Paper Number 4.1 USE OF TRACER DATA FROM THE MADISON SQUARE GARDEN 2005 FIELD EXPERIMENT TO TEST A SIMPLE URBAN DISPERSION MODEL

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ABSTRACT

A simple urban dispersion model is tested that is based on the Gaussian plume model and the Briggs' urban dispersion curves. A key aspect of the model is that an initial dispersion coefficient (σ) of 40 m is assumed to apply in the x, y, and z directions in built-up downtown areas. This initial σ accounts for mixing in the local street canyon and/or building wakes. At short distances (i.e., when the release is in the same street canyon as the receptor and there are no obstructions in between), the initial lateral σ is assumed to be less, 10 m.

Observations from tracer experiments during the Madison Square Garden 2005 (MSG05) field study are used for model testing. MSG05 took place in a 1 km by 1 km area in Manhattan surrounding Madison Square Garden. Six different perfluorocarbon tracer (PFT) gases were released concurrently from five different locations around MSG, and concentrations in the air were observed by 20 samplers near the surface and seven samplers on building tops. There were two separate continuous 60 minute tracer release periods on each day, beginning at 9 am and at 11:30 am. Releases took place on two separate days (March 10 and 14). The samplers provided 30 minute averaged PFT concentrations from 9 am through 2 pm.

This analysis focuses on the maximum 60-minute averaged PFT gas concentration at each sampler location for each PFT for each release period. Stability was assumed to be nearly neutral, because of the moderate winds and the mechanical mixing generated by the buildings. Input wind direction was the average observed building-top wind direction (285° on March 10 and 315° on March 14). Input wind speed was the average street-level observed wind speed (1.5 m/s for both days). To be considered in the evaluation, both the observed and predicted concentration had to exceed the threshold. Concentrations normalized by source release rate, C/Q, were tested. For all PFTs, samplers, and release times, the median observed and predicted C/Q are within 40% of each other, and 43 % of the time the concentration predictions are within a factor of two of the observations. The scatter plots show that the typical error is about the same magnitude as the mean concentration. When only the surface observations are considered, the performance is better, with the median observed and predicted C/Qs within 10 % of each other.

The overall 60 minute-averaged maximum C/Q is underpredicted by about 40 % for the surface samplers and is overpredicted by about 25 % for the building-top samplers.

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1. OBJECTIVES AND BACKGROUND

Meteorological and tracer data taken during urban field experiments are being analyzed in order to develop and test basic scientific relations. The ultimate goals are to increase understanding of urban flow and dispersion in built-up downtown areas, to evaluate dispersion models with the data, and to provide guidance for emergency response. The urban dispersion model comparisons discussed in this paper make use of the Madison Square Garden 2005 (MSG05) field experiment, which took place on 10 and 14 March 2005. Figure 1 is a photograph of part of the experimental domain, showing Madison Square Garden and adjacent tall buildings.

Molina and Molina (2004) discuss the increased air pollution problems associated with the continued growth of cities throughout the world. There are 20 "megacities" with populations exceeding 10 million. For example, Tokyo, Mexico City, New York City, Sao Paulo, and Mumbai are the five largest cities, typically with hundreds of buildings of height greater than 50 m and 10 or 20 of height greater than 200 m, and deep street canyons.

Because of concerns with very large cities, considerable attention has been devoted to urban meteorology during the past five years. The Megacities Initiative: Local and Global Research Observations (MILAGRO) research program. http://milagro.acd.ucar.edu was initiated by the U.S. National Science Foundation (NSF). The boundary layer results of the major field experiment in Mexico City in 2006 are described by Fast et al. (2007) and Doran et al. (2007). However, the focus of MILAGRO is not so much on plume dispersion in the center of the city, but on meteorological and air quality characteristics of the large urban megalopolis, such as that in Mexico City and environs.

Besides the MSG05 dispersion experiment described here, the Joint Urban 2003 (JU2003) field experiment (Allwine et al., 2004) and the Manhattan Midtown 2005 (MID05) field experiment (Allwine and Flaherty 2007) data are being used to further test the simple urban model discussed here. Also, there have been several other detailed urban meteorology and dispersion field experiments outside of the U.S., such as the Zurich urban experiment (Rotach, 1995), the Basel Urban Boundary Layer Experiment (BUBBLE) (Rotach et al., 2005 and Christen, 2005), and the London field experiment known as Dispersion of Air Pollutants and their Penetration in Local Environments (DAPPLE) (Britter, 2005).

Nearly all of the "urban" field data from the European studies are from areas of cities where buildings have heights of no more than a few stories. Besides the JU2003 and the Manhattan field experiments, there are few observations in built-up downtown areas or at heights near street level.

Because of the current concerns with releases of chemical and biological agents in built-up downtown areas, the series of field experiments such as JU2003, MSG05 and MID05 in the U.S. are addressing flow and dispersion in cities with large built-up areas containing at least five or ten tall ($z >$ 100 m) buildings, where z is height above ground. Most of the observations in these field experiments are made at street level deep within urban street canyons and/or near very tall buildings. This paper presents some preliminary results of analyses of tracer data from MSG05.

2. DESCRIPTION OF MADISON SQUARE GARDEN 2005 (MDG05) FIELD EXPERIMENT

The MSG05 (Allwine and Flaherty 2006, Watson et al. 2006, Hanna et al., 2006) field experiment is part of a series of urban experiments (see Allwine, 2007) sponsored by the U.S. Department of Homeland Security (DHS) and the U.S. Defense Threat Reduction Agency (DTRA), in collaboration with other agencies in the U.S., Canada, and the U.K. The Joint Urban 2003 (JU2003) experiment in Oklahoma City (Allwine et al., 2004, and Clawson et al., 2005) has been the most extensive of the series, with more tracer releases and more observing systems. The Salt Lake City (SLC) Urban 2000 (Allwine et al., 2002) and the Mock Urban Setting Tests (MUST, Yee and Biltoft 2004) are also part of the series. The Manhattan Midtown 2005 (MID05) followed the MSG05 experiment, with focus on the Midtown area and took place in August. These urban experiments are intended to address near-surface meteorological conditions and tracer dispersion in the built-up downtown areas. In each experiment, there are typically a few Intensive Observation Period (IOP) days, during which a number of tracer releases take place over several hours, with detailed meteorological observations.

The science goals for MSG05, which took place on 10 and 14 March 2005, were to increase understanding of flow and dispersion in deep urban canyons and of rapid vertical transport and dispersion in recirculating eddies adjacent to very tall buildings in a large urban area. Allwine and Flaherty (2006) and Allwine (2007) describe the experiment in general and give some of the preliminary results. Watson et al. (2006) describe the tracer releases and sampling methodology. Hanna et al. (2006) present some comparisons of five different Computational Fluid Dynamics (CFD) model applied to MSG05, and Hanna et al. (2007) discuss the wind and turbulence observations. The average building heights are found to be about 60 m in the MSG area, and there are several buildings with heights above 150 or 200 m within a few blocks. For example, the tall building in Figure 1 is One Penn Plaza (OPP), at 224 m. Figure 2 is a satellite photo of the MSG05 study domain, and MSG itself is very noticeable because of its round shape. Figure 3 is a Google view of the Midtown area of Manhattan, covering a larger area than Figure 1 and showing the many tall buildings, characteristic of the "megacities" described by Molina and Molina (2004). The MSG and OPP buildings are visible in the upper right corner.

Figures 1 through 3 also illustrate the variability of surface types occurring in a typical city. For example, in Figure 1, the Hudson River (1.5 km wide) is seen only 1 km to the west of the MSG domain. In Figure 3, the East River is seen on the Eastern side of Manhattan, and the large Central Park is visible. Thus the atmospheric boundary layer is often readjusting to new underlying surfaces. But this happens in all cities.

The two Intensive Observation Period (IOP) days during MSG05 included several types of meteorological measurements including seven sonic anemometers at street level and three sonic anemometers on building roofs, with two on very tall buildings (at z > 150 m). Figure 2 shows an example of the observed wind vectors for the period from 9:00 to 9:30 on March 10 (bottom panel). The flow appears complicated, but the effects of the building wakes and street canyons can generally be fairly well simulated by CFD models, as seen in the comparison of five CFD models for this domain reported by Hanna et al. (2006).

As in any complex site, the decisions during MSG05 concerning placement of meteorological instruments and PFT samplers represented a compromise among many considerations. For example, for safety purposes, none of the meteorological towers is mounted on a pole or tower higher than 10 m above a rooftop. But this raises the question of whether the wind sensor may be within the roof top displacement zone. Also, all street level anemometers and tracer samplers were obviously not far from buildings, street corners, and other complications. The general rule followed at street level was that the instrument should be as far away from the building wall and obstructions as possible, but should not be placed near enough to the street that it might be hit by vehicles.

Consequently, most street level instruments were located on the street edge of the sidewalk.

Hanna et al. (2007) analyzed the meteorological data from MSG05 and concluded that both MSG05 IOP days were marked by similar wind speeds (about 5 m s^{-1}) and directions (WNW to NNW) at rooftop. Temperatures were also similar, slightly below 0.0 C, during both IOPs. Both experiments took place during the daytime, between 7 am and 12:30 pm EST, with partly-cloudy skies. Of course, with only two days of observations during similar wind conditions, the conclusions drawn from analysis of the data must be considered preliminary.

The two days of wind observations from the tall buildings during MSG05 suggest that there is a range in wind speed of about a factor of two and in wind direction of about 40 to 60 degrees across the several rooftop sites on each IOP day. Since these two days were more or less optimum from the viewpoint of excellent weather and moderate persistent winds, these ranges in wind speed and direction can be expected to be less than those on most days.

The MSG05 field experiments included concurrent one-hour duration releases of six different perfluorocarbon tracer gases, from five point sources near street-level (at z = 1.5 m) on the sidewalk at the four corners of MSG, and just north of OPP. (See Figure 4) Note that two PFTs were released from one location for quality control. Figure 4 shows the five release locations and Figure 5 shows the 20 street-level and seven rooftop PFT sampler locations. Table 1 gives the UTM coordinates and the latitude and longitude of each release location and sampler. The heights of the seven rooftop samplers are also given in Table 1.

The PFT release and sampling technology has been under development and improvement at Brookhaven National Laboratory (BNL) for over 20 years. Watson et al. (2006) describe the details of the PFT methods used for MSG05 and Allwine and Flaherty (2006) review the PFT part of the experiment in their comprehensive summary of MSG05. There are three major advantages of PFTs over other types of tracers – 1) the global backgrounds of most PFTs are very low, 2) the samplers can measure concentrations down to parts per quadrillion (i.e., 1 ppq = 10^{-15} parts per part volume), and 3) multiple PFTs can be released simultaneously and sampled and distinguished by the same sampler. Thus small amounts of PFT gas can be released and still be detected above the global background. And different PFTs can be released at the same time and their individual concentrations detected by the same sampler.

For MSG05, six PFTs were used, and their characteristics are given in Table 2. Even though they have high molecular weights, they act like neutral or passive gases once they are emitted to the atmosphere because their concentrations are so low. The release mechanism consisted of a small tank and tubing on a small tower on the sidewalk near the street. Each release was from a height of 1.5 m and was of duration 60 minutes. During each IOP day, there were two releases, starting at about 9 am and about 11:30 am. The exact timing and release mass are given in Table 3. Thus, even though there were only four release periods during the two days, there were 24 sets of tracer data. This is because there were six PFTs released during each period.

Each sampler collected the PFTs in 10 adsorption tubes during each day. The sampler pumps were adjusted so that each adsorption tube represented a 30-minute sample. Therefore the total duration of sampling on each day lasted from 9 am to 2 pm. The samples were analyzed in the laboratories at BNL and QA/QC procedures applied (see Watson et al., 2006). Table 4 gives the background concentrations and the derived uncertainty (expressed as a standard deviation, or Stdev) for each PFT. Also listed are the Level of Detection (LOD) and the Level of Quantification (LOQ), which are assumed to equal three and ten times the Stdev, respectively.

The final PFT data set that was entered in the data archive and distributed to researchers contained concentrations expressed as the original raw values minus the sum of the background and the Stdev. It is necessary to subtract the background concentration from observations to properly represent the tracer plume. Allwine and Flaherty (2006) chose to be conservative in estimating the background for removal by defining it as the measured background plus the Stdev rather than as just the measured background. After removing the background, the final step in determining "background-adjusted" values is to set all negative values to zero. Table 5 presents a portion of the MSG05 background-adjusted data set. The time that is listed in the table is the midpoint of the 30-minute sampling period.

Of the six PFTs released, five gave "good" data. However, one of the PFTs, PECH, was determined to have too much uncertainty and was therefore not used in subsequent analyses. In addition, as recommended by Allwine and Flaherty (2006), our analysis used a conservative approach for determining background-adjusted values that are significantly different from zero. That is, only those observed final concentrations that exceeded the LOQ (10 Stdev) were used in our analysis. For example, in Table 5, under iPPCH, only concentrations exceeding an LOQ of 10 ppq would be used. This would eliminate about ½ of the non-zero concentrations listed.

3. COMPARISON OF NORMALIZED MAXIMUM CONCENTRATIONS DURING MSG05 WITH THOSE DURING JU2003

As a check on the MSG05 concentration data, the maximum 30-minute normalized PFT concentrations observed during MSG05 were compared with the normalized concentrations observed during JU2003. As shown in Hanna et al. (2007), the observed SF_6 tracer gas concentrations at JU2003 during the daytime followed a relation:

$$C_{max}u/Q = 4\ x^{-2} \qquad (1)$$

where x (m) is downwind distance, u (m/s) is average wind speed in the urban area, Q (g/s) is source emission rate, and C_{max} (g/m^3) is maximum concentration on the plume centerline at the distance x. A continuous near-ground-level release from a point source is assumed. This type of simple relation for urban areas has been suggested by numerous several authors, including Hanna et al. (2003), Venkatram et al. (2002 and 2004), Batchvarova and Gryning (2006), Britter (2005), and Neophytou et al. (2005).

Figure 6 presents a summary plot of $C_{max}u/Q$ versus x for each release trial in JU2003 for daytime trials that passed a QA/QC test. The values of $C_{max}u/Q$ at three downwind distances during MSG05 are also plotted. The line, $C_{max}u/Q = 4/x^2$, is seen to pass through the middle of the observed points, which have a scatter of approximately ± a factor of three (including about 90 % of the points). Thus it is concluded that the MSG05 concentration observations are consistent with those from another city for another tracer.

4. SIMPLE GAUSSIAN MODEL DESCRIPTION

Figure 6 focused on the maximum concentration across all samplers at predefined downwind distance arcs. But there is also interest in whether the concentrations at the edges of the plume can be satisfactorily estimated using a simple model. This section derives the simple Gaussian urban model that is tested in the remainder of this paper.

Assume that the source is emitted at ground level (this is a valid assumption even if the release height is as high as 10 m in an urban environment, because of the large initial plume spread). The Gaussian formula can be written:

$$C/Q = (1/(\pi u \sigma_y \sigma_z)) * \exp(-y^2/2\sigma_y^2)\ \exp(-z^2/2\sigma_z^2) \quad x > 0 \qquad (2)$$

where C/Q has units s/m^3

z is height of the receptor or sampler above ground level

y is the lateral distance from the plume centerline (assuming that the x axis has been lined up along the plume axis). The plume axis is lined up with the wind direction, which is assumed during MSG05 to line up with the average building top wind direction (285 degrees on 10 March and 315 degrees on 14 March for MSG05).

The downwind distance, x, is defined as the distance from the release point to a point on the plume axis (centerline).

The wind speed, u, is the averaged wind speed for the plume as it is transported in the urban canopy.

σ_y is the lateral cross-wind standard deviation of the concentration distribution.

σ_z is the vertical cross-wind standard deviation of the concentration distribution.

The standard deviations are assumed to be made up of two parts, an initial σ_o due to the mixing in the street canyons at the source location, and a turbulent σ_t due to the usual ambient turbulence, which exists over all types of terrain. Earlier field experiments in urban areas (e.g., McElroy and Pooler, 1976) suggest that the initial $\sigma_{yo} = \sigma_{zo} = 40$ m. We then have the following formulas:

$$\sigma_y = \sigma_{yo} + \sigma_{yt} = 40\ \text{m} + 0.25\ x \qquad (3)$$

$$\sigma_z = \sigma_{zo} + \sigma_{zt} = 40\ \text{m} + 0.25\ x \qquad (4)$$

The parameter (or "constant") 0.25 is in Briggs' urban sigma formulas for neutral conditions. This parameter can be thought of as the turbulence intensity (turbulent standard deviation divided by wind speed). The stability is assumed nearly neutral because of the daytime conditions in March and the moderate wind speeds. Large mechanical mixing is expected in the urban canopy, as confirmed by observations of MSG05 heat fluxes and Monin length, L, reported by Hanna et al. (2007).

On the plume centerline (y = z = 0.0) at large downwind distances, equation (2) approaches the limit $Cu/Q = 5.1/x^2$, which is nearly identical to the relation found in Figure 6. The only difference is that the constant 5.1 occurs in equation 2 while the constant 4 occurs in Figure 6. However, because of the initial plume size of 40 m at x = 0 assumed in equation (2), Cu/Q becomes independent of x, approaching about 0.0002 m^{-2} as x approaches 0.

The parameters "40 m" and "0.25" in the formulas (3) and (4) can be varied in sensitivity studies. Furthermore, it is expected that, at night, the stabilities may be on the stable side of neutral, thus suggesting that the "0.25" might be reduced.

It is implied that the cloud of material spreads out into a hemispherical shape around the source area. Thus there is material dispersing even in the upwind direction (at x < 0.0). This can be accounted for by the following correction for x < 0 where the alongwind σ_{xo} is assumed to also equal 40 m.

$$C/Q = (1/(\pi u \sigma_{yo}\sigma_{zo})) * \exp(-y^2/2\sigma_{yo}^2) \exp(-z^2/2\sigma_{zo}^2) \exp(-x^2/2\sigma_{xo}^2) \quad \text{for } x < 0 \qquad (5)$$

This latter formula should be able to handle the MSG05 samplers that are located in an upwind ($x < 0$) sector.

The simple urban model described above assumes that there is large initial mixing due to the influence of recirculating wakes and street canyon vortices caused by several buildings. Thus the model is most valid after the plume has passed around and/or over several buildings. It can be hypothesized that a downwind distance equal roughly to the average building height is necessary for this initial mixing to take place. Thus in comparisons with MSG05 data, the above model is assumed valid for downwind distances greater than about 100 m. This parameter can also be varied in sensitivity studies.

For samplers at distances from the source less than about 100 m, or when the line-of-sight is unobstructed between the release point and the sampler, it is assumed that the plume remains in the initial street canyon or courtyard and travels more or less unimpeded without being extensively mixed laterally by the multiple large buildings. In this case, we assume that the initial lateral dispersion ($\sigma_{yo} = \sigma_{xo}$) is smaller. A value of 10 m is assumed, but this is also subject to sensitivity analyses. The turbulent dispersion (i.e., 0.25x) remains the same.

For emergency response estimates at x < about 100 m, it can be further assumed that the plume might be carried in any direction due to the recirculating vortices (e.g., see the wind vectors in Figure 2) adjacent to buildings. This upwind or lateral transport extends out to about one building height. Thus the worst case concentration should be assumed to apply for x < about 100 m, with σ_{yo} = 10 m and the plume pointing directly towards a sampler. This condition applies to samplers 8, 10, and 15, for which observed concentrations indicate that the plume sometimes traveled straight towards that receptor, even though it may be upwind or in a lateral direction from the source.

An estimate of the urban wind speed is needed. Hanna et al. (2007) show that the average magnitude of the street-level wind speed is about 2 m/s during MSG05. This is the so-called scalar average. However, the tracer plume is being transported across the urban area at the vector-average wind speed rather than the scalar-average. It is difficult to know the actual vector average during MSG05 because there were only 12 anemometers at street level. But a good estimate is to assume that the vector average u equals 1.5 m/s for the MSG05 field experiment. As sensitivity studies, u = 1 m/s, 2 m/s and u = 4 m/s were also tested. This is much simpler than it sounds, since the wind speed, u, enters equation (2) as a simple division factor. Thus, at all locations, the ratio of the concentrations at two different wind speeds is simply the inverse ratio of those two wind speeds.

4. METHODS

The predictions of the simple urban Gaussian model described above were compared with the PFT observations during MSG05. Tables were created containing pairs of predicted and observed concentrations for each sampler and each PFT release. Pairs were included in the comparison only if both the predicted and observed concentration exceeded the LOQ (i.e., 10 times the Stdev). This assumption resulted in over ½ of the street-level samplers (e.g., numbers 5-7, 9, 11-14, 16-18, 20, V3 –V6, and V7) not being used in the comparisons at all. Numbers 9 and 20 collected no good data, and sampler V7 (at the top of the New Yorker Hotel) was actually inside the hotel. Only a few of the sampler locations (e.g., numbers 1, 2, 3, 4, 10, V1, and V2) had significant concentrations most of the time. Some of the samplers (numbers 8, 15, 19, and V6) were occasionally hit, for specific release locations. In retrospect, it would have been better to increase the mass emission rate of PFTs. After learning this fact from these experiences at MSG05, the release rates were increased during MID05 (Allwine and Flaherty, 2007).

Table 6 is an example of an output table used in the comparisons. This table is for the first IOP day (10 March) and release 1 (from 9 am through 10 am). The notation 101 is used to indicate day 1 and release 1. The release locations (see Figure 4) are indicated for five PFTs. As stated earlier, the PECH data were not used because they did not pass QA/QC tests. Two PFTs were released from site C (SE corner of MSG) as a check on the accuracy of the sampling. Predicted and observed C/Q are listed in the last two columns for a sampler only if both were above the LOQ. See Figure 5 for sampler locations. The table lists the distance from the source to the sampler and the wind direction that would blow directly from the source to the receptor. For ease in analysis, the aloft (building top) samplers rows are shaded blue and the rows for samplers close to the release points are shaded yellow.

As seen in Table 6, the available data pairs were found to be adequate to carry out comparisons. Scatter plots were used, as well as quantitative performance measures. The performance measures in the BOOT statistical model evaluation method (Chang and Hanna, 2004) were used. Assume that X = C/Q in the following definitions:

Fractional Bias

$$FB = 2\langle X_o - X_p\rangle/(\langle X_o\rangle + \langle X_p\rangle) \qquad (6)$$

Normalized Mean Square Error

$$NMSE = \langle (X_o - X_p)^2 \rangle / (\langle X_o \rangle \langle X_p \rangle) \quad (7)$$

Geometric Mean

$$MG = \exp(\langle \ln X_o \rangle - \langle \ln X_p \rangle) \quad (8)$$

Geometric Variance

$$VG = \exp(\langle (\ln X_o - \ln X_p)^2 \rangle) \quad (9)$$

Normalized Absolute Difference

$$NAD = \langle |X_o - X_p| \rangle / \langle X_o \rangle \quad (10)$$

Fraction of X_p within a factor of two of X_o (FAC2) (11)

Fraction of X_p within a factor of five of X_o (FAC5) (12)

In addition, the median, average, and maximum of X_o and X_p are determined and listed. Subscripts p and o refer to predicted and observed, and the symbol < > represents an average.

Scatter plots and tables of performance measures are presented separately for all samplers, for surface samplers, for aloft (building top) samplers, and for surface samplers for the releases from the OPP site.

5. RESULTS

Scatter plots of X_o versus X_p are given in Figures 7, 8 and 9 for all samplers, for only the surface samplers, and for only the aloft samplers, respectively. If there were perfect agreement, all points would be oriented on a straight line at a 45 degree slope on the figures. But since perfect models never happen in the atmospheric sciences, we look to see if the agreement is "within the range" of other air quality models. Generally an air quality model for this type of application is said to be acceptable if its mean bias is less than a factor of two, and its scatter is less than a factor of two or three most of the time (Chang and Hanna, 2004). It is also desirable that the model be able to match the observed maximum concentration within about a factor of two.

Figure 7 is the scatter plot for all sampler data. It shows the middle of the cloud of points roughly falling along the 45 degree line, but with many points in the upper left of the diagram indicating an overprediction for several of the low observed concentrations. Figure 8 contains data only for the surface samplers, showing that most of the area of points with overpredictions have been eliminated.

Figure 9, for the aloft (building-top) samplers, shows the overpredictions occurring at low observed concentrations. The model predicts C/Q of 255 at Sampler V1 and 142 at Sampler V2 for the PFT released at location B, on the NE corner of MSG for all four releases. These match fairly closely the maximum observed C/Qs of 205 and 140 at those locations, which was the intent of the model development. But there are some release trials when observed C/Q was less at those locations.

Table 1 contains the quantitative performance measures for the data in Figures 7, 8, and 9, as well as for two other subsets of the data – the surface data for the release near OPP, and the surface data from the close-in samplers (8, 10, and 15). It is seen that, for all data and for the surface data, the max C_p/Q is about one-half of the max C_o/Q. However, for the aloft data, the max C_p/Q is about 25 % larger than the max C_o/Q.

For the average or the median C/Q, at the surface, the predicted values are within 15 % of the observed values. The most robust measure of the scatter is the mean absolute difference (NAD), which is within the range from 0.62 to 1.48 for all five data combinations in Table 7. This indicates that the typical scatter is close to the mean value. Other robust measures are FAC2 and FAC5. FAC2 is 0.45 for all surface data and FAC5 is 0.89 for those data. Thus almost ½ of the predictions are within a factor of two of the observations, and about 90 % of them are within a factor of five.

The scatter plots and quantitative performance measures are within the ranges for "good" model performance listed by Chang and Hanna for other model evaluation exercises.

6. LIMITATIONS

With 20 surface samplers and 7 samplers aloft, and six different PFT releases during four release periods, there could have been as many as 27 x 6 x 4 = 648 good data pairs (i.e., with both observed and predicted concentrations above the sampler threshold). The final count of good data pairs was only 80, due to some samplers data being missing, one PFT (PECH) not being used, and many observed concentrations below the sampler threshold. This is enough data to arrive at useful conclusions for MSG05, but it is expected that many more good data will be available from MID05, which involved more IOP days, more samplers, and more tracer gas released.

The MSG05 field experiment was of course site specific, as any urban experiment would be. This is another reason to look forward to analyzing the MID05 data, which were taken a few blocks from MSG05. However, because both MSG05 and MID05 took place during the day, there is still a need to test the formulas at night.

The simple urban dispersion model makes use of many assumptions regarding effective wind speeds and dispersion coefficients. As suggested by Hanna et al. (2003), the urban nighttime dispersion coefficients are expected to be less than the daytime values, by about 50 % or so. We are currently testing the formula with the JU2003 field data, which included both day and night runs, and there is a clear difference.

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Figure 1. Photograph of Madison Square Garden (the circular building whose edge is shown), the 224 m One Penn Plaza building (to the right of MSG) and the 153 m Two Penn Plaza building (towards the camera from MSG). The photograph is taken from the top of the Empire State Building, looking WSW. The Hudson River is in the distance. The blue dots show the approximate locations of the rooftop PFT samplers and sonic anemometers. Photo courtesy of R. Michael Reynolds of Brookhaven National Laboratory (BNL).

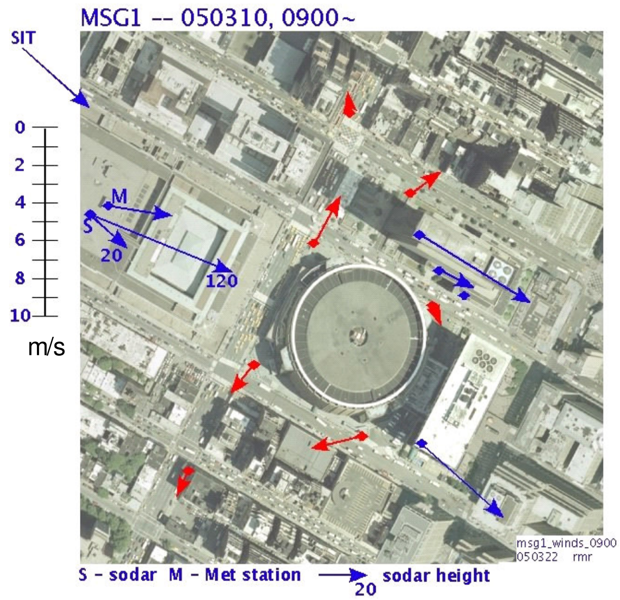

Figure 2 – View of area around Madison Square Garden (MSG) in Manhattan, where MSG is the round building and has diameter 130 m and height 50 m. The 224 m tall One Penn Plaza building is to the NE of MSG and the 153 m tall Two Penn Plaza building is to the ESE of MSG. Wind vectors (red near street level and blue at rooftop) are shown for 9:00 through 9:30 am on 10 March 2005. The SIT measurement was made on a building roof at Stevens Institute of Technology, located on the western side of the Hudson River about 5 km to the southwest. The two vectors originating at "S" on the left edge of the figure represent observations by the sodar at heights of 20 m and 120 m above the Post Office roof. Figure courtesy of R. Michael Reynolds, BNL.

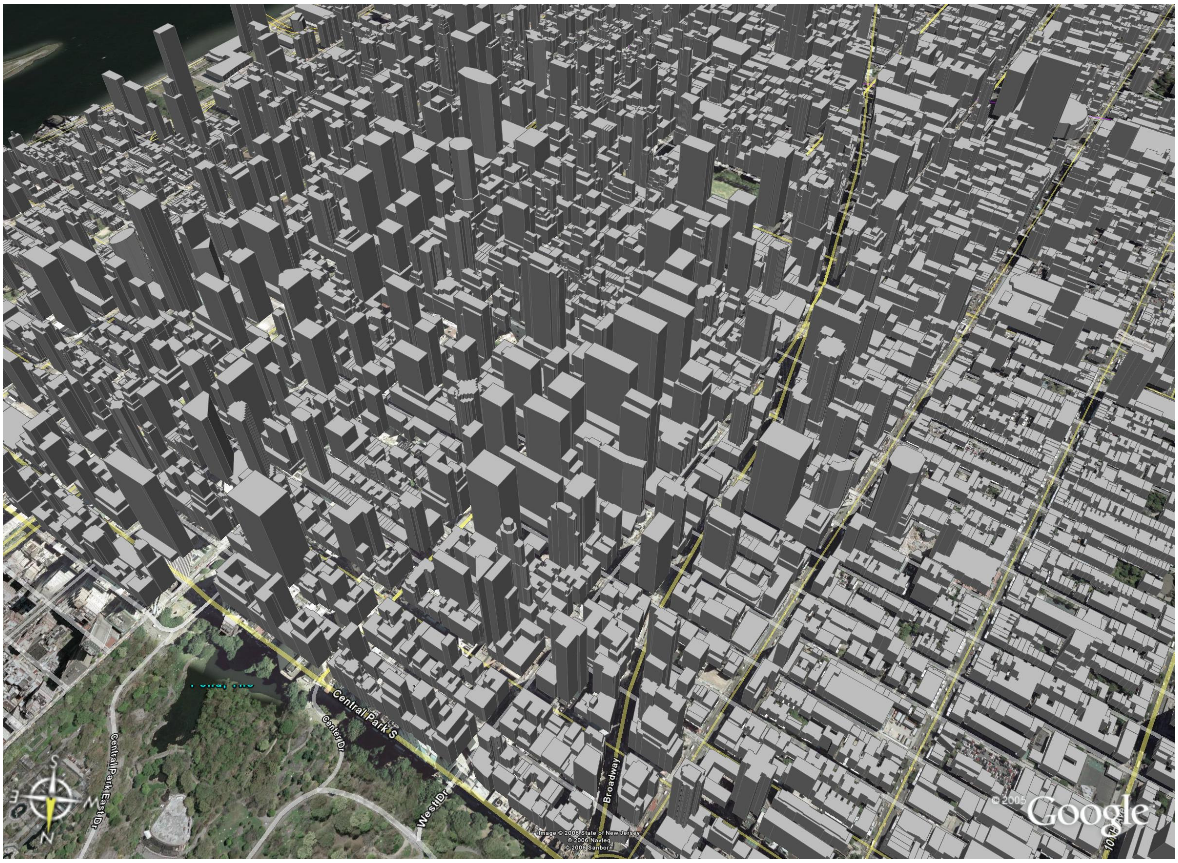

Figure 3. 3-D view of midtown Manhattan area, looking from Central Park towards the South. The MSG domain is in the upper right corner, where the 224 m One Penn Plaza building partially hides Madison Square Garden. The 153 m Two Penn Plaza building is just to the left of One Penn Plaza. Figure courtesy of Google.

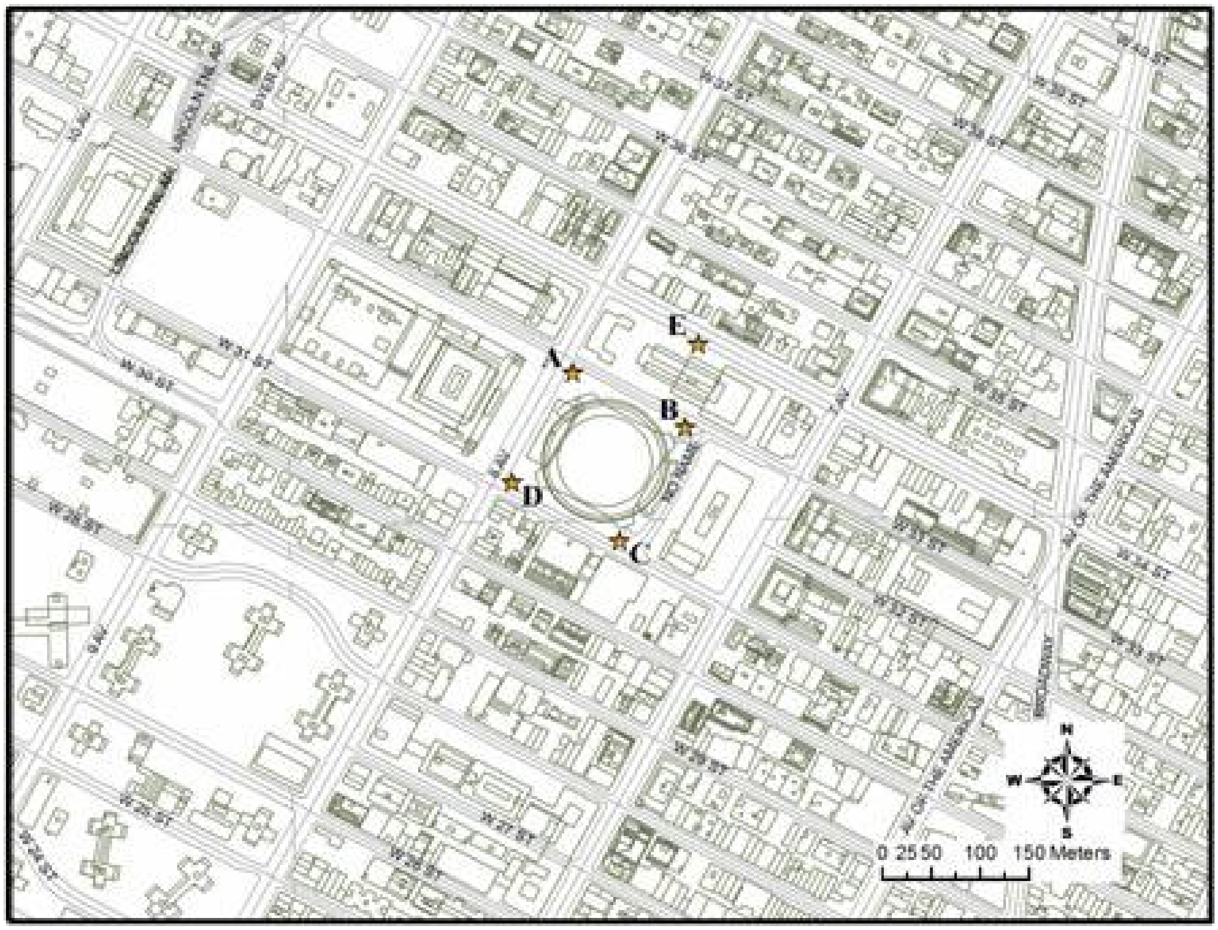

Figure 4. The five tracer release locations during MSG05 (from Allwine and Flaherty, 2006). Table 1 lists the precise locations in UTM and lat-long.

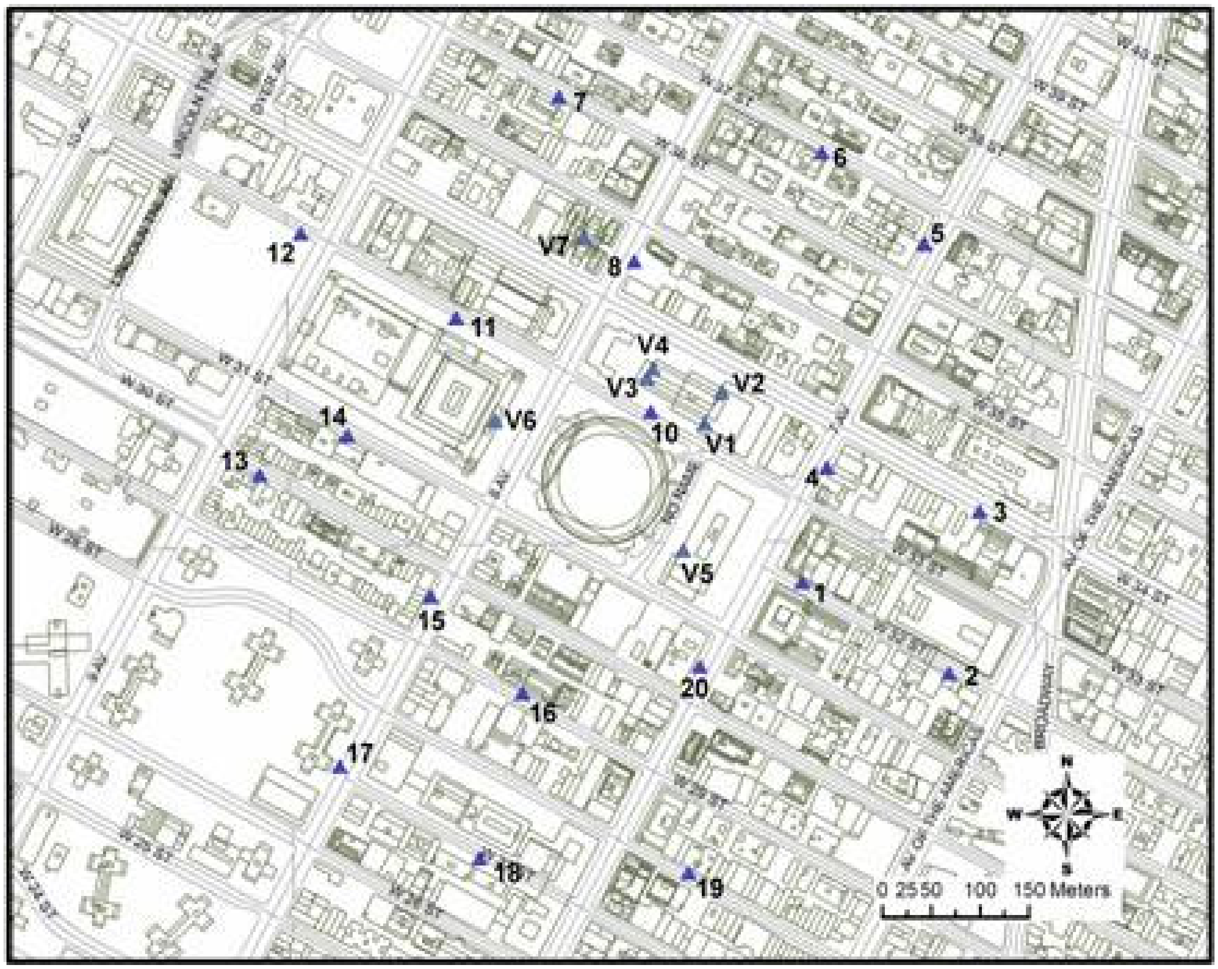

Figure 5. The PFT sampler locations during MSG05. Samplers with labels beginning with V are located above street level on buildings. Table 1 lists the precise locations in UTM and lat-long. Figure from Allwine and Flaherty (2006).

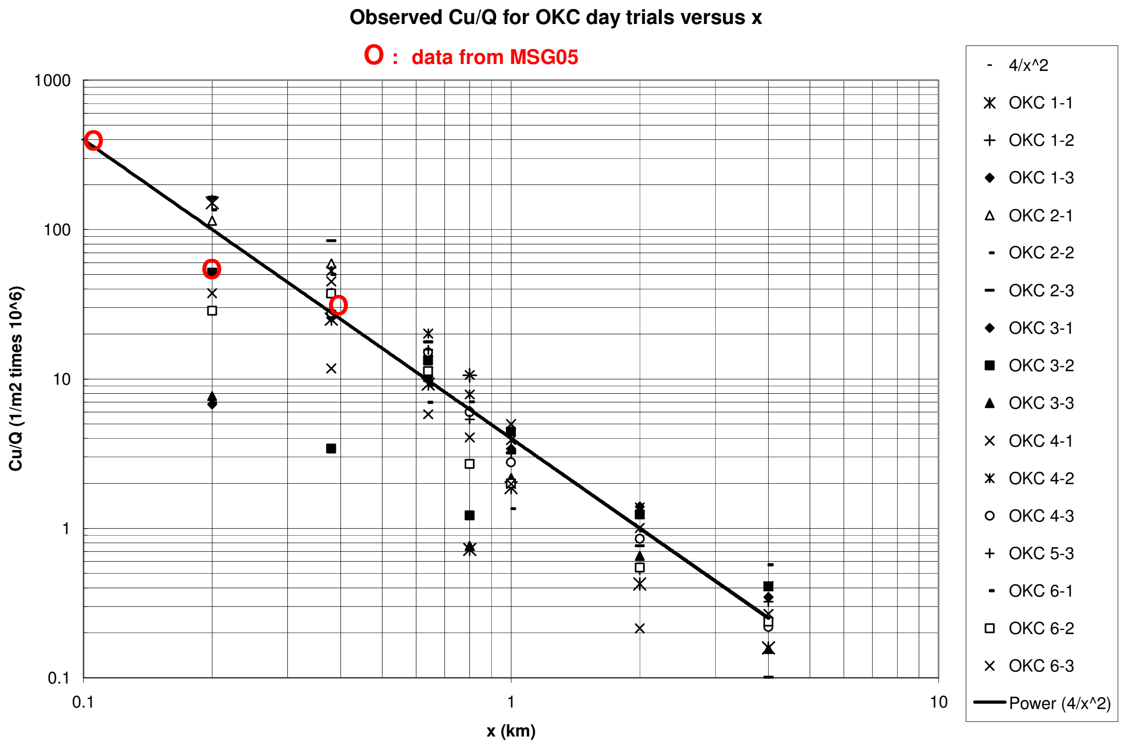

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Figure 6 - Summary plot of observed *Cu/Q* versus *x* for daytime trials during JU2003 at Oklahoma City (OKC) and observed value averaged over all PFT tracers and release trials for MSG05. C is the maximum 30-minute averaged concentration observed along a cross-wind arc of monitors at a given downwind distance, *x*. The line given by $Cu/Q = 4/x^2$ is drawn. The figure without the MSG05 points is in Hanna et al. (2007).

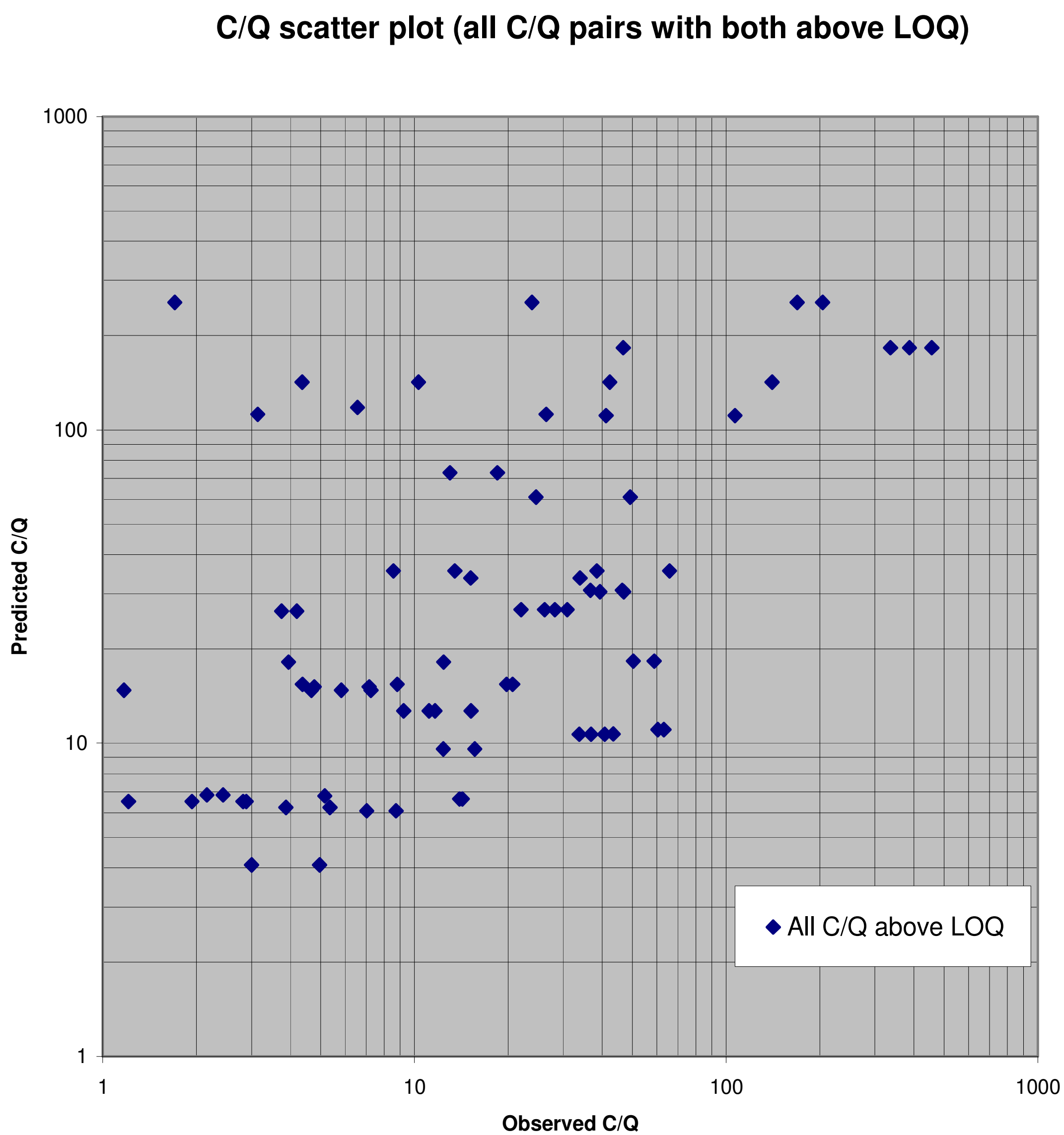

Figure 7. Scatter plot of all data (N = 80) with both observed and predicted C above the LOQ. Units of C/Q are s/m^3 times 10^6.

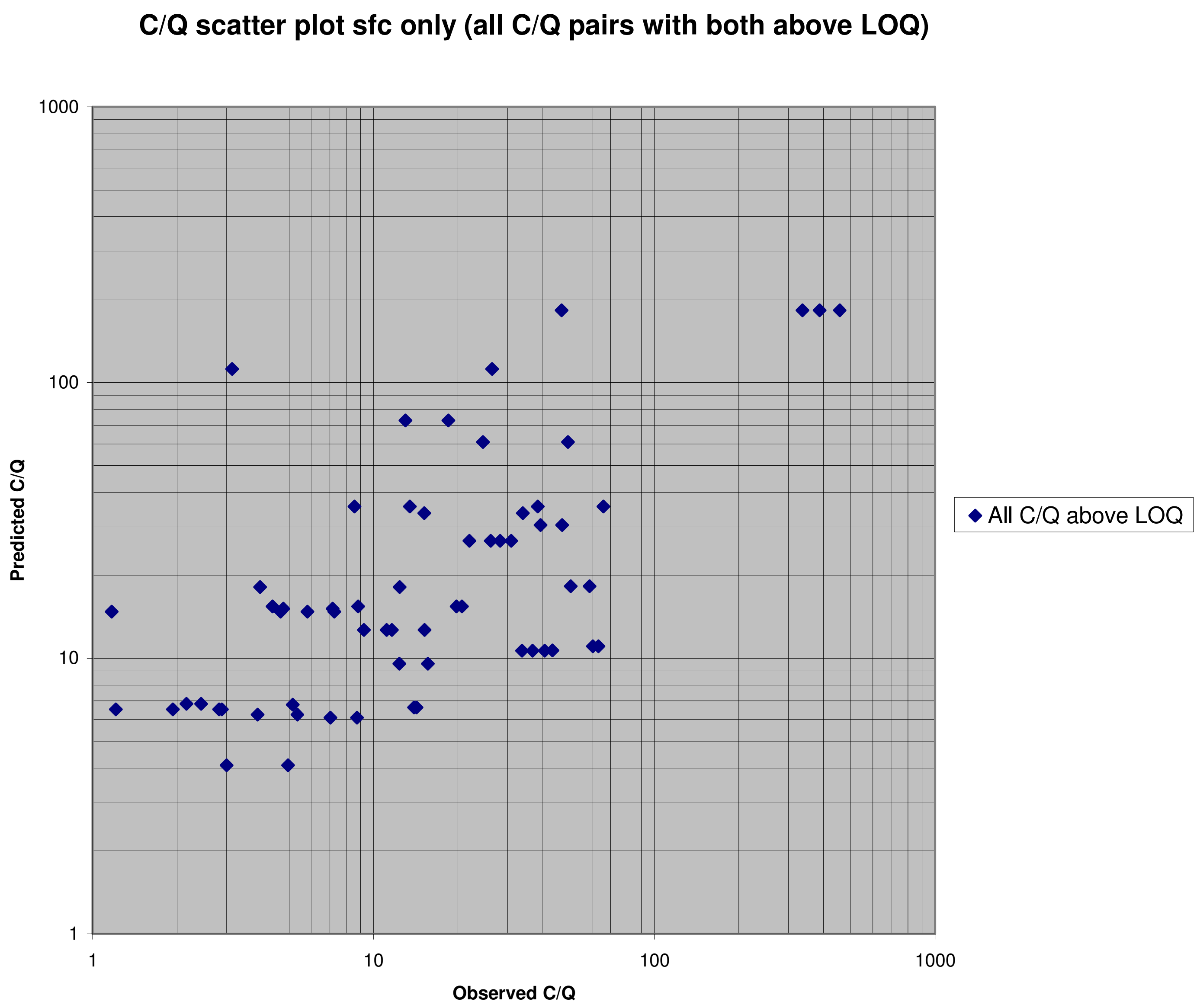

Figure 8. Scatter plot of all surface data (N = 65) with both observed and predicted C above the LOQ. Units of C/Q are s/m^3 times 10^6.

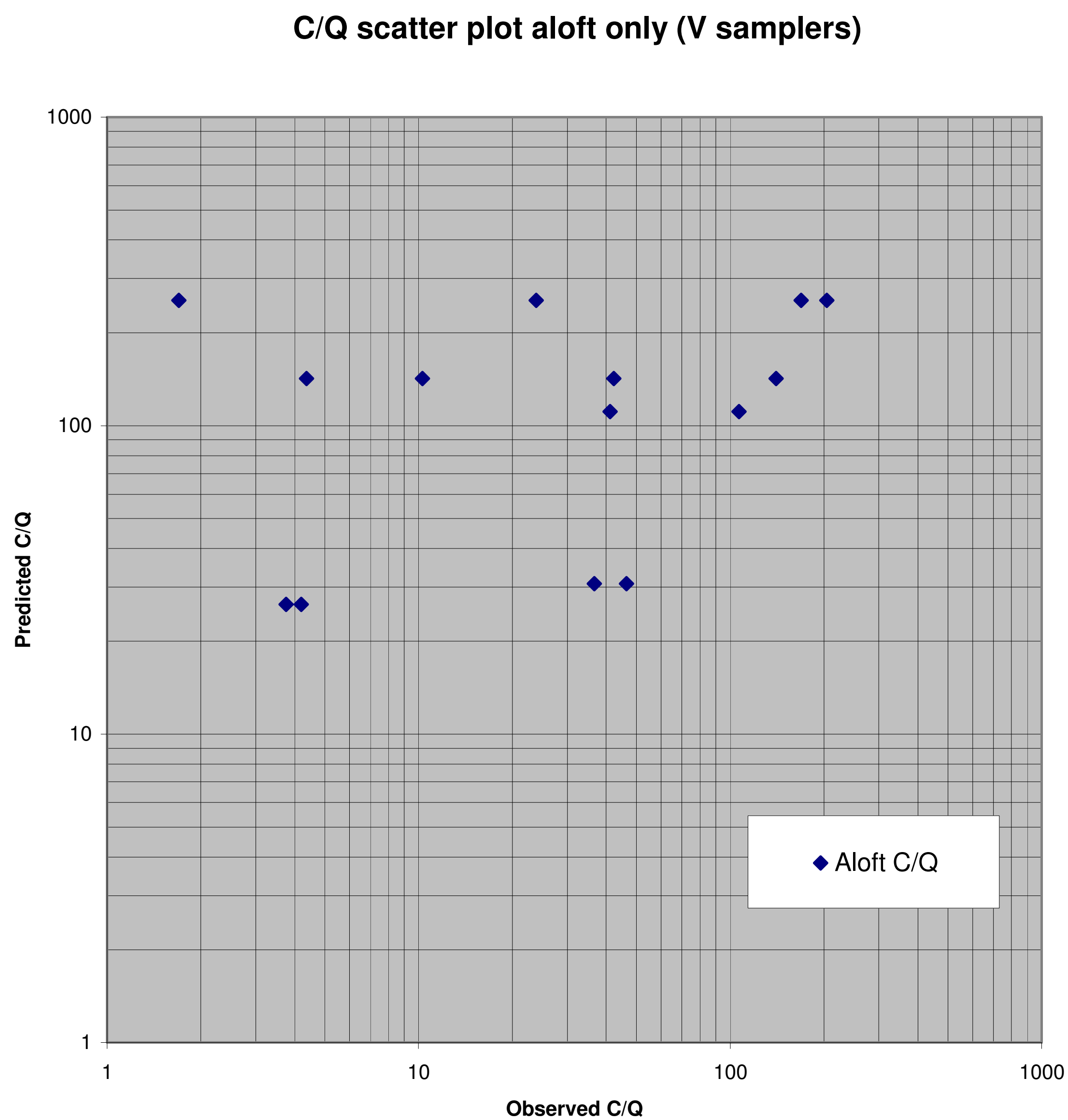

Figure 9. Scatter plot of all aloft data (not at the surface) (N = 15) with both observed and predicted C above the LOQ. Units of C/Q are s/m^3 times 10^6.

Table 1. PFT Instrument/Sampler and Release Locations. Figures 4 and 5 Showed These on a Map of MSG05. Samplers 1 through 20 were at Heights of 3 m. Samplers V1 – V7 were at Elevations of 48 m, 48 m, 227 m, 227 m, 153 m, 42 m, and 117 m, Respectively. The Rooftop Samplers' Approximate Locations are Shown as Blue Dots in Figure 1. From Watson et al. (2006) and Allwine and Flaherty (2006).

Instrument	Location Description	Easting	Northing	Latitude	Longitude
1	7th & 32nd In front of the Hotel Pennsylvania - North side of street	585172	4511447	40.74957	-73.99109
2	west of 6th & 32nd In front of the Blarney Stone Bar - South side	585322	4511354	40.74872	-73.98932
3	34th & Broadway South side - In front of Footlocker	585353	4511518	40.75019	-73.98894
4	Midway between 34th & 33rd East side of 7th - In front of McDonald's	585197	4511563	40.75061	-73.99078
5	Between 36th & 37th In front of Bates Worldwide - West side of 7th	585297	4511789	40.75264	-73.98956
6	232 W. 37th south side In front of West Tandori Club - Midway 7th & 8th	585192	4511882	40.75349	-73.99079
7	Midway 8th & 9th on 36th In front of 320 Goldie Restaurant - S side	584923	4511938	40.75402	-73.99397
8	In front of McDonald's Midway 34th & 35th - East side of 8th	585000	4511772	40.75251	-73.99308
10	One Penn Plaza - Middle of building North side of 33rd	585017	4511619	40.75113	-73.99290
11	In front of the Post Office South side of 33rd - Between 8th & 9th	584818	4511714	40.75201	-73.99525
12	Across from St. Michael's Church South side of 33rd - Between 9th & 10th	584659	4511800	40.75280	-73.99712
13	9th and 30th 370 W. 30th - South side of 30th close to 9th	584617	4511555	40.75060	-73.99765
14	South side of 31st midway 8th & 9th - Across from bay 16 of the Post Office	584707	4511595	40.75095	-73.99658
15	West side of 8th #393 Midway btn 30th & 29th - In front of 8th Ave Garden	584792	4511432	40.74947	-73.99559
16	In front of 29th St Marketplace North side of 29th - Between 7th & 8th	584886	4511334	40.74858	-73.99449
17	8th & 27th Middle of T-bone intersection - West side 8th	584699	4511260	40.74793	-73.99672
18	In front of Nagler Hall on the S side of 27th	584842	4511167	40.74708	-73.99504
19	North side of 28th In front of Center Floral Design - Between 6th & 7th	585056	4511152	40.74692	-73.99250
20	In front of Seven Penn Plaza Between 30th & 31st - West side of 7th	585067	4511361	40.74881	-73.99234
V1	12th story Penn One 33rd St side	585072	4511607	40.75102	-73.99225
V2	12th story Penn One 34th St side	585090	4511639	40.75131	-73.99203
V3	Top of Penn One 33rd St side	585013	4511653	40.75144	-73.99294
V4	Top of Penn One 34th St side	585019	4511663	40.75153	-73.99287
V5	Top of Penn Two	585050	4511479	40.74987	-73.99253
V6	Top of Post office 8th and 33rd	584858	4511610	40.75107	-73.99479
V7	Top of New Yorker Hotel	584949	4511796	40.75274	-73.99368
Release A	8th and 33rd – North corner of MSG	584937	4511643	40.75136	73.99385
Release B	33rd midway between 7th & 8th – East corner MSG	585052	4511585	40.75083	73.99249
Release C	31st midway between 7th & 8th – South corner MSG	584985	4511465	40.74975	73.99330
Release D	8th and 31st – West corner MSG	584875	4511527	40.75032	73.99460
Release E	34th between 7th & 8th – middle of Penn One	585065	4511673	40.75162	73.99233

Table 2. Perfluorocarbon Tracer Characteristics and Conversions. From Watson et al. (2006) and Allwine and Flaherty (2006).

Acronym	**Chemical Name**	**Formula**	**Mol. Wt. (g/mol^{-1})**	**Conversion from ppqv to µg/m^3**
PMCP	Perfluoromethyl-cyclopentane	C_6F_{12}	300	1.34E-5*
PMCH	Perfluoromethyl-cyclohexane	C_7F_{14}	350	1.56E-5
oc-PDCH	Perfluoro-1,2-dimethyl-cyclohexane	C_8F_{16}	400	1.78E-5
PECH	Perfluoroethyl-cyclohexane	C_8F_{16}	400	1.78E-5
i-PPCH	Perfluoro-isopropyl-cyclohexane	C_9F_{18}	450	2.0E-5
1PTCH	Perfluoro-trimethyl-cyclohexane	C_9F_{18}	450	2.0E-5

***Thus 1 ppqv = 1.34E-5 µg/m^3**

Table 3. PFT Release Locations, Start Times, Release Durations, and Release Masses during MSG05. From Watson et al. (2006) and Allwine and Flaherty (2006).

Modified form of Table 3 of the BNL Tracer Report
Tracer Release Data for March 10, 2005
Release duration was nominally 1hr. Tracer releases were terminated at 10:00 and 12:30.
Release mass was computed using 1 atm and 0 degC, which was similar to ambient conditions.
Tracer mass has an error of +/- 3%

3/10/2005 9:00 EST	Tracer Release Location	Start Time	Release Duration (min)	Release Mass (g)
oc-PDCH	A	9:00	60	0.316
PMCP	B	9:05	55	4.624
PMCH	C1	9:00	60	1.739
i-PPCH	C2	9:00	60	0.082
PECH	D	9:02	58	0.592
1PTCH	E	9:16	44	0.090

3/10/2005 11:30 EST	Tracer Release Location	Start Time	Release Duration (min)	Release Mass (g)
oc-PDCH	A	11:30	60	0.320
PMCP	B	11:30	60	5.261
PMCH	C1	11:30	60	1.777
i-PPCH	C2	11:30	60	0.084
PECH	D	11:30	60	0.641
1PTCH	E	11:30	60	0.123

Modified form of Table 4 of the BNL Tracer Report
Tracer Release Data for March 14, 2005
Release duration was nominally 1hr. Tracer releases were terminated at 10:00 and 12:30.
Release mass was computed using 1 atm and 0 degC, which was similar to ambient conditions.
Tracer mass has an error of +/- 3%

3/14/2005 9:00 EST	Tracer Release Location	Start Time	Release Duration (min)	Release Mass (g)
PECH	A	9:06	54	0.570
PMCP	B	9:07	53	4.408
PMCH	C1	9:00	60	1.477
i-PPCH	C2	9:00	60	0.068
oc-PDCH	D	9:06	54	0.269
1PTCH	E	9:00	60	0.116

3/14/2005 11:30 EST	Tracer Release Location	Start Time	Release Duration (min)	Release Mass (g)
PECH	A	11:30	60	0.669
PMCP	B	11:30	60	5.044
PMCH	C1	11:30	60	1.889
i-PPCH	C2	11:30	60	0.089
oc-PDCH	D	11:30	60	0.320
1PTCH	E	11:30	60	0.121

Table 4. Estimates of PFT Backgrounds and Uncertainties, Based on Number of Data Points Indicated. Uncertainties are Expressed as a Standard Deviation (Stdev), Level of Detection (LOD = 3 times Stdev), and Level of Quantification (LOQ = 10 times Stdev). From Watson et al. (2006) and Allwine and Flaherty (2006).

PFT	Number of Data Points Used to Determine Background	Background C in ppqv	Stdev in ppqv	LOD in ppqv	LOQ in ppqv
PMCP	239	19	2.2	6.6	22
PMCH	342	17	2.1	6.3	21
ocPDCH	347	3	0.7	2.1	7
iPPCH	401	6	1	3	10
1PTCH	302	3	1.2	3.6	12
PECH	93	1	3	9	30

Table 5. Portion of Final PFT Tracer Data Base. These Concentrations are Calculated as the Initial Raw Concentration Minus the (Background + Stdev) as Listed in Table 4.

Example of Final Tracer Data Distributed with background + 1 stdev removed

Location	Date	EST_midpoint	PMCP_ppq	PMCH_ppq	ocPDCH_ppq	PECH_ppq	iPPCH_ppq	1PTCH_ppq
1	3/10/2005	9:15	53	796	1	36	22	0
1	3/10/2005	9:45	148	826	0	37	28	0
1	3/10/2005	10:15	98	106	0	1	1	0
1	3/10/2005	10:45	63	8	0	0	0	0
1	3/10/2005	11:15	23	2	0	0	0	0
1	3/10/2005	11:45	561	713	0	22	26	0
1	3/10/2005	12:15	461	1106	1	44	46	0
1	3/10/2005	12:45	132	163	0	3	5	0
1	3/10/2005	13:15	44	7	0	0	1	0
1	3/10/2005	13:45	31	4	0	0	0	0
2	3/10/2005	9:15	49	446	1	7	9	0
2	3/10/2005	9:45	212	512	2	14	17	0
2	3/10/2005	10:15	36	96	0	0	2	0
2	3/10/2005	10:45	15	1	0	0	0	0
2	3/10/2005	11:15	6	0	0	0	0	0
2	3/10/2005	11:45	47	221	0	0	5	0
2	3/10/2005	12:15	85	498	0	12	17	0
2	3/10/2005	12:45	364	144	0	0	1	0
2	3/10/2005	13:15	54	7	0	0	0	0
2	3/10/2005	13:45	12	0	0	0	0	0
2 - Duplicate	3/10/2005	9:15	47	424	1	8	10	0
2 - Duplicate	3/10/2005	9:45	203	496	2	17	17	0
2 - Duplicate	3/10/2005	10:15	35	95	0	0	1	0
2 - Duplicate	3/10/2005	10:45	14	0	0	0	0	0
2 - Duplicate	3/10/2005	11:15	6	0	0	0	0	0
2 - Duplicate	3/10/2005	11:45	45	214	0	1	4	0
2 - Duplicate	3/10/2005	12:15	84	481	0	15	17	0
2 - Duplicate	3/10/2005	12:45	309	101	0	0	2	0
2 - Duplicate	3/10/2005	13:15	43	4	0	0	0	0
2 - Duplicate	3/10/2005	13:45	11	0	0	0	0	0

Table 6. Example of Comparison of Observed and Predicted C/Q (in units of s/m^3 times 10^6) for Release 1 at 9 am on IOP01 (March 10, 2005). Both C_o and C_p must be above the LOQ at a Sampler Location for the Data to be Included on this Table. There are Similar Tables for the other Three Releases. The Yellow Area Marks the Samplers that are Either Close to or in a Direct Line from the Release Site. The Blue Area Marks the Samplers that are on Building Roofs.

IOP and Release	Release Location	PFT	LOQ C/Q units	Sampler number	Sampler height	Sampler distance x (m)	WD toward sampler (degrees)	Cp/Q	Co/Q
101	A NW	ocPDCH	1.47	3	3	434	287	9.57	12.37
		IOP01		4	3	272	287	18.13	3.95
				8	3	144	206	61	24.53
		only		10	3	84	287	112	3.14
				V1	48	140	285	30.78	36.69
				V2	48	154	271	26.36	3.75
	B NE	PMCP	0.19	1	3	182	319	14.77	1.17
				2	3	355	310	6.52	1.21
				3	3	308	283	15.4	20.65
				4	3	147	279	35.51	38.5
				10	3	49	135	183	336.89
				V1	48	30	122	255	23.86
				V2	48	66	215	142	140.4
	C1 SE	PMCH	0.63	1	3	188	276	26.69	26.16
				2	3	354	288	12.68	15.2
				3	3	372	262	6.83	2.16
				4	3	234	245	6.24	3.87
	C2 SE	iPPCH	7.4	1	3	188	276	26.69	21.96
				2	3	354	288	12.68	11.64
	D	ocPDCH IOP02 only	1.47						
	E OPP	1PTCH	4.7	3	3	327	298	18.26	58.74
				4	3	172	310	33.64	15.16

Table 7. Statistical Performance Measures. Note that C/Q has Units of s/m^3 Times 10^6. Equations (6) through (12) Define the Performance Measures.

Performance Measure	All Data	All Sfc Data	All Sfc Data for OPP Release	All Near-Field (8, 10, 15) Sfc Data	Aloft Data (Not at Sfc)
N	80	65	10	10	15
Max Co/Q	457	457	63	457	204
Max Cp/Q	256	183	34	183	256
Average Co/Q	40.7	37.1	38.0	136.3	56.1
Average Cp/Q	51.9	32.1	21.7	122.4	136.2
Median Co/Q	14.2	13.7	43.1	36.6	36.7
Median Cp/Q	18.1	15.0	18.3	112	142
FB	-0.24	0.14	0.55	0.11	-0.83
NMSE	2.36	2.64	1.04	1.12	1.68
MG	0.61	0.76	1.44	0.43	0.22
VG	6.00	3.15	3.03	11.29	93.9
NAD	0.92	0.73	0.62	0.83	1.48
FAC2	.43	.45	.30	.20	.33
FAC5	.83	.89	.80	.80	.53