the edges of the plume a few blocks from the source where a low measurement (blue circle) is surrounded by higher model-computed concentrations (blue-greens). However, in those regions the concentration changes by a factor of 10 - 100 over less than a block distance, indicating that point-to-point comparisons on these spatial scales will be extremely difficult to match. Although one might expect significant channeling along 200E given that the prevailing winds were from 140 to 150 degrees for about 30 minutes (see Fig. 7), the measurements show that the tracer did not travel up this street. The upwind spread appears to be slightly overestimated, as the measurements show a very steep drop off of concentrations immediately south of the release but the model has the plume traveling south of the L-shaped City Centre building. But, overall, the model appears to have performed reasonably, approximating well the large width of the plume and showing similar decay of the concentrations with distance from the source. Figure 12b shows the scatter plot of all the one-hour averaged concentrations paired in both space and time for this trial. Quantitatively, around 42% of the model-computed one hour average concentrations are within a factor of 2 of the measurements and nearly 82% of the points are within a factor of 5. Note that any observed or measured values less than 1e-07 g/m3 is placed on the appropriate axis at 1e-07. Note also that number of matched zeros indicates the number of sampler locations where both the model and measurements both showed a value less than 1e-07.

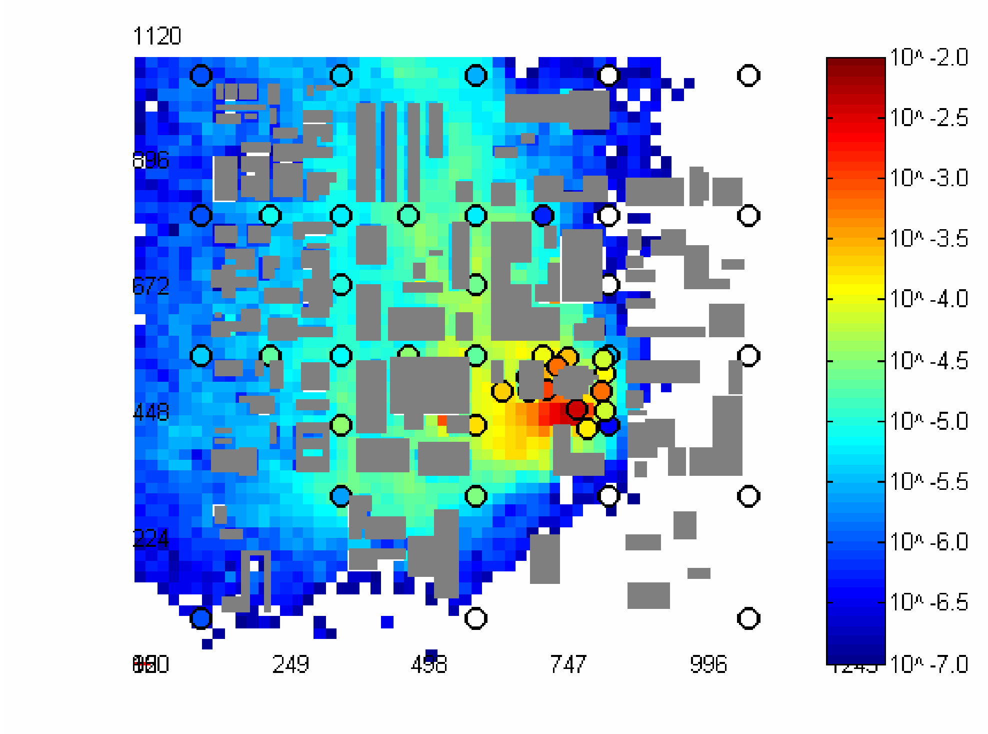
5.2. Trial 2:

Figure 13a shows that the model-computed plume appears to have underestimated the lateral spread of the plume both in the easterly and the southerly directions, as the simulation results show zero values along 300 E in the northeastern part of the domain and along 500 S in the southwestern part of the domain and the measurements clearly shown significant concentration in these areas. There might be significant channeling along 200E and 300E as the prevailing winds were from 140 to 150 degrees for about 40 minutes (see Fig. 7) and the measurements also show that the tracer did travel up this street. It is not clear why the QUIC model did not advect more material northwards given the inflow wind direction. This will be a subject of further investigation. The higher concentration of tracer observed in the southwestern part of the domain as compared to the model-computed values is also problematic. The inflow wind showed a 10 minute period of winds between 80 and 100 degrees (see Fig. 7), and although the plume did travel due west the lateral spread to the south was apparently underestimated. This may be due to inadequacies in the non-local mixing scheme or have to do the lack of intersection algorithms in the QUIC-URB wind model. Near the source, the model shows the bulk of the plume traveling due west-southwest, slightly underestimating the amount of transport due north around the Heber-Wells building.

Overall, the model appears to have performed reasonably, slightly underestimating the large width of the plume and slightly overestimating the decay of the concentrations at large distances from the source. Figure 13b shows the scatter plot of all the one-hour averaged concentrations paired in both space and time for this trial. Quantitatively, around 52% of the model-computed one hour average concentrations are within a factor of 2 of the measurements and nearly 85% of the points are within a factor of 5. The plot also shows that lower concentrations at larger distances downwind were significantly under predicted by the model. Since the lateral extent of the plume was underestimated, this suggests that vertical mixing was overestimated.

5.3. Trial 3:

From Fig. 14a, it is observed that the predicted and observed concentrations are in fair agreement with each other at the locations far from the release point, however near the release location, especially north of the release location along 200E, the predicted values are much lower. The field measurements clearly suggest that the plume is traveling north from the release location. The winds from “Blue Goose” during this trial range from NE to SE. If these winds are assumed to be true representation of upwind condition, the plume will travel north of the release location only due to channeling. If one considers the winds from the HW PWIDS station adjacent to the release block, it shows wind directions ranging from 150- 190° which is mostly SE-S which compares well with the direction of plume spread. Future studies will include comparisons of model-computed winds and measurements. It is also evident from the paired in space and time scatter plot for IOP 10-3rd trial. The scatterplot (Fig. 14b) shows that nearly 52% of the points were within a factor of 2 and around 77% of points were within a factor of 5 of the observed measurements. The scatterplot also shows that the predicted concentration near the release location is much lower than the observed concentration.



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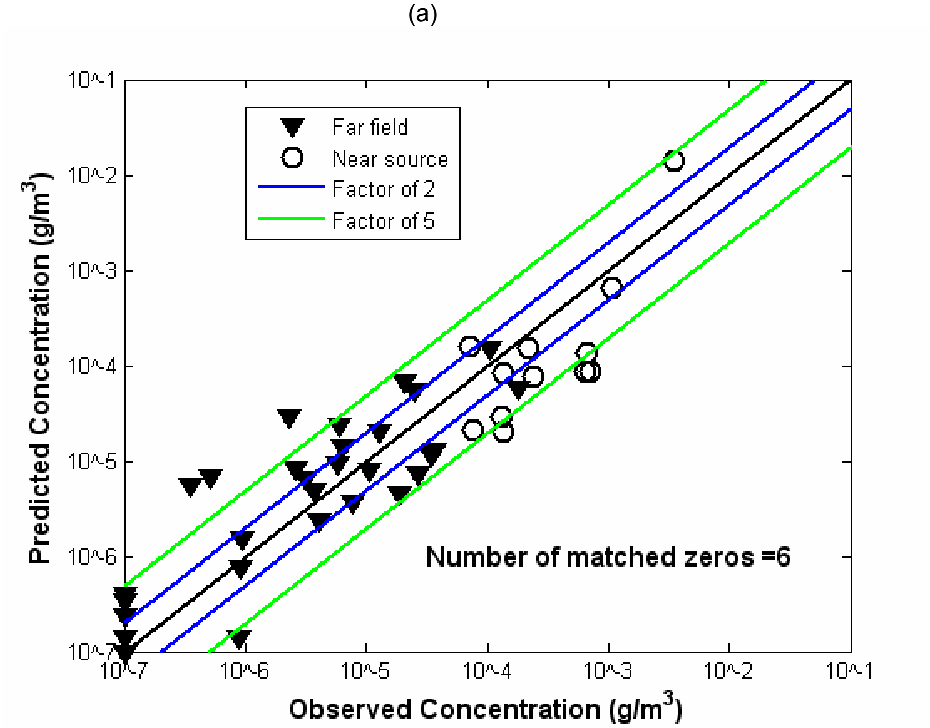
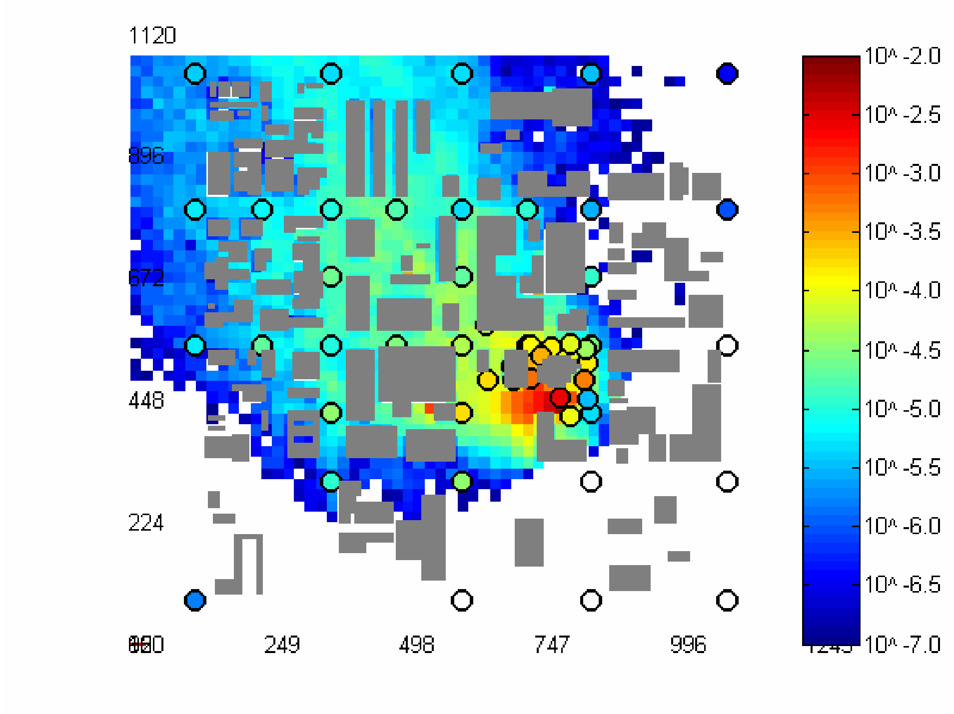


(b)

Fig. 12. One hour average concentrations for IOP 10, Trial 1: a) model-computed contours overlaid with color-filled circles showing field measurements of tracer concentration in g/m^3 and (b) paired in time and space scatter plots for predicted and observed concentrations.



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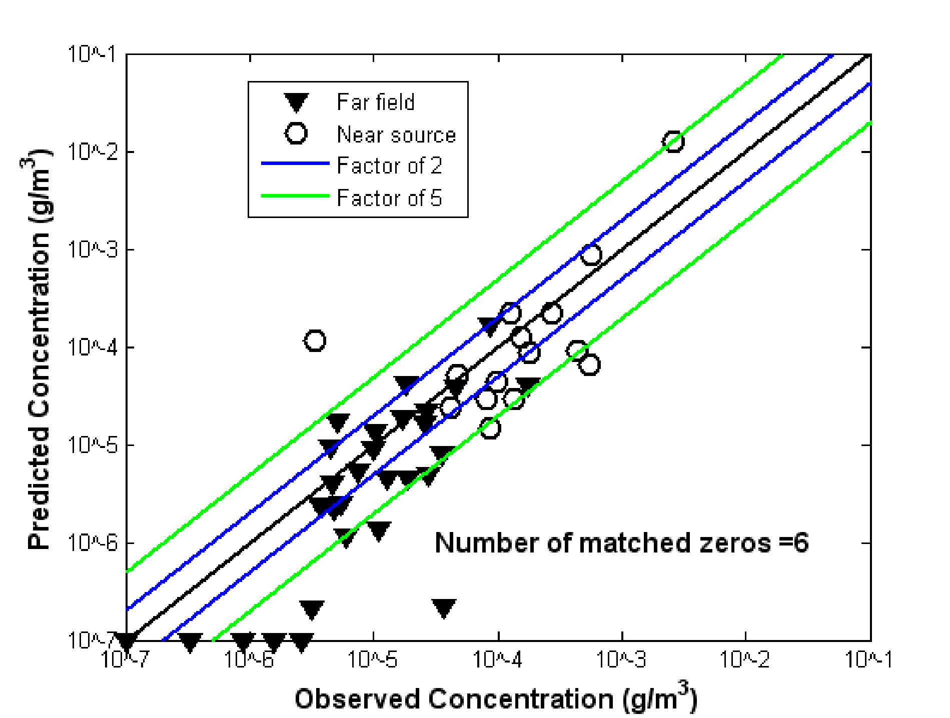
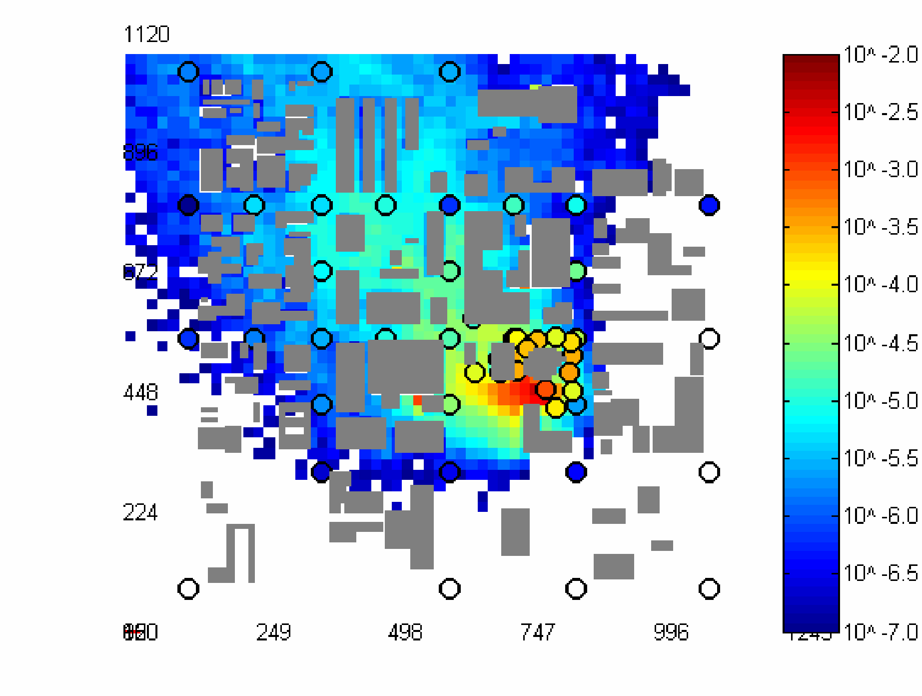


(b)

Fig. 13. One hour average concentrations for IOP 10, Trial 2: a) model-computed contours overlaid with color-filled circles showing field measurements of tracer concentration in g/m^3 and (b) paired in time and space scatter plots for predicted and observed concentrations.



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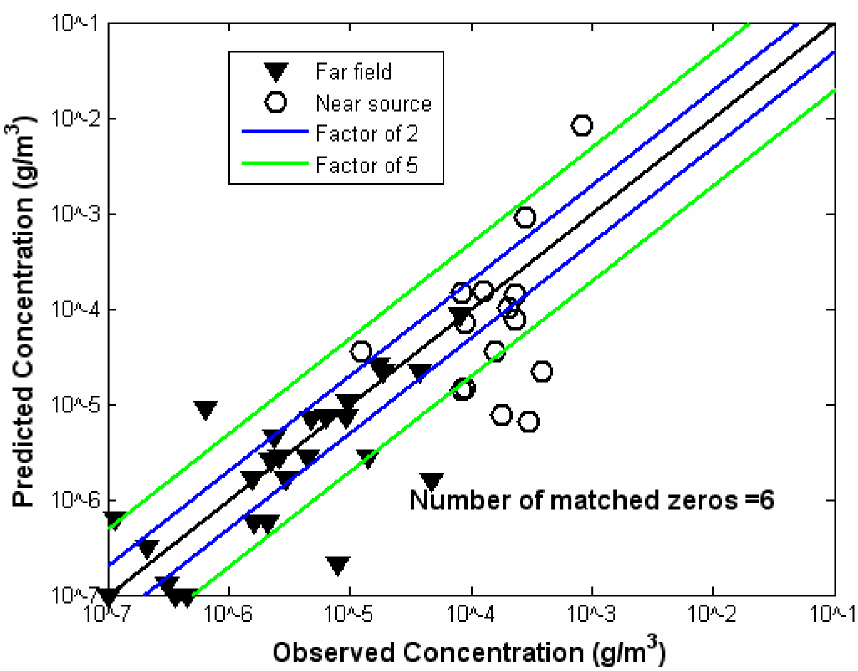

(b)

Fig. 14. One hour average concentrations for IOP 10, Trial 3: a) model-computed contours overlaid with color-filled circles showing field measurements of tracer concentration in g/m^3 and (b) paired in time and space scatter plots for predicted and observed concentrations.

6. CONCLUSIONS

From our study, we can conclude that the QUIC model performed reasonably. The lateral spread of the plume was in good agreement for trial 1, and was slightly underpredicted for trials 2 and 3. The predicted 1-hour averaged concentrations obtained from QUIC were within a factor of two of the measurements 50% of the time. Although not shown here, significant improvements were observed in the model-predicted results by using a time-varying inflow profile instead of using a steady-state profile over the entire hour. The lack of a parameterization for intersections in QUIC-URB, underestimation of non-local mixing in QUIC-PLUME and omission of trees in the domain may have degraded the performance of the model. In addition, the construction of the upwind profile to drive the model was marked with difficulties due to lack of measurements, especially between surface level and 50 m AGL. As an inference of the results obtained during this study, it can be said that the performance of any model is strongly correlated to the prescribed inflow; therefore it would prove to be advantageous to have many measurement locations which can used to derive an upwind profile which is free of local effects

7. REFERENCES

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