4.1 OBSERVED TRACER CONCENTRATIONS IN DOWNTOWN OKLAHOMA CITY AND MANHATTAN – VARIATIONS WITH DOWNWIND DISTANCE AND RATIOS OF ROOFTOP TO SURFACE CONCENTRATIONS

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ABSTRACT

This paper focuses on some straightforward similarity formulas that can be used to describe urban tracer gas concentration observations, such as the simple power law for the decrease of maximum concentration with distance, and the ratio of rooftop to surface concentrations in the near field. Observations from the two Manhattan field experiments (Madison Square Garden 2005 or MSG05 and Midtown 2005 or MID05) and from the Oklahoma City Joint Urban 2003 (JU2003) field experiment are included in the analysis. Six different tracer gases were released at a rate, Q (g/s), from continuous point sources near street level during MSG05 and MID05. SF_6 tracer gas was released during JU2003. Concentrations, C (g/m^3), were observed by many samplers at street level and on building tops, including several tall skyscrapers. It is found that, at downwind distances, x, out to about 1000 m (or about ten times the mean building height H), the maximum concentration, C, varies with distance, x, according to the power law $CuH^2/Q = A/(x/H)^2$. The wind speed, u (m/s), represents the average wind in the lower part of the urban canopy. The "constant" A is found to equal about 10 at night and about 3 during the day. At distances of less than about 100 m from the source, the ratio of rooftop (100 to 250 m) to surface concentrations is usually in the range from 0.01 to 0.05, where the large amount of vertical spread is due to the large recirculating eddies adjacent to the tall buildings.

1. OBJECTIVES

The objective is to improve the accuracy of transport and dispersion models in urban downtown areas. Towards this end, it is useful to analyze urban field observations in order to develop a scientific understanding of physical processes. The current paper analyzes tracer observations from the Joint Urban 2003 (JU2003), Madison Square Garden 2005 (MSG05) and Midtown 2005 (MID05) urban field experiments. We investigate two key aspects of the behavior of the concentrations – i) the variation with downwind distance, x, of the maximum normalized surface concentration, $C_s u/Q$, and ii) the variation with downwind distance of the ratio of the skyscraper rooftop to the surface concentrations, C_r/C_s. Here C_s and C_r are the surface and rooftop concentrations in μg/m^3, respectively, u is the wind speed (m/s) observed near street level, and Q is the tracer release rate in g/s. The concentration averaging time is usually 30 min.

2. DESCRIPTION OF THREE FIELD EXPERIMENTS

The JU2003, MSG05, and MID05 urban field experiments are part of a series of recent DOE, DTRA, and DHS – sponsored studies to improve scientific knowledge and transport and dispersion modeling of toxic materials released to the atmosphere from instantaneous or continuous point sources near ground-level in the built-up downtown areas of large cities in the U.S. Because the details of the field experiments are discussed by the experiment scientific managers (JU2003 by Allwine and Flaherty 2006a; MSG05 by Allwine and Flaherty 2006b; and MID05 by Allwine and Flaherty 2007), here we simply describe the concentration observations used in the current paper.

The JU2003 field experiment in Oklahoma City included ten days (IOPs) of SF_6 tracer releases. There were both continuous and instantaneous releases. Concentrations were observed at a broad network of surface and rooftop samplers, at distances ranging from very close to the source to 4 km away (Allwine and Flaherty, 2006a). **Figure 1** shows the 1.1 by 1.1 km downtown domain and the sampler locations for IOP02. For IOP02, the near-surface point source was near the Westin Hotel at the red star near the center of the figure. Several buildings in the domain have heights exceeding 100 m.

The MSG05 and MID05 field experiments took place in Manhattan in March and August 2005 IAllwine and Flaherty, 2006b and 2007). **Figure 2** is a photo of the Midtown domain, looking north from the Empire State Building. **Figures 3 and 4** show the five PFT source locations (A, B, C, D, and E) and the surface and rooftop (indicated by V) sampler locations in the MSG05 domain, respectively. Madison Square Garden is the circular building in the center. Many of the surface samplers are sited approximately along circles at distances of about 100 m and 200 m from the

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source. There were two 30 minute releases during the mornings of 10 and 14 March.

Figure 5 shows the 2 km by 2 km MID05 domain. Source locations are indicated by yellow stars and letters. Depending on the wind direction, different source locations were used. Three types of samplers are indicated by crosses on the figure. **Figure 6** zooms in on the 1 km by 1 km inner domain and shows the rooftop samplers (symbols starting with "R") that we analyzed. Most of these are at heights exceeding 100 m and some are at heights exceeding 200 m. **Figure 7** is the same domain as Figure 6 but includes both the rooftop and near-surface sampler locations.

3. CONCENTRATION DECREASE WITH DISTANCE

Because there were many near surface samplers available during the field experiments, and they usually were able to capture the maximum (plume centerline) concentration during each release trial, it is possible to study the variation of maximum concentration with downwind distance, x. Several authors (e.g., Britter and Hanna 2003; Venkatram 2004; Hanna et al. 2003, 2004, 2007 and 2009; Neophytou et al. 2005) suggest a simple scaling relation:

$$C_{max}uH^2/Q = A/(x/H)^2 \quad (1)$$

where C_{max} is the maximum concentration in g/m^3 at distance x, Q is the continuous source strength (g/s), u (m/s) is the wind speed in the lower part of the urban canopy, H is mean building height, and A is a dimensionless scaling constant, of order one. Since H^2 appears on both sides of the equation, in most cases we simply plot log ($C_{max}u/Q$) versus log x, and look for the existence of a minus 2.0 slope, plus the value of the constant A. This procedure is applied below to several urban tracer data plots.

3.1 JU2003, DAPPLE, and Urban 2000

Hanna et al. (2007) plotted $C_{max}u/Q$ versus x for the 6 daytime and 4 nighttime IOPS at JU2003 (**Figures 8 and 9**, respectively). The London DAPPLE observations (from Neophytou et al., 2005) are plotted on the daytime graph (**Figure 8**), and the Salt Lake City Urban 2000 (U2000) are plotted on the nighttime graph (**Figure 9**) as single points at the various distances x. It is seen that, for the daytime observations, the relation in eq. (1) is valid from 0.1 to 4 km, with a constant "A" of about 3 or 4 fitting the observations. For the nighttime observations, the relation (with a constant "A" of about 10) holds out to about 1 km (about 10H), in agreement with guidance from Neophytou et al (2005). Beyond 1 km, the C does not decrease as rapidly, probably because of the influence of stability in the suburbs.

3.2 MSG05 and MID05

The MSG05 and daytime JU2003 (OKC) observations are plotted in **Figure 10**. This figure is the same as **Figure 8** except that the DAPPLE observations are not included and the MSG05 observations (with C_{max} averaged over all four release periods and tracers at each x) are included. The power law constant A = 4 is drawn on the figure and is seen to agree with the MSG05 observations as well as the JU2003 observations.

Figure 11 contains six panels, where each panel represents one of the tracer gases at MID05. Here all C/Q observations are plotted, including those that are not on the plume axis. However, as argured by Neophytou et al. (2005) in their analysis of DAPPLE field and laboratory observations, the top envelope of the cloud of points in each panel represents C_{max}. In agreement with equation (1), a line with slope -2 can be seen to agree with the top envelope in these panels. Assuming that the average wind speed in the lower canopy is 1.5 to 2 m/s. then the top envelope in each panel is fairly well fit by A = 4, as with the other daytime sites.

The five independent urban field experiments all show agreement with the simple power law relation in equation (1) with a constant "A" of about 4 during the day and about 10 during the night.

4. ROOFTOP/SURFACE CONCENTRATIONS

The question arises of the amount of vertical dispersion taking place in the urban downtown area, where there are many tall skyscrapers. The JU2003, MSG05, and MID05 field experiments included several concentration observations on tall skyscraper roofs (or on setback roofs partway up the sides), as well as observations at street level near the base of the skyscrapers. For example the rooftop samplers are marked as "V" in **Figure 4** for MSG05 and as "R" in **Figures 5 and 6** for MID05.

Since there was not a deliberate design of rooftop-surface sampler pairings in these field experiments, we have assigned the nearest surface sampler to a rooftop sampler. This occasionally leads to seemingly odd results, such as when the release location is between the assigned surface and rooftop samplers, or when the surface sampler is in an E-W street, while the skyscraper with the rooftop sampler is on a N-S street and the wind is from the south. We eliminated these cases from the analysis after review of the entire set of possible pairings and considering the wind direction, source location, and relative positions of the rooftop and surface samplers.

The MSG05 and MID05 tracer sampler observations included many cases where two tracers were released at the same location and where several tracer concentrations were sampled at the same location. Comparisons of these collocated tracers and samplers can allow estimation of the sampling uncertainty. Some results for MID05 are summarized here. This is somewhat complicated by the fact that the five different

PFT tracers and the SF6 tracer have different thresholds for concentration. Thus it was not possible to determine uncertainties at low concentrations. At high concentrations, we compared normalized concentrations, C/Q, generally for values exceeding 1000 μs/m^3. There seemed to be a steady improvement from one IOP to the next as the six IOPs progressed. For IOP2, about 50 % of the collocated comparisons showed differences less than a factor of two. By IOP5 and IOP06, 50 % of the comparisons showed differences less than about 10 to 20 %, with little mean bias.

JU2003 Rooftop/Surface Ratios – We analyzed concentration observations from rooftop samplers for Release 2 in IOP08 (nighttime)), when the source was at the "Westin" location in the middle of the area of tall skyscrapers (see **Figure 1**). Of the 22 ARL FRD samplers, 10 were at rooftops (from z = 18 to 115 m). Of 20 LLNL Blue Box (near-field) samplers, 9 were at rooftop (from z = 12 to 148 m). The 23 surface samplers were at heights of 1.5 m (ARL FRD) and 1 m (LLNL Blue Box). Five rooftop samplers (with height averaging about 40 m) were close together near Park Avenue, about 170 m from the source and close to the plume centerline. They indicated C of about 16,000 ppt, while two nearby surface samplers indicated an average of 14,000 ppt. Thus the ratio of 40 m rooftop to surface C is close to unity at x = 170 m.

The two tallest buildings with samplers during IOP08 are:

1) The Bank One building (z = 148 m) is located 82 m NNE of the release, on the east edge of the plume. Observed C is 2790 ppt while the nearby surface concentration is about 21000 ppt, giving a ratio of rooftop to surface concentration of about 0.13.

2) The Kerr-McGhee building (z = 115 m) is located 320 m NNW of the release and on the plume centerline. C at rooftop is 1865 ppt, which is about a factor of four less than the C of 7230 ppt at street level. Thus the ratio of rooftop to surface concentration is about ¼ for this tall building.

As expected, the ratio of rooftop to surface concentrations depends on distance downwind and building height, for samplers that are close to the plume centerline. In the near field, the ratio is about 0.15 at a very tall building. At a distance of 320 m, the ratio is about 0.25 for another very tall building. For buildings of height less than about 50 m, the ratio quickly approaches unity as distances increase beyond about 100 or 200 m. This is clearly relevant for emergency response planning, since it is clear that the public will not be "safe" even if climbing to the rooftops of skyscrapers. Note that the analysis reported here is for a nighttime case, when the ratio of rooftop to surface concentrations should be minimized.

MSG05 Rooftop/Surface Ratios – There were two rooftop samplers (on the S and N sides) of the One Penn Plaza (OPP) building roof (z = 223 m) and they gave average normalized (C/Q) concentrations of 0.84 and 5.78 μs/m^3, respectively. This is for the two days with two releases each day and for four PFT releases around MSG (across the street from OPP), at distances away of about 40 to 150 m. **Figure 3** shows the release locations and **Figure 4** shows the sampler locations. With a surface concentration of 86 μs/m^3, this gives an average ratio of rooftop to surface concentration of 0.038. The Two Penn Plaza building (z = 153 m) was nearby and the observed ratio of rooftop to surface concentration was 0.058. Thus for these four daytime release periods during moderate winds in March, the ratio of Manhattan rooftop to surface concentrations is about 0.05 for very tall buildings in the near field.

MID05 Rooftop/Surface Ratios – There were many rooftop and surface samplers, and many release locations during MID05 (see **Figures 5 – 7**). For this paper, we have selected a few rooftop-surface pairings as examples.

In the near field (x < 100 m) there is a wide array of ratios of rooftop to surface concentrations, probably depending on the locations of the samplers and the building recirculating vortices. For cases where the surface concentration is high (C/Q > 1,000,000 μs/m^3), the ratio is in the range from 0.003 to 0.05. The largest magnitude ratio in this class is 0.05 for PMCP for IOP4 for rooftop sampler R10 (Lehmann Bros SE at z = 168 m) and surface sampler 29, which are about 90 m from the CL source.

The largest rooftop concentration (about 200,000 μs/m^3) occurred during IOP03 for PTCH at sampler R08 (1270 Ave Am. at z = 127 m), about 90 m from the CR source. The ratio R08/37a = 2, indicates much vertical mixing. It should be noted that several rooftop concentrations exceeding 50,000 μs/m^3 were observed during MID05, which are relevant to emergency response guidance.

At distances beyond 100 to 200 m, the ratio quickly increases, such that it approaches 0.2 to 0.5 at x = 200 or 300 m, and unity at 400 to 600 m. In many cases the ratio is larger than 1.0, and this sometimes reflects the fact that the tracer plume has lofted above the buildings and is transported downwind by the upper air flow rather than by the street-level flow. Thus the plume at the building tops may move faster towards a rooftop sampler, while the street-level plume is retarded or is advected in a slightly different direction.

From the point of view of practical guidance for persons in the path of the plume, or for persons giving emergency response guidance, it is found that skyscraper rooftop concentrations may be dangerously high and it is not "safe" for persons to walk or take elevators to higher levels of skyscrapers. The rapid vertical mixing in the city causes tracer material to be quickly transported and dispersed to rooftops of skyscrapers.

5. FURTHER COMMENTS

The analysis of tracer observations at several built-up downtown urban areas shows consistency in basic physical relations from one city to another. However, there needs to be work to show how these relations change as the buildings become less tall and less dense.

The simple urban dispersion model described by Hanna and Baja (2009) approaches equation (1) at distance away from the initial street canyon, yet distances not so far that the plume passes out of the built-up downtown area. At small distances, as the near surface point source is approached, the initial maximum concentration can be calculated given assumptions about initial plume size. Hanna and Baja (2009) suggest an initial minimum plume width and height of about 20 m. This gives an initial C_{max} of $Q/u(20\ m)^2$. Thus as x approaches 0, the maximum of $C_{max}u/Q$ approaches about 0.0025 s/m^3 or 2500 $\mu s/m^3$. This is close to what is seen in Figure 11 for MID05, which is the only field experiment in this paper where concentrations were observed and reported very close to the source.

ACKNOWLEDGEMENTS

This research has been sponsored by the Defense Threat Reduction Agency, with Rick Fry as project manager and by the JEM IV&V office, with Brian Boyle as project manager. Additional support is from National Science Foundation under grant 0750878 to the Harvard School of Public Health.

REFERENCES

Allwine, K.J. and J.E. Flaherty, 2006a: Joint Urban 2003: Study Overview and Instrument Locations. Pacific Northwest National Laboratory, Report no. PNNL-15967, 92 pp.

Allwine, K.J. and J.E. Flaherty, 2006b: Urban Dispersion Program MSG05 Field study: Summary of Tracer and Meteorological Measurements. Pacific Northwest National Laboratory, Report no. PNNL-15969, 27 pp.

Allwine, K.J. and J.E. Flaherty, 2007: Urban Dispersion Program Overview and MID05 Field Study Summary. Pacific Northwest National Laboratory, Report no. PNNL-16696, 63 pp.

Allwine, K.J., J.H. Shinn, G.E. Streit, K.L. Clawson and M. Brown, 2002: Overview of Urban 2000, A multiscale field study of dispersion through an urban environment. *Bull. Am. Meteorol. Soc.*, **83**, 521-536.

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

Hanna, S.R. and E. Baja, 2009: A simple urban dispersion model tested with tracer data from Oklahoma City and New York City. *Atmos. Environ*. **43**, 778-786.

Hanna, S.R., E. Baja, J. Flaherty and J. Allwine, 2007: Use of tracer data from the Madison Square Garden 2005 experiment to test a simple urban dispersion model. Paper 4.1, AMS Urban Environ. Conf. www.ametsoc.org

Hanna, S.R., R.E. Britter, and P. Franzese, 2003: A baseline urban dispersion model evaluated with Salt Lake City and Los Angeles Tracer data. *Atmos Environ*. **37**, 5069-5082.

Hanna, S., P. Fabian, J. Chang, A. Venkatram, R. Britter, M. Neophytou and D. Brook, 2004: Use of Urban 2000 field data to determine whether there are significant differences between the performance measures of several urban dispersion models. Paper 7.3, AMS Fifth Conference on Urban Environment, www.ametsoc.org

Hanna, S.R., J. White and Y. Zhou, 2007: Observed winds, turbulence, and dispersion in built-up downtown areas in Oklahoma City and Manhattan. *Bound.-Lay. Meteorol*. **125**, 441-468.

Neophytou, M.K., R. Britter, D. Martin, C. Price, G. Nickless and D. Shallcross, 2005: Results from a tracer field experiment in London (UK) and comparisons with predictions from urban dispersion models. Proceedings of the 5th International Conference on Urban Air Quality, Valencia, March 29-31, 2005. Editors: R. Sokhi, M. Milan and N. Moussiopoulos.

Venkatram, A., V. Isakov, D. Pankranz, J. Heumann and J. Huan, 2004: The analysis of data from an urban dispersion experiment. *Atmos. Environ*. **38**, 3647-3659.

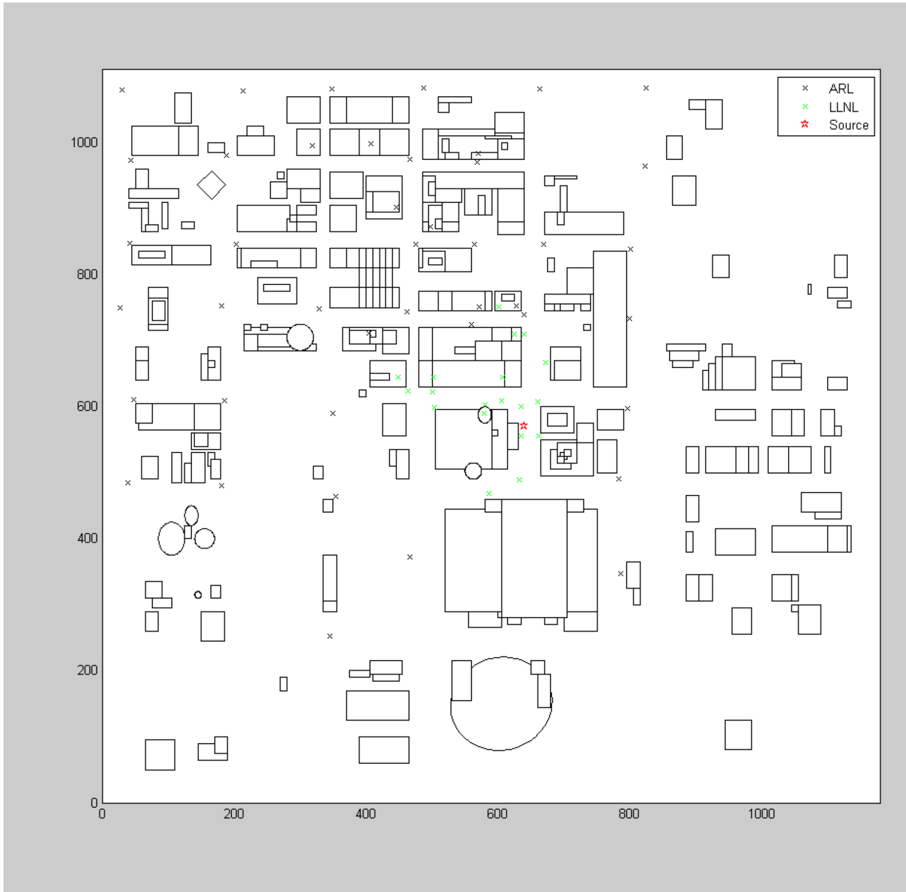

Figure 1. Locations of SF_6 source (red star) and samplers (x's) on downtown JU2003 modeling domain during IOP02.

Figure 2. Manhattan domain for MSG05 and MID05 field experiments. Looking north from Empire State Building.

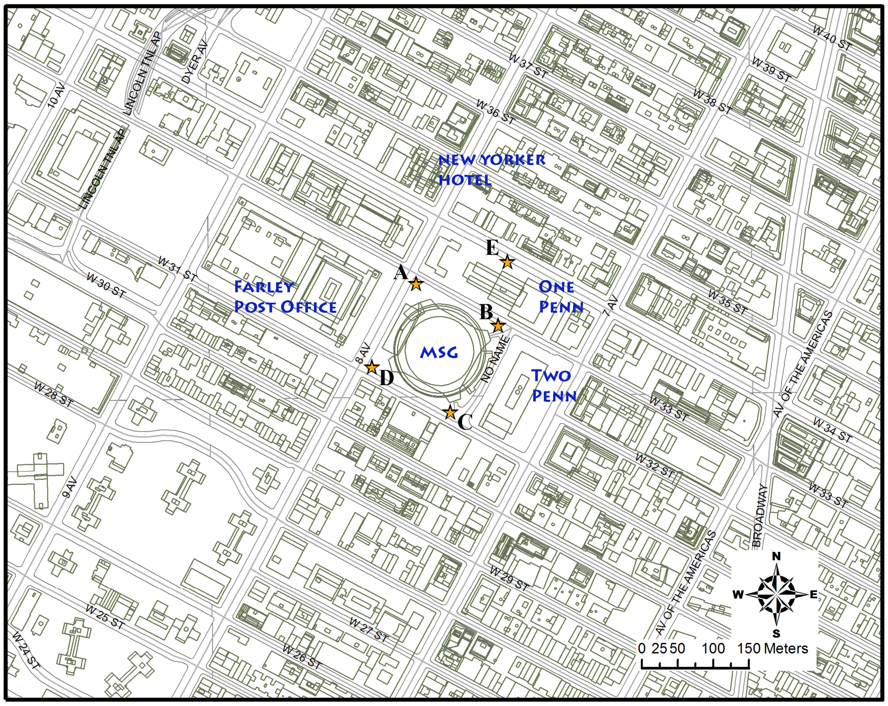

Figure 3. MSG05 tracer release locations (yellow stars).

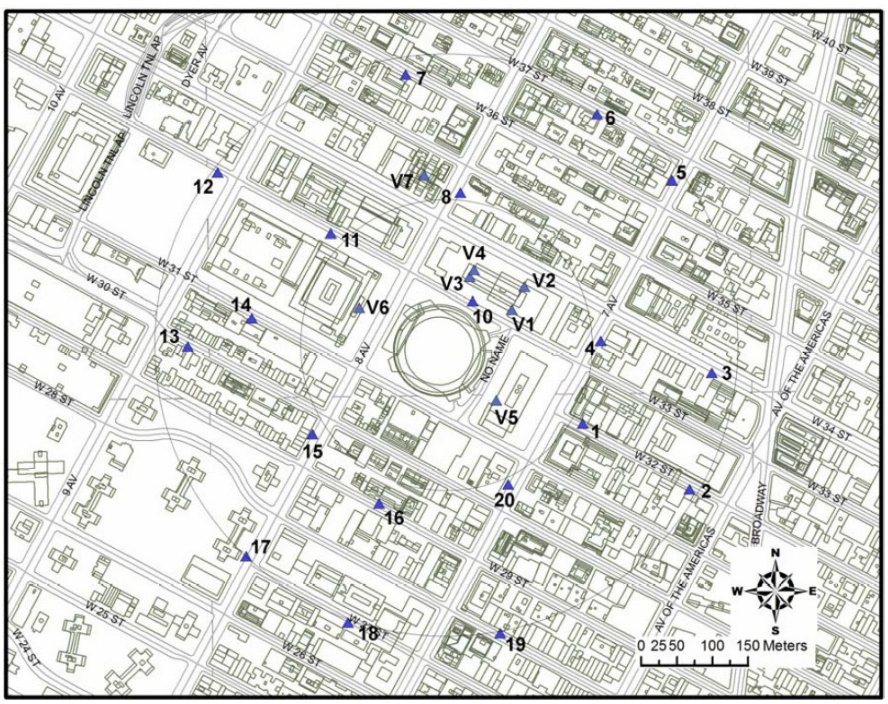

Figure 4. MSG05 Sampler locations. “V” indicates a rooftop sampler.

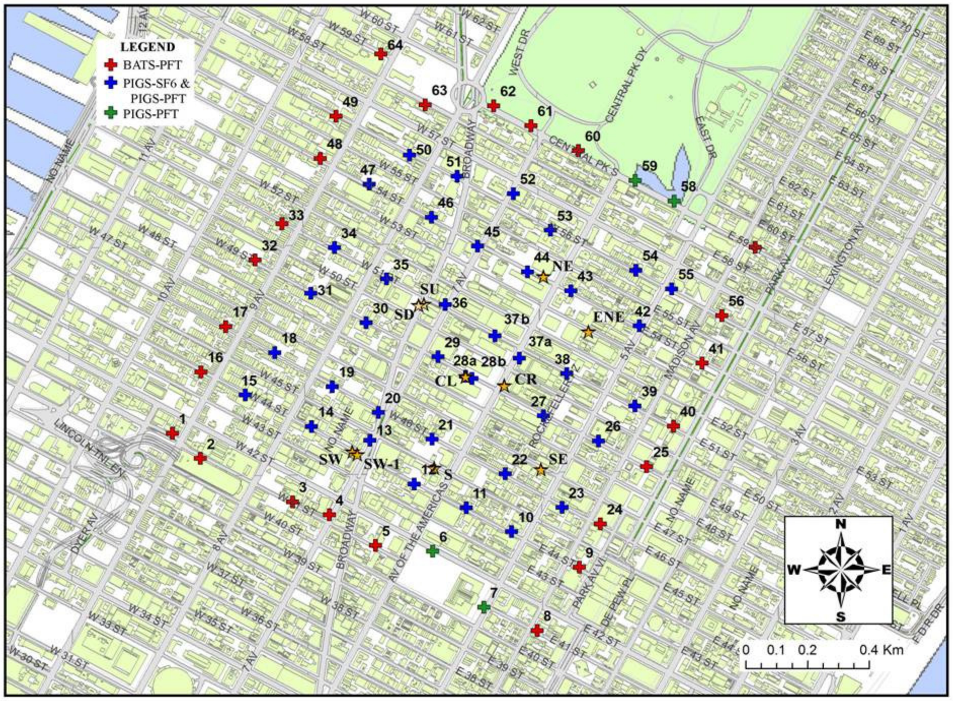

Figure 5. MID05 tracer release (yellow stars) and surface tracer sampling locations

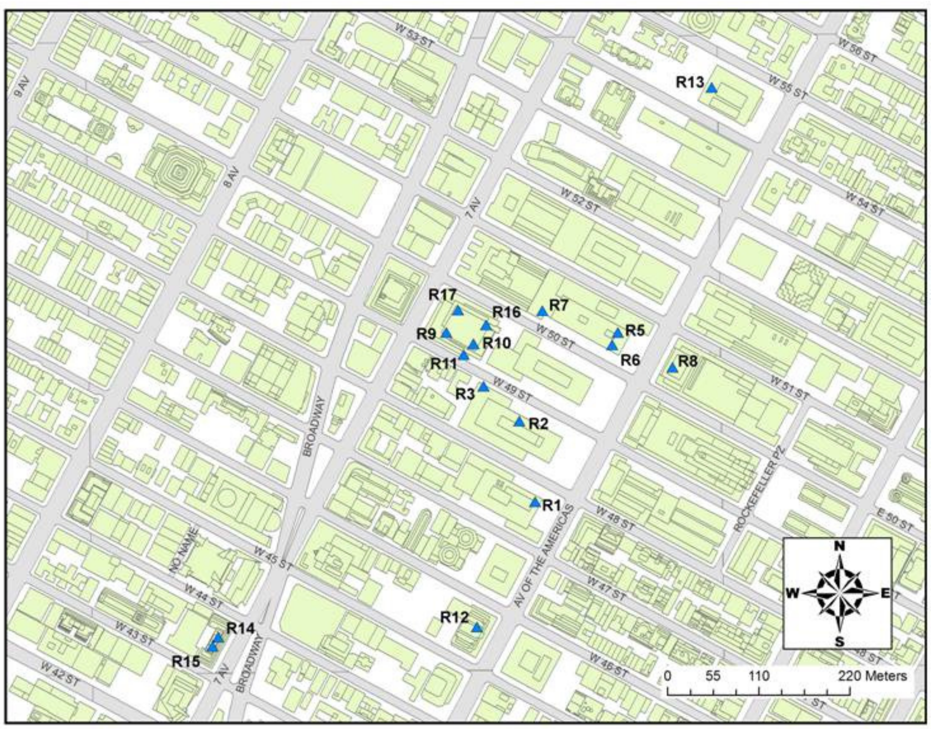

Figure 6. MID05 rooftop sampler locations (28 to 197 m agl).

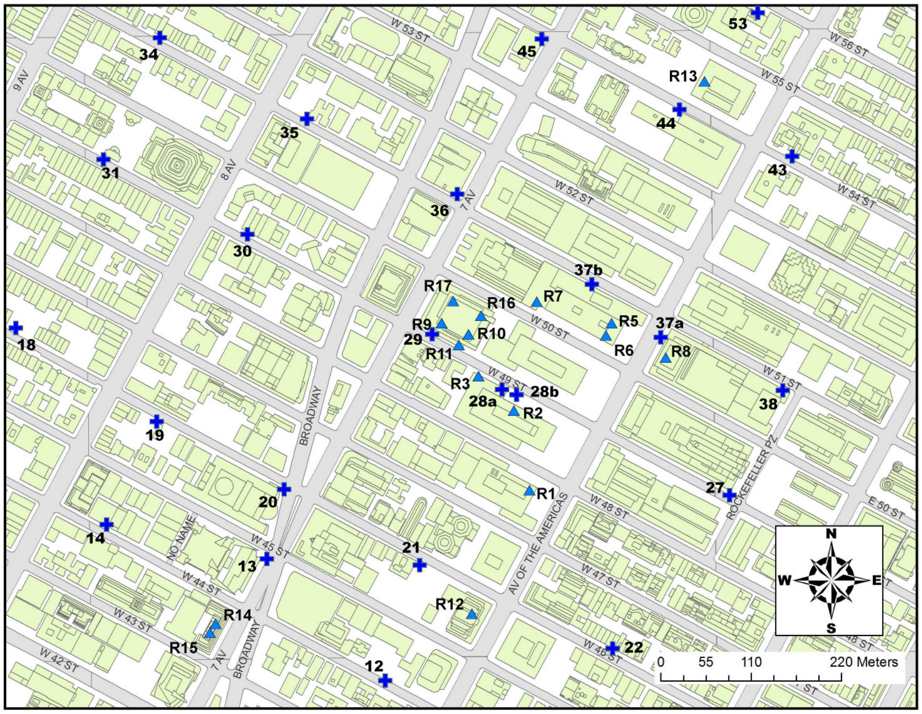

Figure 7. Selected MID05 surface (crosses) and rooftop (triangles) samplers, providing rationale for pairings.

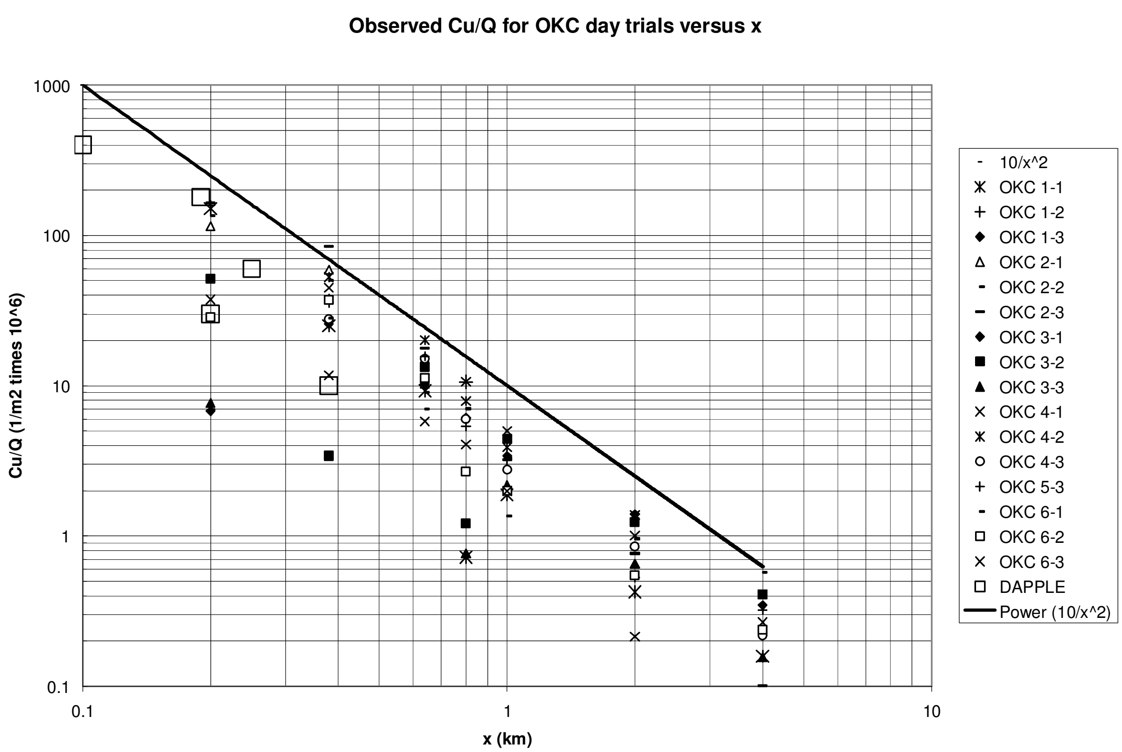

Figure 8. Summary plot of observed Cu/Q versus x for daytime trials during JU2003 and observed averaged for DAPPLE. C is the maximum 30-minute averaged concentration observed along a cross-wind arc of monitors at a given downwind distance, x. The line given by $Cu/Q = 10/x^2$ is drawn, which Neophytou and Britter (2004) and Hanna et al. (2004) and others have suggested as valid for $x/H < 50$, or for $x < 1$ km when mean building height, H, is 20 m.

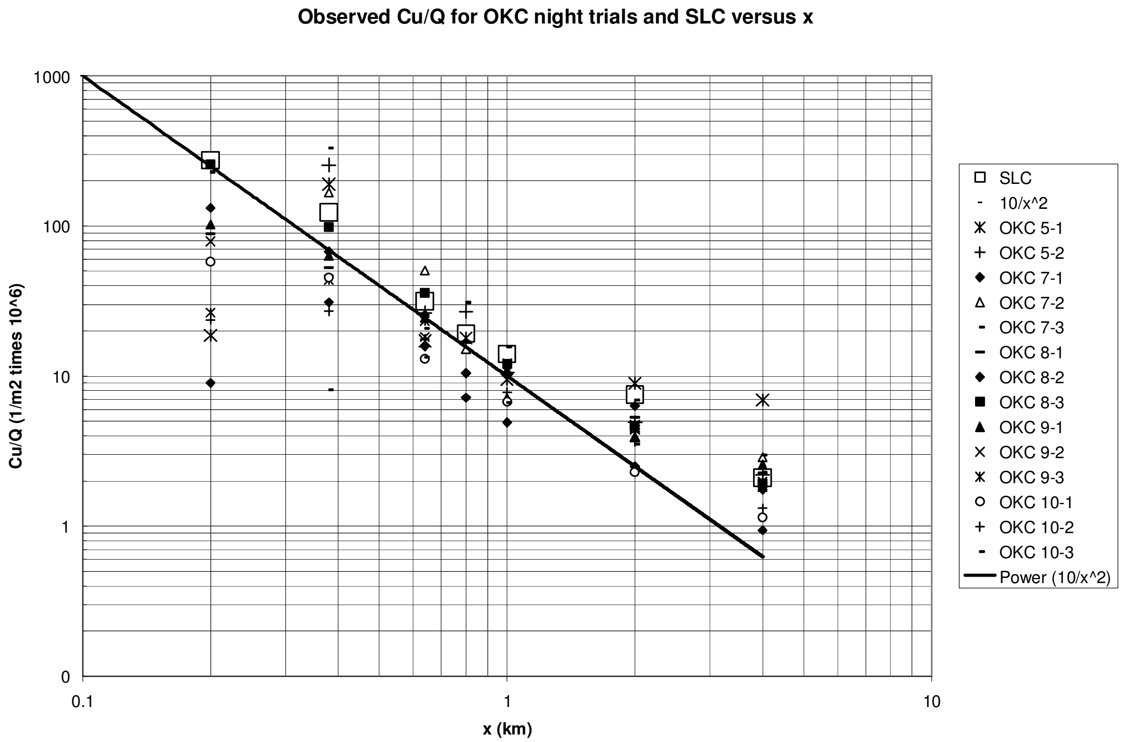

Figure 9. Summary plot of observed Cu/Q versus x for nighttime trials during JU2003 and observed averaged values for Urban 2000. C is the maximum 30-minute averaged concentration observed along a cross-wind arc of monitors at a given downwind distance, x. The line given by $Cu/Q = 10/x^2$ is drawn, which Neophytou and Britter (2004) and Hanna et al. (2004) and others have suggested as valid for x/H < 50, or for x < 1 km when mean building height, H, is 20 m.

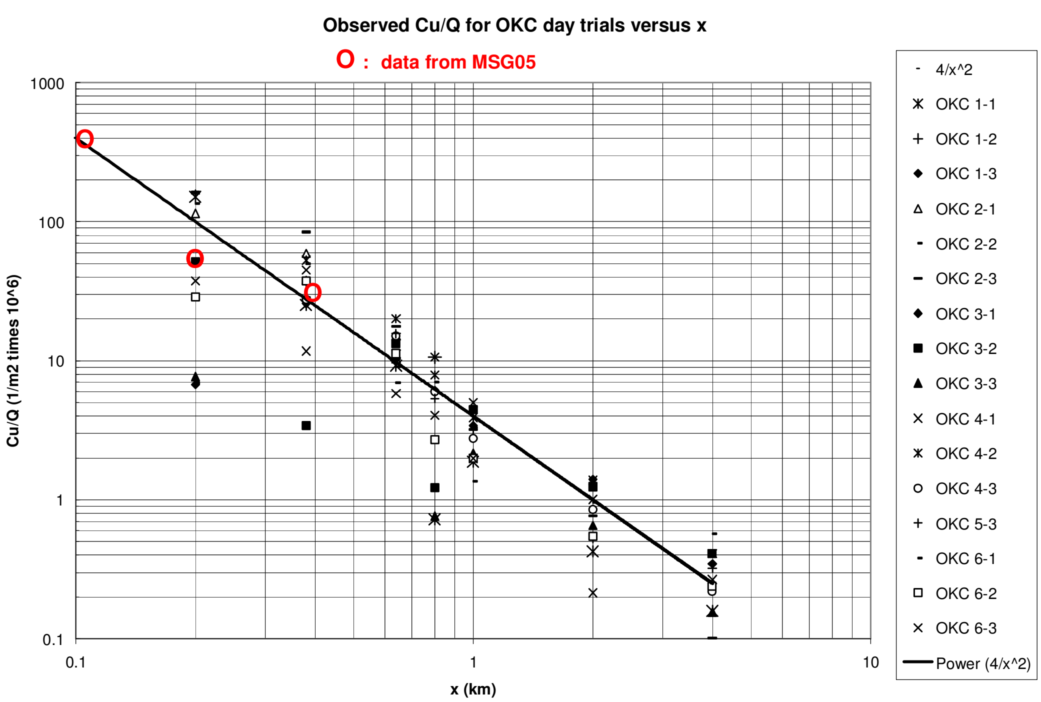

Figure 10. Summary plot of observed *Cu/Q* versus *x* for daytime trials during JU2003 at Oklahoma City (OKC) and observed value averaged over all PFT tracers and release trials for MSG05. C is the maximum 30-minute averaged concentration observed along a cross-wind arc of monitors at a given downwind distance, *x*. The line given by $Cu/Q = 4/x^2$ is drawn. This is almost the same as **Figure 8,** which includes the DAPPLE points but not the MSG05 points.

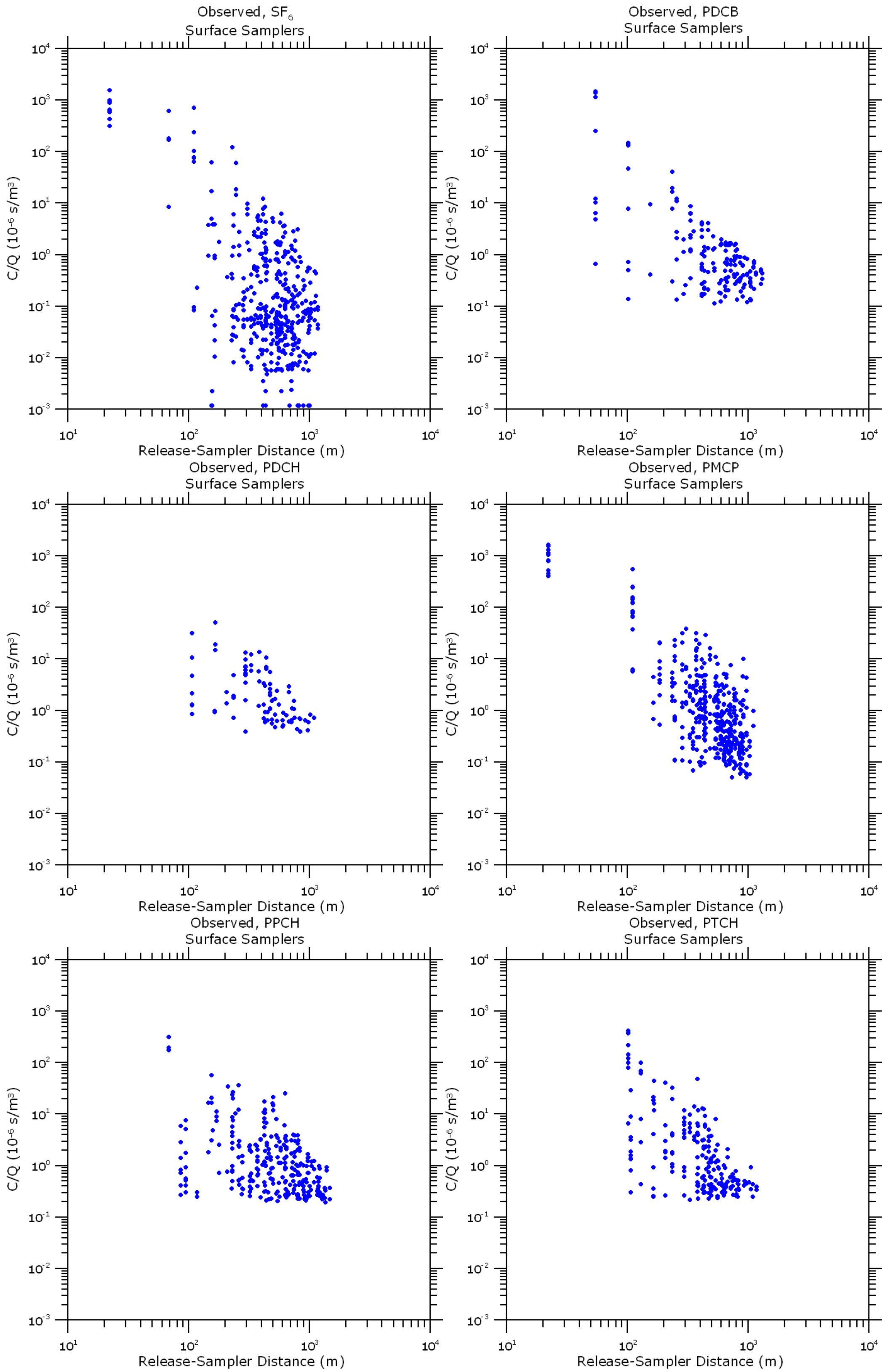

Figure 11. MID05 observed C/Q plotted versus x for six tracers.

Table 1. Summary information for MSG05 tracer releases. Source locations (A – E) are shown in **Figure 3**.

IOP	Release	Month	Day	Hr (EST)	PDCH	PMCH	PMCP	PPCH	PTCH
1	1	3	10	9	A	C	B	C	E
	2	3	10	11.5	A	C	B	C	E
2	1	3	14	9	D	C	B	C	E
	2	3	14	11.5	D	C	B	C	E

Table 2. Summary information for MID05 weather observations and tracer release locations (see **Figure 5**). There are three tracer release times each day, at 0600, 0800 and 1000 EST, with 30 min duration.

IOP	**Date**	**Weather**	**Met Life Z=247 m U (m/s)**	**Met Life WD (°)**	**LGA U (m/s)**	**LGA WD (°)**	**PDCB**	**PDCH**	**PMCP**	**PPCH**	**PTCH**	**SF6**
1	8 Aug	Most cloudy 25-28 C	1.8	221	3.1	205	NONE	NONE	CL	SW-1 to SW	CR	SW
2	12 Aug	Part cloudy 30 C	1.3	NE, variable	1.3 to 4.7	50	NONE	NONE	CL	ENE to SE	CR	ENE To SE
3	14 Aug	Part cloudy 30-35 C	2.8	230	3.4	210	NONE	NONE	CL	SW	CR	SW
4	18 Aug	Part cloudy 25 C	4.9	57	5.5	50	NE	CR	CL	S	CR	CL
5	20 Aug	Cloudy 25-28 C	2.6	185	4.2	175	NE	CR	CL	S	CR	CL
6	24 Aug	Clear 25 C	4.2	0	4.7	10	NE	CR	CL	S	CR	CL