Observations of Complex Behavior in Nearly Idealized Urban Transport and Dispersion

Matthew Nelson, Ph.D.
Group A-1 Information Systems & Modeling

Introduction

Urban areas affect the mean and turbulent flow characteristics of the atmospheric surface layer. Subsequently, atmospheric transport and dispersion of contaminants in urban areas is far more complex than it is over open terrain, particularly in the region near the source. Not only will the buildings act to enhance turbulence and therefore the turbulent diffusion of the contaminant, but phenomena such as channeling and recirculation can significantly affect the lateral spread and duration of the plume. There is a large range of scales that affect the flow structures in urban areas. There are neighborhood-scale flow structures that involve multiple buildings such as the street-canyon vortex and channeling. The size of the flow structures around individual buildings (i.e., downwind cavity, wake, rooftop vortices, side-wall vortices, and upwind vortices) will depend on the dimensions of the building. The size of individual buildings can vary by two to three orders of magnitude between those found in the suburbs to the tallest skyscrapers, causing some overlap between the neighborhood-scale and the building-scale flow structures. The effect of these flow structures on the plume dispersion is dependent on the relative scale of the plume compared to the scale of the flow structures.

Academic studies of urban flow and transport and dispersion usually focus on highly idealized conditions. Countless studies of both simulations and wind-tunnel models involve perfectly two-dimensional street canyons with steady wind speed and wind direction exactly perpendicular to the street canyon. The Joint Urban 2003 field campaign includes a continuous plume release, intensive observation period 6 release 2 (IOP6-R2), under nearly ideal conditions. IOP6-R2 took place on 16 July 2003 from 1100 to 1300 CDT and had steady 15-minute averaged wind speed and direction with an average wind direction within about 10 degrees of perpendicular to the street canyons over the course of the two-hour period.

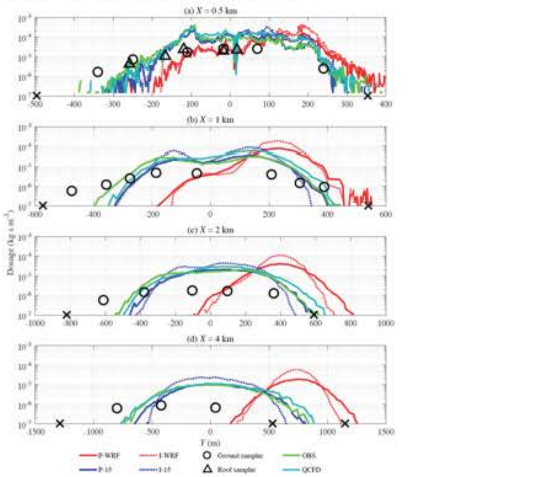

Figure 1. Terrain-following airborne dosage collected on 16 July 2003 from 1100 to 1300 CDT along the 0.5-km (a), 1-km (b), 2-km (c), and 4-km (d) sampling arcs compared with dosage simulated by the QUIC system. Note that the lateral scale of the plots changes from arc to arc in order to show as much detail as possible on each arc.

Discussion

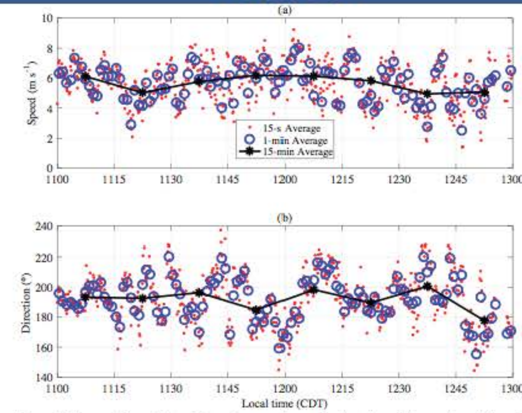

Figure 2. Comparison of the effect of averaging period on the wind speed and direction for the time period of 1100 to 1300 CDT 16 July 2003.

Figure 1 shows the dosage arcs for IOP6-R2 using several different Quick Urban & Industrial Complex (QUIC) simulations using both WRF- and observation-based meteorology. The simulations tend to overpredict the observed dosage values. In spite of the idealized conditions, none of the simulations accurately predicts the rapid lateral spread on the western side of the plume. The OBS simulation, which accounted for the small-scale spatial variations in the wind field, was closest to reproducing the plume observations. A closer examination of the wind speed and direction observations (see Fig. 2) indicates that the steady 15-min average wind direction is actually due to oscillating over smaller time scales. The wind direction had a 15-min period during the first 15 min of the release and 7-min period during the last 15 min of the release. Outside of the urban core, one would naturally consider these motions as large-scale turbulence, however it is less obvious how these types of oscillations should be treated within the urban core.

The QCFD simulation uses 1-min average observations and a simplified CFD wind solver instead of the QUIC-URB empirical-diagnostic wind solver to simulate the flow around the buildings. Figure 3 shows the near-surface dosages from the inner-grid from, (left) the OBS simulation using the 15-min averaged spatially-varying observations, and (right) the QCFD simulation using 1-min averaged wind observations. The oscillations around a nominally perpendicular wind direction will cause the channeling flow through the street canyons to switch directions and potentially causing complex interactions and enhanced vertical mixing. The overestimation of the effects of channeling on the eastern edge of the plume might be due to the fact that individual wind time steps in the QUIC system are generated as if the wind field is in a steady state. At 1-min time scales, the wind field will certainly not be in a steady state throughout the urban core. The flow that channels down the long street canyons may run into the flow that begins to enter the other end of the street canyon. Such an interaction could produce large updrafts, as there would temporarily be a convergence zone, where the two masses of air run into each other.

Conclusions

IOP6-R2 had very steady 15-, 30-, and 60-min averaged wind directions that were nearly perpendicular to the predominant street-canyon direction, but oscillations were observed in the wind direction with a period ranging between 7 and 15 min over the release. This likely contributed to the rapid near-source plume spread and lower peak dosages that none of the simulations were able to replicate, even when using the 1-min averaged winds and the higher-fidelity QUIC-CFD wind simulations. While these oscillations would normally be treated as large-scale variability in undisturbed surface-layer flow, the scales imposed on the flow by the buildings within the urban core make treating these oscillations as large-scale turbulence inappropriate within the urban canopy. It is possible that oscillations in the prevailing wind direction may cause complex interactions as the flow oscillates back and forth in the street canyons. It would be instructive to investigate whether or not a large-eddy simulation would be able to accurately predict the observed behavior of this release. Large-eddy simulation has the potential of reproducing the complex transient flow interactions that the oscillations in the prevailing wind direction could produce within the street canyons and therefore might be able to simulate the low near-surface dosage levels. Other complex phenomena such as infiltration into and subsequent exfiltration out of the underground parking garage just north of the Botanical Gardens (northwest of the source) due to the ventilation systems that are typically used in these structures may also be a factor in producing the observed lateral plume spread. Both possible explanations for the overprediction of simulated near-surface dosages should be further investigated in the future.

The complex behavior found during JU2003 IOP6-R2 calls into question the applicability of the highly idealized urban street canyon studies. The details that are usually neglected, such as wind meander, non-perpendicular wind direction, and possibly infiltration/exfiltration of individual buildings and structures can have significant effects on the near-source transport of contaminants in urban environments. These near-source effects can propagate several km downwind and can cause significant errors in the prediction of hazard zones.

The work presented here is based on excerpts from:

Nelson et al. 2016: A Case Study of the Weather Research and Forecasting Model Applied to the Joint Urban 2003 Tracer Field Experiment. Part 2: Gas Tracer Dispersion, B-Layer Meteor., 161, Issue 3, pp 461–490.

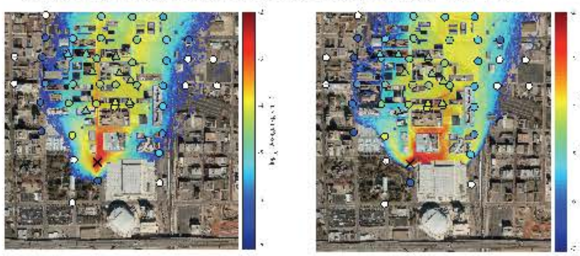

Figure 3. Comparison of observed and simulated dosages from the release from 1100 to 1130 CDT 16 July 2003 using 15-minute average observations (left) and 1-minute .average observations (right). Note the large amount of lateral spread to the northwest of the source.