J7.1 ANALYSIS OF JOINT URBAN 2003 (JU2003) AND MADISON SQUARE GARDEN 2005 (MSG05) METEOROLOGICAL AND TRACER DATA

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1. INTRODUCTION

As a first step towards a comprehensive analysis of the Oklahoma City Joint Urban 2003 (JU2003) data and the New York City Madison Square Garden 2005 (MSG05) urban field data, the authors have begun analyzing the meteorological and tracer data and developing and testing basic scientific relations. The ultimate goals are to increase understanding of urban flow and dispersion, and to evaluate dispersion models with the data.

Texts (e.g., Pasquill 1974, Stull 1997) on wind and turbulence profiles and dispersion in atmospheric boundary layers generally focus on rural surfaces where the roughness elements are relatively small (heights less than 1 or 2 m). Oke (1987), who was one of the first to include discussions of urban boundary layers in a basic text, points out the need to account for the flow at heights near and below the roughness elements (i.e., buildings). In the past ten years, there has been increased interest in urban boundary layers and extensive analyses of wind and turbulence profiles are reviewed by Rotach (1996), Roth (2000), and Britter and Hanna (2003).

However, nearly all of the "urban" field data presented in these references are from areas of cities where wind observations can be made at heights ranging from the building tops up to about two or three times the mean building heights, H_r. The buildings that are studied are typically no more than a few stories high. There are few observations in built-up downtown areas or at heights below the building tops. Because of the current concerns with possible terrorist releases of chemical and biological agents in built-up downtown areas, a new series of field experiments is addressing flow and dispersion in cities with tall skyscrapers. Most of the observations are made deep within urban street canyons and/or near very tall buildings. It is the goal of this paper to present some preliminary results of analyses of data from two recent experiments – Joint Urban 2003 (JU2003) in Oklahoma City in July, and Madison Square Garden 2005 (MSG05) in New York City in March.

The intent is to try to identify fundamental scientific relations that are suggested by the field data in urban downtown areas. For example, Britter and Hanna (2003) present some tentative similarity formulas that allow the wind speed and turbulence deep within the urban canopy to be parameterized simply. They suggest similarity relations for dispersion and test them with data from several cities. The current paper extends this analysis.

It should be mentioned that the authors are also investigating the details of urban boundary layers using CFD models (e.g., Hanna et al. 2002), but recognize that such models are too slow to be used for emergency response. Nevertheless, the CFD results are being used to assist in the similarity formula parameterizations.

The JU2003 (Allwine et al., 2004) and MSG05 (Hanna et al., 2004) field experiments are part of a series of urban experiments sponsored by the U.S. Department of Homeland Security (DHS) and Defense Threat Reduction Agency (DTRA), with collaborations with other agencies in the U.S., Canada, and the U.-K. The Salt Lake City Urban 2000 (Allwine et al., 2002) and the Mock Urban Setting Tests (MUST, Biltoft et al. 2002 and Yee and Biltoft 2004) are part of the series. In August 2005, the Urban Dispersion Program (UDP) carried out a follow-

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on to MSG05, shifting the domain slightly to the Manhattan Midtown area. These experiments are all intended to address near-surface releases from continuous and instantaneous point sources in the downtown areas. In each experiment, there are a few Intensive Operating Period (IOP) days, during which a number of tracer releases took place over several hours, with detailed meteorological observations.

The JU2003 and MSG05 field experiments will be described in Sections 2 and 3. JU2003 had 10 IOPs and MSG05 had 2 IOPs. Section 2 addresses the winds and turbulence, and Section 3 addresses the tracer studies. Conclusions are given in Section 4.

2. WINDS AND TURBULENCE

There are three basic types of boundary layer wind and turbulence instruments used in the JU2003 and MSG05 field experiments – 1) sonic anemometers which measure fast response (10 Hz or more) wind and temperature fluctuations in either two or three dimensions; 2) routine aerovane or cup anemometers, which provide horizontal wind speed and direction measurements as well as the standard deviation of wind direction fluctuations (σ_θ), but have slower response than the sonic anemometers; and 3) remote sensors such as sodars, which provide vertical profiles of winds and turbulence. Generally the sonic anemometers can measure to very low speeds, whereas the cup anemometers have a starting speed or threshold of about 0.5 to 1.0 m/s. The sodars provide averages over a volume with typical dimension of 10 to 50 m. The current paper focuses on the sonic anemometers and the routine anemometers.

2.1 *Oklahoma City Joint Urban 2003 (JU2003)*

Allwine et al. (2004) provide an overview of the measurements during the Oklahoma City (OKC) Joint Urban 2003 (JU2003) experiment. The data are archived in the JU2003 data server at Dugway Proving Ground (DPG, 2005). The current study used some averages and turbulence files from the data archive, but in most cases, the winds and turbulence have been calculated directly from the "raw" (fast response 10 Hz) data files. The main reason for the independent calculations was that the data archive contains information only for specific averaging times, but a variety of averaging times was of interest or this study.

Figure 1 is an example of the many maps of the OKC JU2003 domain that are available in the data archive. This particular map shows the buildings in the downtown domain and the locations of some of the DPG sonic anemometers, whose data are listed in tables later in this paper. There were over 100 fixed anemometers (of types 1 and 2 defined above), as well as several remote sounders, both inside the downtown domain and at locations in the suburbs and surrounding rural areas. In some locations, vertical profiles of winds were observed by sonic anemometers mounted at various heights on a tower or a building or a cable hanging from a crane. The Park Avenue street canyon, which was the subject of an intense special study, had over 20 sonic anemometers in a one-block domain.

The hourly mean and turbulent wind observations from over 150 anemometer sites in the JU2003 domain have been calculated and the results have been separated into seven groups depending on surroundings. The intent was to try to identify common behavior of the data within each group. The groups are defined as follows:

1a) Exposed building tops in downtown area (7 sites with 14 m < z < 153 m)
1b) Sheltered roofs and sides of buildings in downtown (23 sites with 19 m < z < 47 m)
2) Semiexposed downtown in midst of buildings but not street level (5 sites with z > 10 m)
3) Street canyons downtown (20 sites, z = 8 m)
4) Semi-exposed downtown park or residential area (10 sites with z = 8 to 10 m)
5) Suburban/rural upwind and downwind
6) Airports (3)

Table 1 contains the mean wind speed and wind direction results for each of the ten JU2003 Intensive Operating Periods (IOPs) for each group. Averages are listed for the entire period for each group, and for groups for each IOP. The "all group" overall mean wind average (wind speed = 3.0 m/s and wind direction = 191degrees) is listed in the bottom right corner.

IOPs 01 through 06 were daytime and IOPs 07 through 10 were nighttime. Because of the relatively strong winds and the enhanced mechanical mixing of the urban area, stabilities were always close to neutral (adiabatic) over the downtown area, and Table 1 shows no noticeable variation between the data from day and night. These similar wind and stability conditions were, in a way, pre-ordained by the project team's criteria for having a field experiment on a given day or night, since the tracer sampling network extended to the north of the city and experiments were run only with south winds with sufficient magnitude and persistence to be sure that the tracer plume would be captured. There is only a factor of two range (from 1.8 to 4.0 m/s) in mean wind speed and a 68 degree range (from 149 to 217 degrees) in mean wind direction over the 10 IOPs.

Table 1 shows that there is a significant difference (factor of eight) between the mean wind speeds across the seven groups. An interesting result, which is found to be true for data from several cities, is that the average wind speed (5.0 m/s) at the downtown building tops (group 1a) is approximately equal to the average wind speed (5.4 m/s) at z = 10 m at the airport outside the city. This was also found by Hanna et al. (2003) in SLC (Urban 2000) and is shown in Section 2.2 to be true for MSG05. This finding could be very useful for emergency response modeling, since often the only wind speed that is available is from the nearby airport.

Initially we were puzzled by the low wind speeds (averaging 0.7 m/s) in Group 1b, which includes anemometers on low roofs in the downtown area, but the investigators (e.g., M. Brown, private communication) have stated that those anemometers were in sheltered locations and/or on the sides of buildings.

Another general result is that the average wind speeds (1.5 m/s) near street level in downtown street canyons (group 3) are about 1/3 of those at building rooftops (group 1a). This ratio was also found for SLC (Hanna et al., 2003).

The JU2003 turbulence summaries are given in Tables 2 and 3. Table 2 assumes a 30 minute sampling time for the statistical calculations based on the data from the 20 DPG sonic anemometers. Complete sets of turbulence results for each 30 min period and each anemometer are available in spreadsheets, but there is space in this paper only for the summary table. Note that the mean wind speed is 1.73 m/s which is close to that in Table 1 for the mean in Group 3, which includes most of the same sonic anemometers. There is a consistent positive average vertical velocity (about 0.12 m/s), although its magnitude is so low that it is not significantly different from 0.0. The standard deviation of vertical velocity fluctuations, σ_w, averages 0.69 m/s, with not much variation from one IOP to the next. The ratio, σ_w/u^*, averages 1.56, which is about 20 % larger than the value of 1.3 typically found in rural boundary layers, and reported by Roth (2000) in several urban areas.

The friction velocity, u*, reported in the tables is a "local" value, calculated as the square root of the average of u'w' at the sonic anemometer location over the 30 minute period. Pasquill (1974) points out that u* is affected by eddies with larger scales than w'w' (or σ_w^2), and therefore a 30 minute sampling time in an urban area may not be sufficient to fully capture u* (not to mention the spatial variability). Consequently it may be that the calculated σ_w/u^* would be a slight overestimate. Of course, as Britter and Hanna (2003) point out, a better measure of u* would be either the value above the buildings, or the value based on the surface drag. Venkatram et al. (2002, 2004) state that the u* above the buildings is a major scaling velocity for urban areas. However, neither of these two alternate estimates of u* are available.

Note that the symbol σ_h is used to represent the horizontal turbulent velocity fluctuations ($\sigma_h^2 = \sigma_u^2 + \sigma_v^2$). Usually, over flat surfaces, the u component is lined up with the direction of the wind. However, in urban street canyons, the turbulence has the same magnitude as the mean wind and the "u" and "v" directions become ambiguous. Since it is generally found over flat terrain that $\sigma_u = 2.2u^*$ and $\sigma_v = 2.0u^*$, σ_h is expected to equal about 3.0u*. In Table 1, σ_h is observed to equal to about 3.6u*, which is about 20 % larger than the expected value. The 20 % figure was also reported above for the normalized vertical turbulence, σ_w/u^*.

The standard deviation of temperature fluctuations, σ_T, which also is listed in Table 2, averages 0.3 C. Separate calculations (not listed) of the temperature scale, T*, show that it is about 0.01 to 0.1 C, leading to the ratio σ_T/T^* equal to about 3 to 30. This ratio is expected for very-nearly neutral conditions on a similarity plot of σ_T/T^* versus z/L, where L is the Monin-Obukhov length. Roth's (2000) σ_T/T^*

observations, taken at rooftop and higher in urban/residential areas with smaller buildings, were shown to roughly agree with Monin-Obukhov theory and had magnitudes ranging from 0.5 to 3.5, which are less than the value found in JU2003. However, Roth's data were taken when conditions were moderately unstable. We conclude that the relatively large magnitudes of the JU2003 σ_T/T^* observations are further evidence that the urban boundary layer is close to neutral conditions, day or night.

Turbulence, as indicated by σ_v, can also be analyzed from the routine anemometers, which produce outputs of σ_θ as well as mean winds. Table 3 contains JU2003 observations of mean wind speed, u, standard deviation of wind direction fluctuations, σ_θ, and calculations of $\sigma_v = u\tan(\sigma_\theta)$ for five of the anemometer groups. It is seen that, for the four urban groups, the turbulence σ_v is fairly constant, at a value of about 1.1 m/s, and agrees with the sonic anemometer observations in Table 2. In contrast, for the suburban/rural group, the observed turbulence σ_v is about 1/3 of that for the urban groups. It is suggested that for dispersion models that use estimates of turbulence, σ_v can be assumed to equal about 1 m/s for downtown urban locations in street canyons and on building roofs.

The most important result of the JU2003 turbulence tables is that the turbulence is much more "robust" than the wind speeds, which often have very small magnitudes at street level. Britter and Hanna (2003) and Venkatram et al. (2002, 2004) suggest that, once the averaged turbulence (σ_h and/or σ_w and/or u*) is known in an urban area, then that value can be assumed to apply throughout the urban canopy, even down to street level.

As an additional exercise with the JU2003 turbulence data, we used the observed variation of horizontal turbulent fluctuations, σ_h^2, with sampling time, T_s (5, 10, 15, 30, and 60 minutes in our case), to estimate the turbulence time scale, T_t. The methodology used a set of analytical equations suggested by Pasquill (1974), who states that the sampling time can be thought of as a high-pass filter and the averaging time (0.1 sec for our observations) can be thought of as a low-pass filter. Assuming an exponential autocorrelogram and the associated Markov shape for the energy spectrum, the following equation is valid for the ratio of the variance, σ_h^2, for sampling time, T_s, to the variance, σ_h^2, at infinite sampling time:

$$\sigma_h^2(T_s)/\,\sigma_h^2(\text{very large } T_s) = 1.0 - 2(T_t/T_s)(1-(T_t/T_s)(1-\exp(-T_s/T_t))) \qquad (1)$$

It is assumed here that σ_h^2 for T_s = 60 minutes captures all of the turbulence and represents the "very large" sampling time. Given the observations of the variances for various T_s, then equation (1) can be solved for T_t. As a test, this approach was applied to the JU2003 turbulence observations from IOP02, resulting in T_t calculated to be about 20 seconds for sampling times of 5, 10, 15, and 30 minutes. Assuming a mean wind speed u of about 2 m/s, this implies an integral turbulent length scale $L_t = uT_t = 40$ m, which makes sense in an urban downtown area where the streets and the buildings have that approximate spacing.

2.2 *New York City Madison Square Garden 2005 (MSG05)*

The science goals for MSG05, which took place in Manhattan 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 (Hanna et al., 2004). The average building heights (H = 60 m) in the MSG area in Manhattan are about three or four times what they are in OKC, and Manhattan is about four or five times broader in size. The two IOPs took place with six different PFT tracer gas releases near street level at five locations around MSG, with gas samplers at street level on two concentric circles at approximate distances of 200 and 400 m, and at rooftop on two tall buildings. The tracer data are still being QA/QC'd and are not yet released.

Supporting meteorological instruments included seven sonic anemometers at street level, several sonic anemometers on building roofs, a minisodar on the Post Office roof just west of MSG, and a wind profiler to the west (upwind) in Hoboken, NJ. Figure 2 presents the locations of the anemometers (top panel) and an example of the observed wind vectors for the period from 9:00 to 9:30 on March 10 (bottom panel). Unlike JU2003, there were sonic anemometers in MSG05 on the roofs of the skyscrapers, as well as at street level.

The observed mean wind speeds and wind directions during MSG05 are listed in Table 4. Averages are given over the five hour duration of each IOP. Besides the anemometers in Figure 2, several additional anemometers on tall buildings are included (CCNY in northern Manhattan, EML in Greenwich Village (about 2 km south of MSG), and LBR in Times Square (1 km north of MSG)). Winds from JFK airport are also listed.

It is seen that both IOPs were marked by similar wind speeds and directions. Wind speeds were moderate out of the Northwest. Temperatures were also similar, slightly below 0.0 C, during both IOPs.

As remarked earlier, the MSG05 data confirm the finding at other cities, that the observed wind speed at the tall building tops (R1 at 229 m at R2 at 153 m) averages close to (within about 10 to 20 %) the observed wind speed at z = 10 m at the nearby airport (JFK). The wind directions are also similar (within about ten degrees).

Also similar to JU2003, the mean wind speeds observed by the seven sonic anemometers at street level (z = 3 m) average about 1/3 of the wind speeds at building tops. However, the wind directions at street level have almost no relation to the wind directions at the building tops, due to the influence of recirculating wakes near buildings and/or channeling by street canyons. For example, site S7 is located along 8th Avenue, which is oriented towards 29 degrees (east of north), and the wind direction observed at that site is 17 degrees for IOP01 and 28 degrees for IOP02.

Table 5 contains the turbulence observations for MSG05, in a format similar to the JU2003 turbulence observations in Table 2. Data are presented for six sonic anemometers (R1 and R2 on building tops, and S1, S4, S5, and S7 at street level). Thirty minute sampling periods are used in both Tables 2 and 5.

Note that the average vertical velocities are larger in MSG05 than in JU2003, possibly due to the much taller buildings and hence larger recirculation zones. The positive average w (on order of 1 m/s) for the rooftop sites is thought to be due to the fact that the anemometers, which were located about 10 m from the upwind edge of the roofs, are probably influenced by the rooftop displacement zone.

The observed σ_h/u^* and σ_w/u^* for the street-level sites at MSG05 are similar to those in Table 2 for the street level sites in JU2003. σ_h/u^* averages 3.63 for both JU2003 and MSG05, while σ_w/u^* averages 1.56 for JU2003 and 1.29 for MSG05. The rooftop σ_h/u^* and σ_w/u^* in MSG05 are larger: 6.37 and 1.79 respectively. Note that u* at MSG05 is only about 15 % larger at rooftop than at street level. It is surprising that a reasonable u* can be found at rooftop in the area of the displacement zone.

The standard deviation of turbulent temperature fluctuations, σ_T, is 44 % as large at JU2003 as at MSG05 (0.31 C vs 0.71 C). Nevertheless, it is surprising how close the observations are at the two sites, confirming our expectation that there are universal similarity laws acting. As evidence of this agreement mounts, it should be possible to use these fundamental relations to suggest simple but effective basic guidance for real-time models and for emergency responders.

3. TRACER CONCENTRATIONS IN OKLAHOMA CITY JU2003

The OKC JU2003 tracer data that were placed in the data archive at DPG (2005) have been used in this analysis. However, the MSG05 tracer data are still going through QA/QC and have not been released for analysis. Consequently only the JU2003 tracer data are analyzed in this section.

3.1 *Continuous Releases*

Three continuous releases of SF_6 were made at two-hour intervals during each of the ten IOPs in JU2003. The release duration was 30 minutes. Samplers were set out on a grid in the downtown area, and in three concentric arcs (at 1, 2, and 4 km) to the north of the downtown area. Figure 3 shows the sampler set-up for IOP04. Averaging time for the samplers was 5, 15, or 30 minutes. In the downtown area, we arbitrarily assigned the gridded samplers to arc distances defined at 0.2, 0.37, 0.62, and 0.85 km.

The authors plan to evaluate emergency response models such as HPAC (DTRA, 2004) and QUIC-PLUME (Williams et al., 2004) with these sampler data. In most cases, the observations and predictions will be compared at specific monitors and times (i.e., paired in time and space) using standard model evaluation software.

However, the current paper focuses on the maximum concentration, C_{max}, observed by the monitors on a given distance arc. The paper tests several similarity relations in order to identify fundamental scientific laws acting in urban areas. The authors (Hanna et al., 2003) and many other scientists (e.g., Britter 2005 and Venkatram et al. 2002 and 2004) studying urban dispersion in cities throughout the globe have found that there are some fundamental scientific laws supported by the data. For example, Britter (2003) and Neophytou and Britter (2004) suggest a dimensionless similarity relation for continuous releases near street level in downtown areas:

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

where F indicates a generalized function, u is the spatially-averaged wind speed in the downtown urban canopy, H is the average building height, Q is the continuous mass emission rate, and x is downwind distance. Neophytou and Britter (2004) and Britter (2005) suggest that F(x/H) equals about $10(x/H)^{-2}$ for x/H < about 50. Hanna et al. (2003) suggest a slightly more complicated, but still analytical, formula for F for the Salt Lake City Urban 2000 observations.

Figure 4 presents a summary plot of Cu/Q versus x for four urban data bases. Table 6 contains the quantitative data used for Figure 4. The points for the SLC Urban 2000 SF_6 tracer data were originally plotted by Hanna et al. (2003) on a similar diagram. The OKC JU2003 data that are plotted are derived from the current analysis. For example, the over-all average wind speed for each IOP in Table 2 is used for the wind speed, u. The London-DAPPLE data are from reports by Britter (2003) and Neophytou and Britter (2004). We note that the mean building height, H, is 19 m for Urban 2000, 27 m for JU2003, and 22 m for DAPPLE. In addition, the observations from the MUST field experiment (Biltoft et al 2002 and Yee and Biltoft 2004) are plotted on Figure 4. MUST was intended to be about a 1/10 scale "urban area" created out of many shipping containers of height H = 2.54 m. The observed MUST data represent a median over the experiments plotted by Yee and Biltoft (2004), and have been scaled up to full size for this plot (i.e., the on-site observations at x = 25 m are equivalent to a full-sale urban area at x = 250 m). The so-called "OKC rooftop" concentrations are plotted separately because they are at higher elevations than the bulk of the samplers. However, it appears that there is sufficient vertical mixing that the rooftop observations are consistent with the trend of the surface observations.

The line, $Cu/Q = 10/x^2$, is plotted for x < 1000 m, which is about 50H for most of the field experiments. Most of the points at x < 1000 m are within a factor of two of this line. In general, the points for Urban 2000 and MUST are a factor of 2 or 3 above those for JU2003, although the slopes are similar even at 1 < x < 4 km. The DAPPLE points have smaller magnitudes than the JU2003 by about a factor of 2 or 3, on average, but Neophytou and Britter (2004) point out that the samplers may not have captured the observed maximum at each distance.

Wind tunnel observations by Robins (2003), carried out as part of the DAPPLE project, suggested that a $50/x^2$ relation was appropriate. However, since the wind tunnel misses much of the lateral meandering, the "50" may be an overestimate for the real atmosphere.

3.2 *Instantaneous (Puff)Releases*

There were three or four instantaneous (puff) releases carried out during each IOP, from the same release location as the continuous releases. Release intervals of 20 minutes were used for most puffs, so that the first puff would clear the sampling network before the next puff was released. Ten real-time fast-response samplers were placed downwind of the release, at distances ranging from about 100 m to about 1000 m.

Concentration time series have been plotted for each IOP and sampler. Figure 5 is presented as an example, for IOP05 and sampler #8, which is located 583 m to the NW of the source. This is one of the better-looking time series, with four clearly identifiable puffs with fairly high concentrations.

For puffs over any type of surface, the trailing part of the puff has a longer tail than the leading part. This can be explained simply because the puff is always growing, so has a smaller size (as indicated by σ_x or σ_t) when it first reaches a sampler than when it is departing the sampler. In fact, for σ_u/u approaching unity or larger, the puff is dispersing backwards faster than its center is being transported forwards, so the concentration may not reach zero for hours at a given receptor location.

For puffs moving through groups of urban buildings, there can be other explanations for the long tail in the time series. One explanation is that part of the tracer gas can become trapped in building wakes and is only slowly detrained. Another explanation is that the tracer gas may initially move upwind in the eddy on the windward side of a tall building. Some of the time series not shown here exhibit this type of very slow decrease in concentration on the tail.

Table 7 contains quantitative estimates of the characteristics of the four puffs in the time series in Figure 4. The analysis methodology follows that used by Hanna and Franzese (2000) in their analysis of along-wind dispersion using data from ten field experiments. The methods for estimating the standard deviation (σ_t) of the distribution of concentration in time are robust, in the sense that they are not overly sensitive to outliers. For example, if the actual full C(t) time series is used to calculate σ_t by the second-moment technique, then σ_t could be dominated by one or two outliers. These outliers frequently occur with puff time series in urban areas. Rather than use the second moment technique, we identified the times at the leading and trailing edges of the puff when $C = C_{max}/10$ occurred, and used the Gaussian relation that σ_t equals the difference in these times divided by 4.3. Note that the method does not account for the fact that the trailing edge has a longer tail.

The reader can compare Figure 4 and Table 7 to see how the numbers were estimated. Although the procedure has been automated, it is best to "look" at the time series to confirm the results.

Knowledge of the "time when max was observed" and the time of puff release can be used to estimate the effective transport speed of the puffs. The distance to sampler #8 is 583 m. The average puff speed from source to sampler #8 is calculated to be 2.5 m/s, which compares favorably with the "all group" average wind speed of 2.8 m/s for IOP05 (see Table 1).

The estimated σ_t values in Table 7 have an average of 62 seconds. Since the average wind speed is about 2.8 m/s, the along-wind dispersion coefficient, $\sigma_x = \sigma_t u$, is about 174 m. This can be compared with the similarity theory estimate of $\sigma_x = \sigma_u t = 287$ m, or the suggestion by Hanna and Franzese (2000) that $\sigma_x = 2u^*x/u = 2^*(0.45\ \text{m/s})^*(583\text{m}/2.8\text{m/s}) = 187$ m. This value of u* is the average observed value in Table 2 for IOP05. Thus the observed and similarity theory-estimated σ_x values in IOP05 are in good agreement (well within a factor of two).

The puff data, including the maximum concentrations for various averaging times and the dosages shown in Table 7, will be used to carry out a full evaluation of transport and dispersion modeling systems such as HPAC/SCIPUFF (DTRA, 2004) and QUIC-PLUME (Williams et al., 2004). It must be recognized, though, that a single puff is just one member of an ensemble of similar puffs that is being simulated by the model. Therefore, the plan is to group the puffs into similar scenarios. HPAC/SCIPUFF's estimate of the variance of the puff concentrations in the ensemble can also be checked.

4. CONCLUSIONS AND PLANS

This paper has presented some results of preliminary analyses of the JU2003 and the MSG05 field experiment data. The results are encouraging in the sense that similar scientific relations appear to be evident in more than one city, and some general similarity formulas can be suggested for use in future research and in operational emergency response modeling.

The following tentative conclusions have been reached:

Mean Winds and Turbulence:

When there are multiple wind observations available from a research study in an urban area, representative mean winds and turbulence can be generated by averaging within a few groups of categories, such as "downtown rooftops" or "downtown at street level" or "upwind/downwind suburban/rural".

Wind data from three cities (SLC, OKC, and NYC) support the finding that the mean wind speed and direction on the tops of tall downtown buildings are approximately equal to winds observed near the surface at a nearby airport.

The mean wind speed at street level is about 1/3 of the mean wind speed at the tops of tall downtown buildings.

The wind direction at street level in the downtown area can be in any direction (not necessarily equal to the wind direction at the tops of buildings), due to the convergences and divergences near the surface in recirculation zones near the tall buildings.

Turbulence calculations from sonic anemometer data in downtown areas suggests that the turbulence quantities such as σ_u, σ_w, σ_T, and u* are fairly robust, with little variation from street level to rooftop or from one anemometer to the next. For example, one cannot go far wrong by simply assuming that σ_w is 0.5 or 1.0 m/s for moderate wind speeds. Similarity relations such as $\sigma_w/u^* = 1.5$ are shown to be valid for these urban data. Turbulence integral time scales in downtown areas are found to equal about 20 seconds (corresponding to an integral length scale of about 40 m).

No effect of day versus night (i.e., stability) is seen for these urban downtown wind and turbulence data, supporting the hypothesis that the boundary layer is nearly-neutral most of the time in large city centers. This effect is primarily due to the strong mechanical mixing caused by the buildings.

Dispersion of Tracer Gas:

The JU2003 concentration observations from the continuous SF_6 release trials were analyzed and compared with normalized observations from three other urban field experiments (SLC Urban 2000, London-DAPPLE, and MUST). When the maximum concentration, C_{max}, on a sampling arc is considered, the observations of $C_{max}u/Q$ versus distance, x, are similar for the four experiments. At distances less than about 500 to 1000 m, for full-scale urban downtown areas, the formula, $C_{max}u/Q = 10/x^2$ is valid. In dimensionless terms, $C_{max}uH^2/Q = 10/(x/H)^2$ at $x/H < 50$. At $x/H > 50$, a similarity formula is still valid but the exponent in the x/H term slowly decreases to about -1.5.

For the JU2003 instantaneous puff trials, an example is presented showing how the puff speed and the along-wind dispersion coefficient, σ_x, can be calculated from the C(t) time series. The average puff speed for the four trials in IOP05 is found to be within 10 % of the observed average wind speed over all the anemometer groups. The observed σ_x for the puffs is seen to agree well with the similarity formula $\sigma_x = \sigma_v t$ or, alternatively, $\sigma_x = 2u^*t$.

The following activities are planned over the next year:

Data from the JU2003 data archive at DPG (2005) are being used to calculate additional parameters, such as turbulent speeds and averaged concentrations for various averaging times. Some of these data have been discussed in this paper. This effort will continue and the newly-calculated parameters, along with text descriptions of methodologies, will be added to the JU2003 data archive.

The data from the March 2005 MSG05 field experiment will be set up in a DPG data archive similar to that for JU2003. The wind and turbulence data are nearly ready to be placed in the data archive, but the concentration data are still going through QA/QC and will be released soon.

The authors will continue to seek fundamental scientific relationships supported by the field data from several cities. The current paper describes some tentative examples. Once these relationships are confirmed at different urban areas around the globe, they can be confidently applied to other large urban areas, in order to aid emergency responders and/or air pollution agencies.

A fundamental question is how to parameterize the effects of stability on the urban boundary layer. It is concluded above that the boundary layer is nearly always close to neutral in the built-up downtown areas of the large cities studied here. However, these field experiments tend to be carried out when wind speeds are at least moderate. As wind speed becomes light and variable, stability should become more important. There also should be a transition from nearly neutral conditions in the downtown area to more stable or unstable conditions in the surrounding suburbs and rural areas. It is anticipated that, as in Monin-Obukhov theory, the effect of stability will depend on the ratio of the momentum flux to the heat flux, where the heat flux in the urban area should include anthropogenic heat inputs as well as solar heating of buildings.

A major goal for the next year is to evaluate the performance of urban transport and dispersion models, such as HPAC (DTRA, 2004) and QUIC-PLUME (Williams et al., 2004). These exercises will compare predicted concentrations paired in time and space, as well as maximum concentrations on distance arcs. Model internal parameters such as puff transport speed and σ_x, will also be compared with observations.

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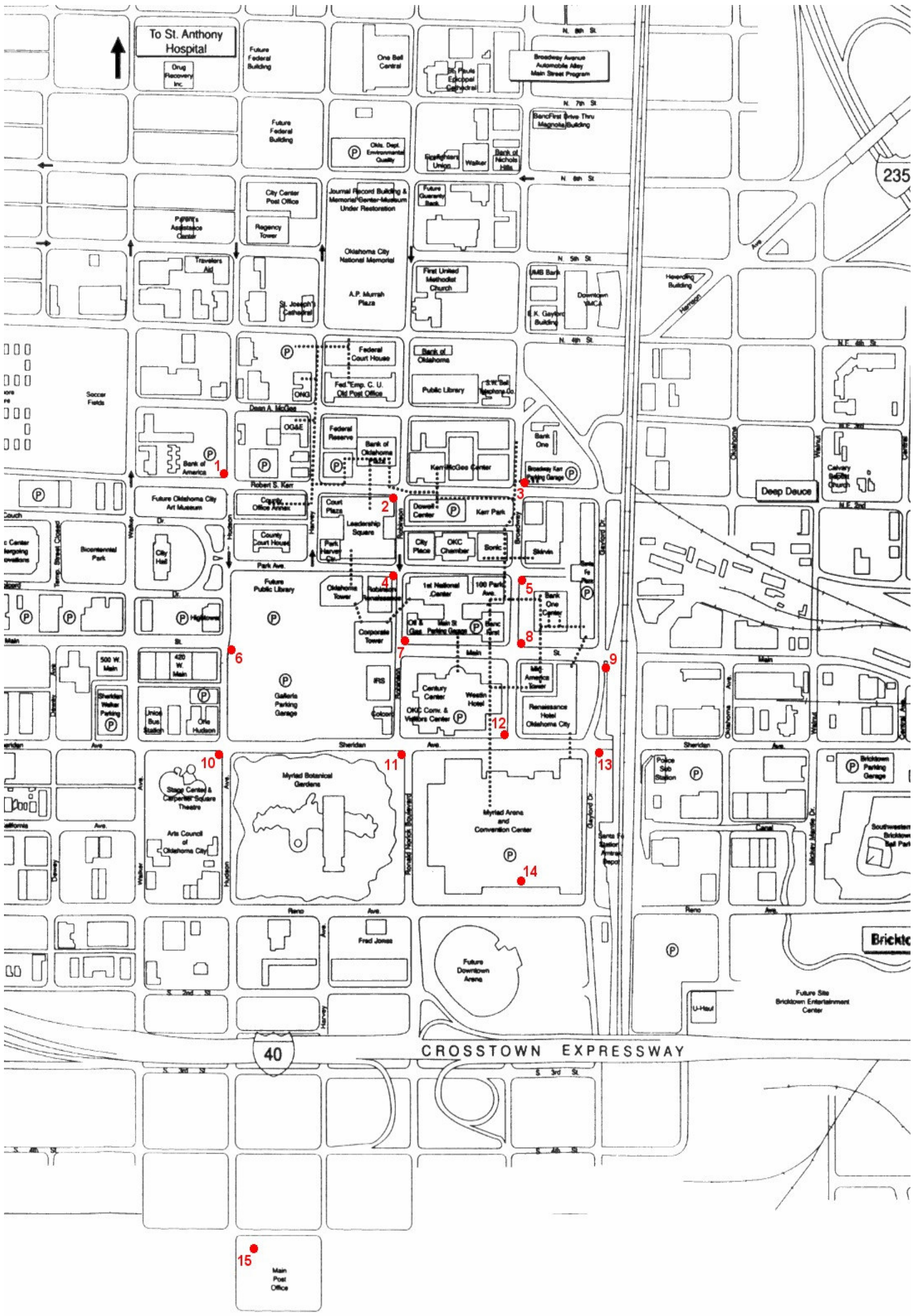

Figure 1. Map of downtown Oklahoma City, site of Joint Urban 2003 (JU2003) field experiment. Locations of DPG sonic anemometers are shown. Data from these anemometers, as well as many additional anemometers, were analyzed to generate the summary results in this paper.

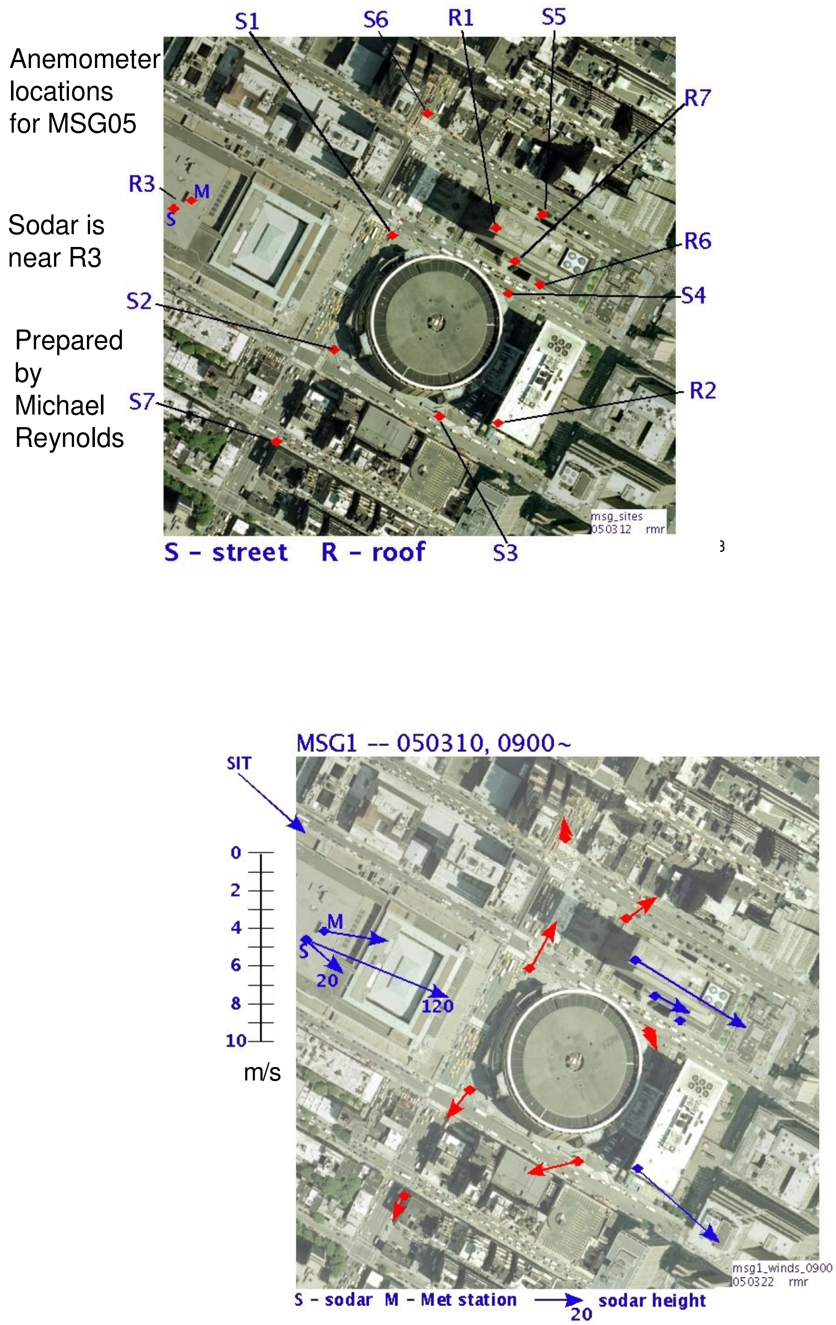

Figure 2 – View of area around Madison Square Garden (MSG) in Manhattan, where MSG is the round building and has diameter 130 m and height 50 m. The 229 m tall One Penn Plaza building is to the NE of MSG and the 153 m tall Two Penn Plaza building is to the ESE of MSG. Top: Anemometers used for wind observations are shown (S near street level and R at rooftop). The small "S" on the left edge of the figure indicates the sodar location on the Post Office roof (24 m above street level). Bottom: Observed 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. Figures courtesy of Michael Reynolds, Brookhaven National Laboratory

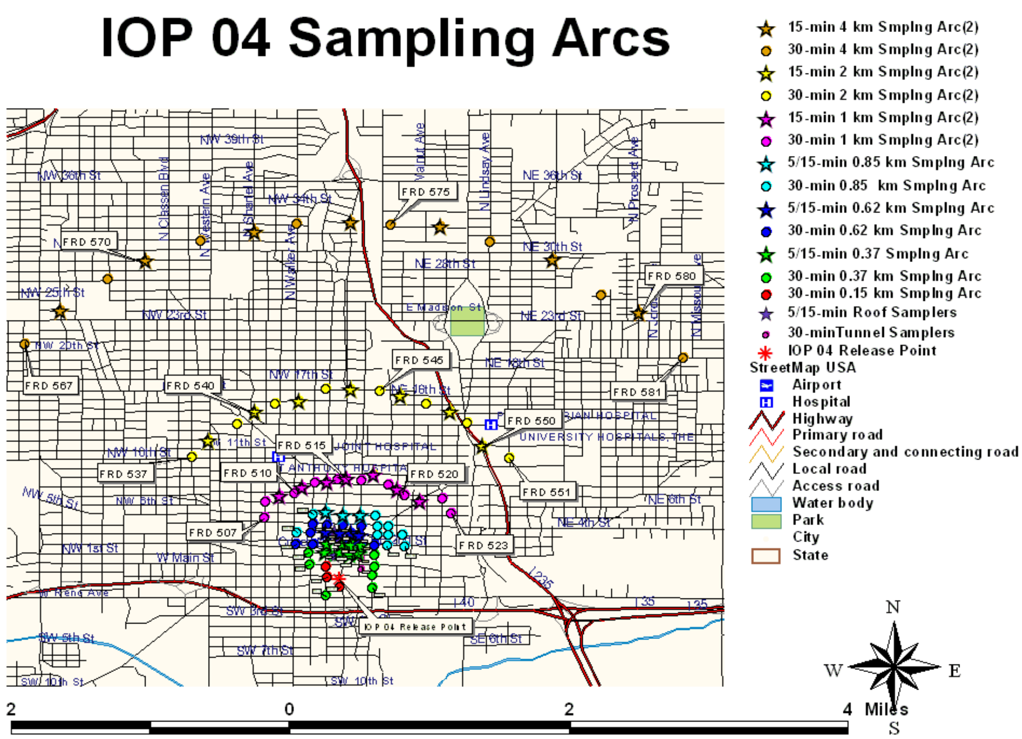

Figure prepared by John White of DPG

Figure 3. Map of downtown Oklahoma City, site of Joint Urban 2003 (JU2003) field experiment. Locations of NOAA Air Resources Laboratory Field research Division (ARLFRD) SF_6 samplers are shown, as used in IOP04. Data from these samplers were analyzed to generate the summary results for continuous releases in this paper.

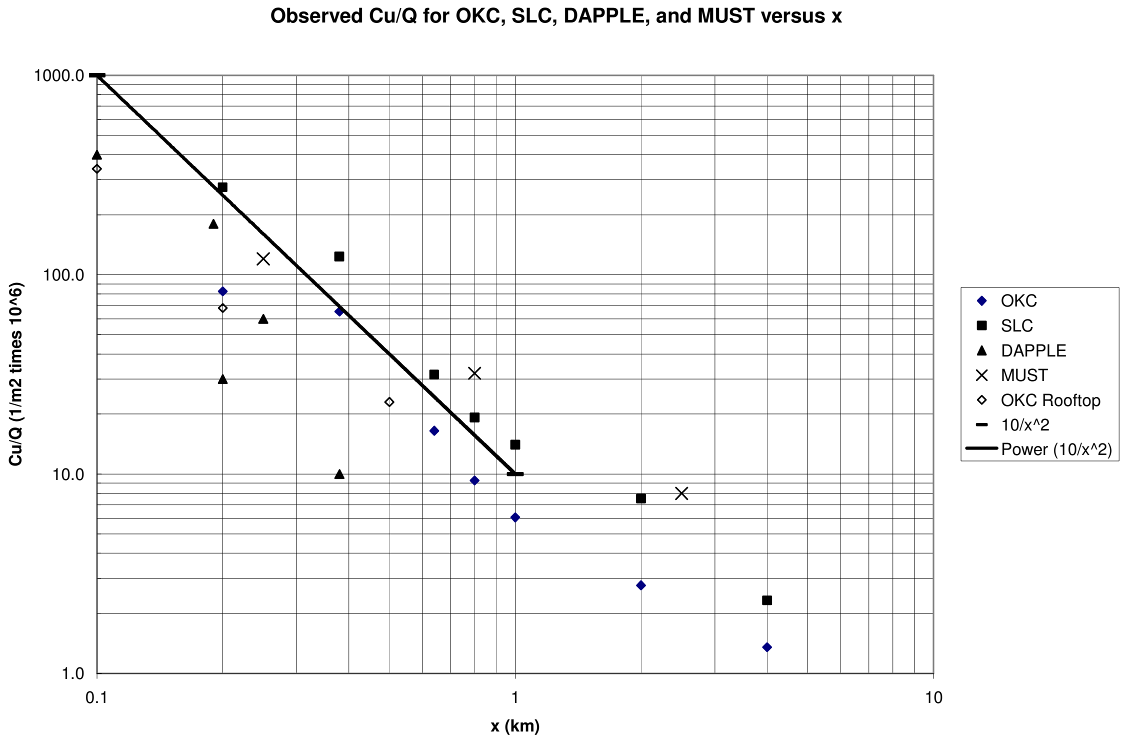

Figure 4. Summary plot of Cu/Q versus x for four field data sets (OKC, SLC, London DAPPLE, and MUST). C is the maximum 30-minute averaged concentration observed along a cross-wind arc of monitors at a given downwind distance, x. The line given by $Cu/Q = 10/x^2$ is drawn, which Neophytou and Britter (2004) and others have suggested as valid for $x/H < 50$, or for $x < 1000$ m when mean building height, H, is 20 m.

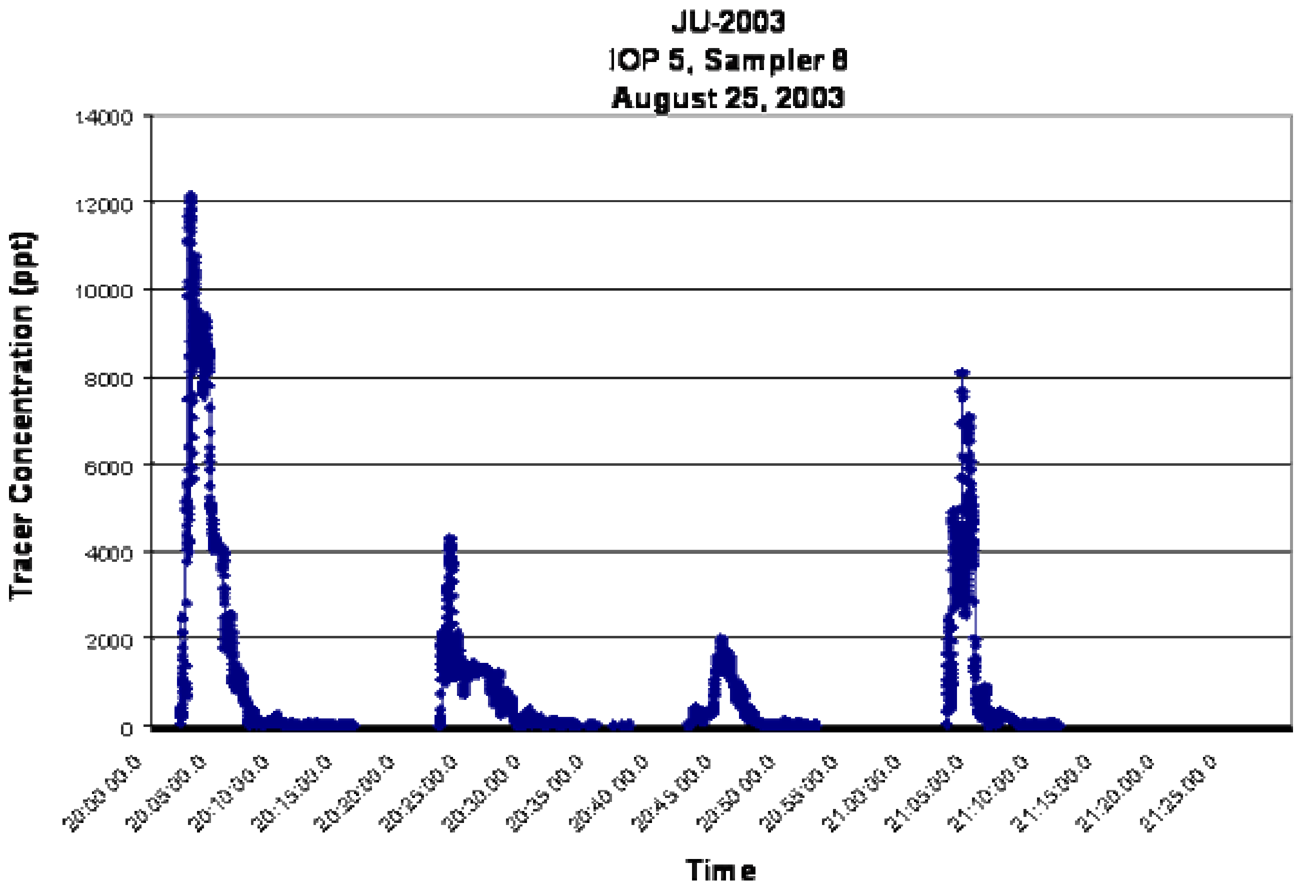

Figure 5. Observations of concentrations (ppt) by fast-response Sampler #8 during IOP05 of JU2003. Time is in UTC (LDT = UTC – 5:00). Instantaneous releases of puffs of SF_6 occurred at a location 583 m to the southeast of this sampler. Four puffs were released: puff 1 at 20:00:00, puff 2 at 20:20:00, puff 3 at 20:40:00, and puff 4 at 21:00:00 UTC. The results of the analysis of these data are given in Table 7.

Table 1. Summary of Observed Wind Speed (WS) and Wind Direction (WD) during Joint Urban 2003 (JU2003) in Oklahoma City. Winds are Averaged over Each 8-Hour Duration Intensive Operating Period (IOP). Winds are Also Averaged within Seven Groups of Similar Types of Anemometer Locations. Overall Averages are given in the Right Two Columns and in the Bottom Row.

	Exposed bldg top downtown 7 sites dpg & pnnl z = 14 to 153 m		Sheltered Bldg tops in dense downtown area 14 lanl and 9 uou sites z = 19 to 47 m		Semiexposed downtown in bldgs but not street level 5 dpg sites z > 10 m		Street canyon down-town all z = 8 m 18 dpg and 2 OU sites		Semi-exposed park or resid. 7 dpg, 1 llnl crane 2 arl towers, all 8-10 m		Suburban/rural upwind/downwind		Airport		Average over all groups	
	Wind group 1a		Wind group 1b		Wind group 2		Wind group 3		Wind group 4		Wind group 5		Wind group 6		Avg WS	Avg WD
	WS m/s	WD	WS m/s	WD	WS m/s	WD	WS m/s	WD	WS m/s	WD	WS m/s	WD	WS m/s	WD	m/s	
Avg IOP01	3.4	167	0.78	207	1.5	150	1.1	155	1.5	138	2.7	193	1.8	35	1.8	149
Avg IOP02	4.3	215	0.77	275	2.6	191	1.4	222	1.8	221	3.5	214	5.0	177	2.8	216
Avg IOP03	6.4	196	0.58	232	3.6	178	1.9	205	2.7	182	5.4	201	5.7	177	3.7	196
Avg IOP04	6.1	203	0.77	235	3.9	184	2.1	212	2.8	184	5.3	204	6.8	171	4.0	199
Avg IOP05	3.8	192	0.74	222	1.8	172	1.2	189	1.6	194	3.2	193	7.5	174	2.8	191
Avg IOP06	4.3	195	0.44	202	2.6	180	1.4	198	2.2	176	3.7	196	7.1	209	3.1	194
Avg IOP07	4.8	207	0.82	270	2.5	189	1.6	211	1.5	213	2.9	197	3.3	230	2.5	217
Avg IOP08	6.1	143	0.93	170	2.8	147	1.7	152	2.9	157	4.3	165	8.1	167	3.8	157
Avg IOP09	5.5	182	0.49	153	2.8	153	1.4	199	2.3	168	3.3	186	6.2	198	3.2	177
Avg IOP10	5.0	193	0.67	227	2.7	173	1.5	209	1.9	184	2.5	192	2.6	223	2.4	200
Avg All	5.0	189	0.70	219	2.7	172	1.5	195	2.1	192	3.7	194	5.4	176	3.0	191

Table 2. Summary Results of Turbulence Calculations for 20 DPG Sonic Anemometers in Oklahoma City (JU2003). All are at a Height of 8 m in the Downtown Area. Each Intensive Operating Period (IOP) has Duration 8 Hrs. Since the Turbulence is Calculated for 30 Min Periods, there are a Maximum of n = (20 Anemometers) times (16 Records per IOP) = 320 Data Points for each IOP.

IOP	n	WS	WD	w	T	sigma_u	sigma_v	sigma_w	sigma_h	sigma_T	TKE	u_star	(sigma_h)/u*	(sigma_w)/u*
		m/s	degree	m/s	K	m/s	m/s	m/s	m/s	K	m^2/s^2	m/s		
1	320	1.14	150	0.095	300.5	0.75	0.76	0.50	1.09	0.31	0.82	0.33	3.30	1.50
2	320	1.49	213	0.107	306.7	0.99	1.04	0.65	1.47	0.49	1.36	0.41	3.60	1.59
3	312	2.04	192	0.116	304.0	1.48	1.36	0.85	2.08	0.37	3.55	0.55	3.81	1.56
4	298	2.19	208	0.105	305.1	1.32	1.38	0.88	1.95	0.44	2.57	0.55	3.54	1.60
5	320	1.54	170	0.069	306.6	1.54	0.96	0.64	1.95	0.36	4.87	0.45	4.35	1.44
6	320	1.80	181	0.127	306.2	1.07	1.06	0.65	1.55	0.47	1.82	0.42	3.66	1.53
7	319	1.58	218	0.143	303.7	0.70	0.76	0.56	1.04	0.17	0.76	0.34	3.09	1.66
8	304	2.17	150	0.125	300.0	1.57	1.26	0.86	2.12	0.13	3.78	0.56	3.81	1.55
9	320	1.69	177	0.194	301.9	1.13	1.06	0.69	1.62	0.17	2.57	0.44	3.67	1.57
10	280	1.63	199	0.156	304.7	0.85	0.89	0.60	1.26	0.21	1.36	0.36	3.47	1.65
mean		**1.73**	**186**	**0.124**	**303.9**	**1.14**	**1.06**	**0.69**	**1.61**	**0.31**	**2.34**	**0.44**	**3.63**	**1.56**

Note that $(\text{sigma\_h})^2 = (\text{sigma\_u})^2 + (\text{sigma\_v})^2$ [or $\sigma_h^2 = \sigma_u^2 + \sigma_v^2$]

Table 3. Estimates of Lateral Turbulence σ_v from Wind Direction Standard Deviation σ_θ from Standard Anemometers at JU2003 for IOP10

Anemometer Group	**1a-Building Tops**	**2-Downtown Semi-Exposed**	**3-Downtown 8m Street Level**	**4 - Urban Park/Residential**	**5 – Suburban/Rural Upwind/Downwind**
Mean Wind u	4.83 m/s	2.46 m/s	1.52 m/s	1.80 m/s	2.59 m/s
σ_θ (degrees)	13.4 degrees	23.0	47.4	30.4	6.7
$\sigma_v = u\tan\sigma_\theta$	1.15 m/s	1.04 m/s	1.66 m/s	1.05 m/s	0.30 m/s

Table 4. Summary of Observed Wind Speed (WS) and Wind Direction (WD) during Madison Square Garden 2005 Field Experiments IOP01 (5 Hrs on March 10) and IOP02 (5 Hrs on March 14). Locations of R (Rooftop) and S (Surface) Sites are Shown in Figure 2 (top). The Two Remote Sounders (e.g., SODARS) are not Included in the Analysis.

Site	Name	z (m) agl	IOP01 WS m/s	IOP01 WD deg	IOP02 WS m/s	IOP02 WD deg	ΔWS m/s	ΔWD deg	Comment
R1	One Penn Plaza	233	7.3	286	7.0	327	-0.3	+41	Tall rooftop
R2	Two Penn Plaza	133	5.8	306	3.8	318	-2.0	+16	In OPP wake 02
R3	Post Office	34	3.6	281	3.9	269	+0.3	-12	In bldg wake 02
CCNY		50	5.2	266	5.2	309	0	+43	Open rooftop
SIT		52	5.7	297	6.9	335	+1.2	+38	Open rooftop
EML		75	3.3	286	4.3	323	+1.0	+37	Open rooftop
LBR	Lehmann	200?	4.7	286	3.6	308	-1.1	+22	Open rooftop
JFK		3.4	6.2	290	6.5	320	+0.3	+30	Flat airport
S1	NW MSG	3.0	3.0	212	2.7	187	-0.3	-25	See figure
S2	SW MSG	3.0	1.7	27 steady	1.2	80 variable	-0.5	variable	See figure
S3	SE MSG	3.0	3.3	76 steady	2.6	Variable W-E	-0.7	variable	See figure
S4	NE MSG	3.0	1.6	Variable NNW-SSE	3.6	165 steady	+2.0	variable	See figure
S5	NW OPP	3.0	2.6	238	1.7	292	-0.9	+54	See figure
S6	Front New Yorker	5.0	1.2	162	---	---	---	---	Channeled 10
S7	8th Ave S of MSG	3.0	1.2	17	2.0	28	+0.8	+11	Channeled

Table 5. Summary Results of Turbulence Calculations for Six MSG05 Sonic Anemometers in New York City. R1 and R2 are on One Penn Plaza and Two Penn Plaza Rooftops at Heights of 223 m and 153 m, Respectively. S1, S4, S5 and S7 (all at z = 3 m) are on the NW Corner of MSG, the NE Corner of MSG, the NW Corner of One Penn Plaza, and along 8th Avenue to the S of MSG, Respectively (see Figure 2, Top Panel). Each Intensive Operating Period (IOP) has Duration 5 Hrs. The Means and Turbulence are Calculated for 30 Min Periods.

IOP	station	speed m/s	direction degrees	w m/s	T C	sigma-u m/s	sigma-v m/s	sigma-w m/s	sigma-h m/s	sigma-T C	TKE m^2/s^2	u* m/s	sigma-h/u*	sigma-w/u*
1	R1	6.38	293.0	1.61	-6.15	2.72	2.13	1.16	3.47	0.91	6.78	0.79	4.58	1.46
2	R1	6.32	324.2	1.49	-2.00	1.92	2.78	1.23	3.38	1.09	6.61	0.68	5.19	1.81
1	R2	4.80	306.2	0.84	-3.59	2.95	2.35	1.14	3.78	0.79	7.84	0.60	8.07	1.89
2	R2	3.16	321.6	0.57	0.48	2.52	2.57	1.17	3.60	0.76	7.22	0.54	7.63	2.15
2	S1	2.48	191.3	0.17	1.89	1.49	1.41	0.78	2.06	0.58	2.45	0.68	3.05	1.15
1	S4	1.34	280.2	0.14	-4.36	1.43	2.02	0.70	2.47	0.44	3.45	0.61	4.21	1.15
2	S4	3.82	164.7	0.81	-0.72	0.94	1.71	0.80	1.95	0.43	2.27	0.70	2.90	1.14
1	S5	2.41	246.2	-0.01	-3.34	1.07	1.72	0.69	2.03	0.54	2.31	0.45	4.61	1.53
1	S7	0.95	22.2	-0.96	-3.23	0.80	1.22	0.61	1.46	0.56	1.25	0.50	3.00	1.21
2	S7	1.95	29.1	-0.91	0.47	0.97	1.38	0.69	1.68	0.55	1.68	0.47	3.61	1.46
avg	R1	6.35	308.6	1.55	-4.07	2.32	2.45	1.19	3.42	1.00	6.69	0.73	4.89	1.62
avg	R2	3.98	313.9	0.71	-1.55	2.74	2.46	1.15	3.69	0.78	7.53	0.57	7.85	2.01
avg	S1	2.48	191.3	0.17	1.89	1.49	1.41	0.78	2.06	0.58	2.45	0.68	3.05	1.15
avg	S4	2.58	222.4	0.48	-2.54	1.19	1.86	0.75	2.21	0.44	2.86	0.66	3.55	1.14
avg	S5	2.41	246.2	-0.01	-3.34	1.07	1.72	0.69	2.03	0.54	2.31	0.45	4.61	1.53
avg	S7	1.45	25.6	-0.93	-1.38	0.89	1.30	0.65	1.57	0.55	1.46	0.49	3.30	1.33
avg	rooftop	5.16	311.2	1.13	-2.81	2.53	2.46	1.17	3.56	0.89	7.11	0.65	6.37	1.79
avg	street	2.23	variable	-0.07	-1.34	1.16	1.57	0.72	1.97	0.53	2.27	0.57	3.63	1.29
avg	all	3.70	variable	0.53	-2.08	1.84	2.01	0.94	2.76	0.71	4.69	0.61	5.00	1.54

Note that $(\text{sigma\_h})^2 = (\text{sigma\_u})^2 + (\text{sigma\_v})^2$ [or $\sigma_h^2 = \sigma_u^2 + \sigma_v^2$]

Table 6. Observations of Averaged Cu/Q (in Units of 10^6 m^{-2}) at Different Downwind Distances (x) from Four Field Experiments. These Data are Plotted in Figure 4.

x (km)	*0.1*	*0.19*	*0.2*	*0.25*	*0.38*	*0.5*	*0.64*	*0.8*	*1*	*2*	*2.5*	*4*
OKC (JU2003)			83		65.4		16.5	9.27	6.06	2.76		1.35
London DAPPLE	400	180	30	60	10							
DPG MUST				120				32			8.0	
OKC (JU2003) ROOFTOP	340		68			23.0						
SLC (Urban 2000)			274		123		31.5	19.2	14.0	7.53		2.32

Notes:

C is the maximum observed concentration on the arc of monitors at distance x.

The London DAPPLE data are listed by Britter (2003) and Neophytou and Britter (2004) as CuH^2/Q and have been converted to Cu/Q assuming H = 22 m.

The DPG MUST data were presented by Yee as CuH^2/Q. These were converted to Cu/Q using H = 2.54 m. In addition, since the MUST experiment was a "1/10 scale" field experiment, the data have been further converted to full scale for the above exercise.

The OKC (JU2003) rooftop data are separately plotted, since they are from greater heights than the other data.

Table 7. Summary of Analysis of Fast-Response Time Series of Concentrations Observed by Sampler #8 during IOP05 of JU2003. Instantaneous Releases of Puffs of SF_6 Occurred at a Location 583 m to the Southeast of this Sampler. The Concentration Time Series is Plotted in Figure 5.

Puff*	Conc Max (ppt)	Time when max was observed	Puff arrival time	Puff departure time	Puff duration (s)	Puff dosage (ppt-s)	σ(time) (s) = (C>Cmax/10 duration)/ 4.3	First time when 10% of max value observed	Last time when 10% of max value observed	Duration (s) of the period when values are at least 10% of max	Max conc (ppt) of 1 minute moving average	Max conc (ppt) of 5 minutes moving average	Max conc (ppt) of 10 minutes moving average
1	12140	20:03:07.0	20:02:20.0	20:10:23.0	483.0	1475010	63.4	20:02:25.5	20:06:58.0	272.5	9408	4820	
2	4288	20:23:36.5	20:22:49.0	20:33:20.5	631.5	450314.4	78.5	20:22:52.0	20:28:29.5	337.5	2538	1407	786
3	2018	20:45:00.5	20:42:39.0	20:48:38.0	359.0	213730.4	63.2	20:42:56.5	20:47:28.0	271.5	1541	699	
4	8098	21:04:03.0	21:02:50.5	21:08:36.0	345.5	510219.7	42.1	21:02:52.0	21:05:53.0	181	4755	1755	

*Release times of puffs: puff 1 at 20:00:00, puff 2 at 20:20:00, puff 3 at 20:40:00, puff 4 at 21:00:00 UTC (LDT = UTC -5:00)