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ORIGINAL PAPER

Observed winds, turbulence, and dispersion in built-up downtown areas of Oklahoma City and Manhattan

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Abstract Wind and tracer data from the Oklahoma City Joint Urban 2003 (JU2003) and the Manhattan Madison Square Garden 2005 (MSG05) urban field experiments are being analyzed to aid in understanding air flow and dispersion near street-level in built-up downtown areas. The mean winds are separately calculated for groups of anemometers having similar exposures such as "near street level" and "on building top". Several general results are found, such as the scalar wind speed at street level is about 1/3 of that at building top. Turbulent standard deviations of wind speed components and temperature, and vertical fluxes of momentum and sensible heat, are calculated from sonic anemometers near street level at 20 locations in JU2003 and five locations in MSG05, and from two rooftop locations in MSG05. The turbulence observations are consistent with observations in the literature at other cities, although the JU2003 and MSG05 data are unique in that many data are available near street level. For example, it is found that the local (i.e., at the measuring height) σ_w/u_* averages about 1.5 and the local u_*/u averages about 0.25 in the two cities, where σ_w is the standard deviation of vertical velocity fluctuations, u_* is the friction velocity, and u is the wind speed. The ratio of temperature fluctuations to temperature scale, σ_T/T_* , averages about -3 in both cities, consistent with similarity theory for slightly unstable conditions, where σ_T is the standard deviation of temperature fluctuations, and T_* is the temperature scale. The calculated Obukhov length, L, is also consistent with slightly unstable conditions near street level, even at night during JU2003. The SF_6 tracer concentration observations from JU2003 are analyzed. Values of uC_{max}/Q for the continuous releases are calculated for each release and arc distance, where C_{max} is the 30-min average arc maximum concentration, Q is the continuous source emission rate, and u is the spatial-averaged wind speed in the downtown

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area. The basic characteristics of the JU2003 plot of averaged uC_{max}/Q agree reasonably well with similar plots for other urban experiments in Salt Lake City and London (i.e., at $x < 1000$ m, $C_{max}/Q = Ax^{-2}$). A is found to be about 3 during the day and about 10 during the night.

Keywords Similarity laws · Turbulence in cities · Urban boundary layers · Urban dispersion

1 Introduction

1.1 Background

As part of a comprehensive analysis of the Oklahoma City (OKC) Joint Urban 2003 (JU2003) data and the New York City (NYC) Madison Square Garden 2005 (MSG05) urban field data, the meteorological and tracer data are analyzed and the results are studied and discussed 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.

Molina and Molina (2004) provide a comprehensive review of air pollution problems associated with the growth of cities throughout the world, and note that there are 20 "megacities" with populations exceeding 10 million. The largest five cities are Tokyo, Mexico City, New York City, Sao Paulo, and Mumbai, all characterized by broad built-up downtown areas of width 5 or 10 km or more, with hundreds of buildings of height greater than 50 m and several of height greater then 200 m, and deep street canyons.

Standard texts (e.g., Pasquill 1974; Stull 1997) on wind and turbulence profiles and dispersion in the atmospheric boundary layer generally emphasize rural surfaces where the roughness elements are relatively small (heights less than about 1 m) with observations made at heights exceeding about ten roughness element heights. At such heights, the influence of an individual roughness element is minimized. An 'early" urban boundary-layer experiment took place in St. Louis in the mid-1970s and observations of turbulent velocities were made in several locations ranging from rural to suburban to urban (Clarke et al. 1987). The results revealed the presence of not-unexpected large increases in the turbulent velocities over the urban area, with the difference accentuated at night. Oke (1987) was one of the first to include a discussion of the urban boundary layer in a basic text, describing the need to account for the flow at heights near and below the roughness elements (i.e., buildings). In the past 15–20 years, there has been increased interest in the urban boundary layer and reviews of extensive analyses of wind and turbulence profiles can be found in Rotach (1995, 1996, 2005), Roth (2000), Macdonald (2000), Hanna and Britter (2002), Britter and Hanna (2003), and Kastner-Klein and Rotach (2004).

In addition to the OKC JU2003 and the NYC MSG05 field experiments, there have been several other detailed urban meteorology and dispersion field experiments. Some examples include the Zurich urban experiment (Rotach 1995), the Basel Urban Boundary Layer Experiment (BUBBLE) (Rotach et al. 2005; Christen 2005), the Marseille field experiment (Mestayer et al. 2005; Grimmond et al. 2004), 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 presented in the references (such as Grimmond and Oke 2002; Roth 2000) 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 height, H. Generally there are only limited observations made at heights below H. The buildings that are studied are typically no more than a few storeys high. 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, a new series of field experiments in the U.S. is addressing flow and dispersion in cities with large built-up areas containing at least five or ten tall ($z > 100\,\text{m}$) 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 mean winds, turbulent velocities, and heat and momentum fluxes from two of these experiments—JU2003 and MSG05. Tracer concentrations are analyzed for JU2003.

1.2 Review of literature on turbulence in cities

Observations of local turbulent velocity components and momentum and sensible heat fluxes described by Rotach (1995, 1996, 2005) indicate that the standard deviations of the turbulent velocity components (σ_u, σ_v, and σ_w) and the local (observed at the anemometer height) friction velocity, u_*, are maximized at about one or two times the mean height of the buildings, H, and decrease by a factor of about two or more at lower heights near the mid-level of the buildings. Roth (2000) showed that turbulence observations in urban areas roughly agreed with Monin–Obukhov similarity theory, but with much scatter and some differences in empirical coefficients. Hanna and Britter (2002) and Britter and Hanna (2003) present some non-dimensional relations that allow the wind speed and turbulence deep within the urban canopy to be parameterized simply. Basic similarity relations for urban dispersion are presented by Hanna et al. (2003), Venkatram et al. (2002, 2005) and Britter (2005), and we extend these simple analyses using the JU2003 and MSG05 data.

Venkatram et al. (2002, 2005) have observed u_* and other turbulent variables in their urban boundary layer studies in residential and industrialized areas in San Diego and Wilmington, CA, and conclude that the local u_* observed above the buildings is a useful scaling velocity. Given the u_* value above the building tops, it is possible to estimate the turbulent speed components and hence the rate of plume dispersion. Their field experiments took place, though, where the buildings were only one or two storeys high and turbulence instruments were placed at heights in the range from about 1.5–2H. But in the downtown areas of major cities such as Oklahoma City and Manhattan, the buildings are so high that it is difficult to make observations at 1.5 or 2H.

Britter and Hanna (2003) point out that the friction velocity, u_*, can be determined and defined a number of different ways. The traditional engineering definition is that u_* is proportional to the square root of the drag exerted by the surface roughness elements on the boundary layer of the atmosphere. In meteorology, recognizing that the drag is proportional to the momentum flux, the primary definition of u_* is based on the $u'w'$ and $v'w'$ covariances, measured close enough to the surface for u_* to be considered the "surface" value. Note that u', v', and w' are the turbulent velocity components measured by a fast-response anemometer (usually a sonic anemometer in the current study) in the x, y, and z directions, respectively, and are usually based on averaging times of a few tens of minutes.

The above definition of u_* is most often used for ground surfaces such as mowed grass where the observation is made at a height, z, that is at least a factor of ten larger than H. This is not possible in forest canopies and urban areas, where H is usually $> 10\,\text{m}$, and wind observations are usually made at heights on the order of H or less than H. As stated above, in urban areas (or within any deep roughness layer, such as a forest), u_* is known to have a minimum near the ground level, increase to a maximum at about one or two H, and decrease slowly above that level. As Cheng and Castro (2002) point out, the observed vertical profile of local u_* is likely to vary from location to location in any canopy (vegetation or urban). In the current paper, the u_* that is discussed is always the local value, and averaging times of 30 min are used.

Besides H, the urban building morphology (i.e., the three-dimensional structure) is often parameterized by the frontal and plan area indices, λ_f and λ_p, respectively (see Macdonald 2000). λ_f is the average of the total building frontal area (facing the wind) divided by the average of the total surface area of the lot, and is typically about 0.2–0.5 in downtown areas of large cities. λ_p is the average of the total building plan area divided by the average of the total surface area of the lot, and has a value slightly less than λ_f in areas with buildings that are taller than they are wide. Grimmond and Oke (1999) carried out a comprehensive analysis of surface roughness length, z_o, and displacement length, d, in many cities. Britter and Hanna (2003) suggest empirical formulae for the ratios, z_o/H, d/H, and u(near street level)/$u(H)$, as functions of λ_f and λ_p.

Some suggested values for the magnitudes of urban winds and turbulence and associated similarity relations are listed in Table 1, based on a review of the literature. These relations are tested with the JU2003 and MSG05 data in later sections. Britter and Hanna's (2003) recommendations, based on a survey of many urban observations, are included. In addition, Table 1 contains recommendations from the following six studies: (1) Rotach (1995) collected and analyzed observations in Zurich, (2) Macdonald (2000) studied observations in small-scale field experiments and fluid modelling experiments, (3) Grimmond et al. (2004) focused on results from a field experiment in Marseille, (4) Roth (2000) investigated turbulence data from 14 cities, (5) Morrison and Weber (2005) analyzed data from Birmingham, U.K. and (6) Kastner-Klein and Rotach (2004) studied a wind-tunnel simulation of Nantes. As mentioned previously, very few of the data in the references are from the mid to lower levels of the urban canopy (UC).

1.3 Introduction to JU2003 and MSG05 field experiments

The JU2003 (Allwine et al. 2004; Clawson et al. 2005) and MSG05 (Hanna et al. 2006) field experiments are part of a series of urban experiments 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 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. These urban experiments are intended to address near-surface meteorological conditions for use in assessing releases from continuous and instantaneous point sources in the 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 JU2003 and MSG05 urban turbulence observations analyzed in this paper are made using sonic anemometers, which are necessary in urban street canyons, where wind speeds are generally low, often in the range of about 0.01–0.10 m s^{-1}. It is difficult to site the anemometers in an urban area because no site is "representative" in such a complicated setting. Oke (2004) gives some guidelines for siting anemometers in urban areas, but it is impossible to completely avoid interferences by nearby buildings.

Table 1 Summary results from some papers in the Literature Concerning Turbulence Observations and similarity relations in and above urban canopies (UCs), for Nearly–Natural Conditions H is the mean building height

Turbulence quantity	Britter & Hanna (2003)Recs	Rotach (1995) & Macdonald (2000) Observations	Grimmond et al. (2004)Obs in Marseille	Roth (2000) 14 cities	Morrison & Weber (2005) Birmingham	Kastner-Klein & Rotach (2004)
σ_u/u_*	1.6 in UC, 2.4 near & above H	1.2–1.6 in mid to upper UC		2.4 near H		
σ_u/u	0.45 in UC		0.4 at 1.5–3 H			
σ_v/u_*	1.4 in UC, 1.9 near & above H					
σ_v/u	0.39 in UC		0.35 at 1.5–3 H			
σ_h/u_*	2.1 in UC, 3.1 near & above H					
σ_w/u_*	1.1 in UC, 1.3 near & above H					
σ_w/u	0.31 in UC		0.35 at 1.5–3 H	0.25 near H		
σ_w					$0.4\,\mathrm{ms}^{-1}$ at night; $0.8\,\mathrm{ms}^{-1}$ in day in UC	
TKE/u_*^2	2.87 in UC, 5.53 near & above H Ratio = 0.52					Ratio = 0.3 for value in UC to value near H
σ_T/T_*				−3 near H for slightly unstable		
u_*/u	0.28 in UC for downtown area		Obs. 0.15 near H. Formula gives 0.44 near surface in UC	0.2–0.3 near H		Near 0 in sheltered areas to larger at intersections

For anemometers near street level, placement in a street canyon can predetermine the dominant local wind directions and the ratio of the wind speed to the above-roof-level wind speed. For this reason, if a sufficient number of sonic anemometers is available, they should be spaced so as to cover a range of expected street orientations and intersections. Most of the analysis in later sections concerns the averages of the observations from several anemometers over a several hour period. However, estimates of the space and time variability are also given.

2 JU2003 and MSG05 descriptions and mean wind results

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

2.1 Oklahoma City Joint Urban 2003 (JU2003)

Each of the ten IOPs during JU2003 involved intense observations over a period of about eight hours (Allwine et al. 2004; Clawson et al. 2005; DPG 2005). An IOP was conducted only if the wind speed and direction were suitable to ensure that the tracer plume would blow over the array of samplers, which were generally located to the north of the downtown area. Another criterion was that there should be no precipitation. The first six IOPs took place during the day and the last four IOPs took place during the night. The present analysis uses averages and turbulence data from the JU2003 archive (DPG 2005), but in most cases, the winds and turbulence have been calculated independently using the "raw" (fast response 10 Hz) data files. The main reason for the independent calculations was that a variety of averaging times and parameters were of interest for this study. For example, there was a desire to calculate the standard deviation of the temperature fluctuations, σ_T, and cross products such as $w'u'$ and $w'v'$ (from which the momentum flux and the friction velocity u_* can be determined) and $w'T'$ (proportional to the vertical sensible heat flux).

Figure 1 shows the locations of the 20 DPG sonic anemometers in the JU2003 downtown domain, from which turbulence quantities are presented in tables later in this paper. The DPG sonic anemometers were mounted 8 m above ground level on small towers, were located about 5 m or more from the nearest building, and were sited near intersections. Where there is more than one sonic anemometer at an intersection, they were placed at opposite corners.

The JU2003 data archive contains mean wind observations from about 150 fixed anemometers spread across the OKC metropolitan area, as well as several remote sounders. The fixed anemometers were located 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 attached to a cable

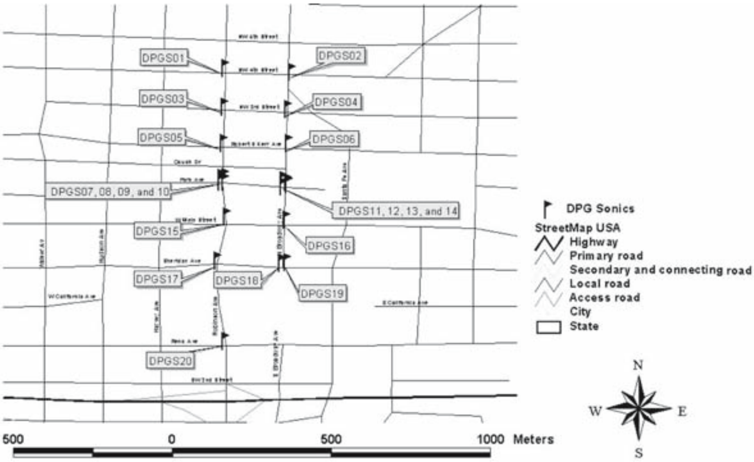


Fig. 1 Map of downtown Oklahoma City, site of Joint Urban 2003 (JU2003) field experiment. Locations of DPG sonic anemometers are shown. Data from these anemometers, as well as many additional anemometers, were analyzed to generate the summary results

hanging from a crane. The analysis did not use anemometers that were obviously obstructed, such as several anemometers mounted over the side of a building.

The siting of the anemometers on building roofs was a compromise among several considerations, such as ensuring employee safety, avoiding rooftop displacement zones, avoiding obstructions such as HVAC systems, reducing costs, conforming to restrictions set by building owners, and so on. None of the sites is perfect, but there do not seem to be any major problems in the sites selected for analysis.

The number of JU2003 anemometers whose mean wind data are presented here was reduced to about 80 by excluding those in locations that the authors arbitrarily decided had significant local obstructions. The anemometers have been subjectively separated by the authors into seven groups depending on surroundings and whether they are near ground-level or on rooftops. The intent was to avoid problems caused by lumping anemometers in street canyons with anemometers at building tops, and to identify common behaviour of the data within each group. This grouping procedure follows the recommendation of Britter and Hanna (2003), who point out that, while any two nearby individual anemometers may show differences in wind speed and direction, the spatial average at a given height range may be more appropriate for comparisons with theories. The anemometer groups are defined as follows:

Group (1a) Exposed building tops in downtown area (7 sites with $14\,\mathrm{m} < z < 153\,\mathrm{m}$)
Group (1b) Sheltered roofs in downtown area (23 sites with $19\,\mathrm{m} < z < 47\,\mathrm{m}$)
Group (2) Semi-exposed downtown in midst of buildings but not street level (5 sites with $z > 10\,\mathrm{m}$)
Group (3) Street canyons downtown (20 sites, $z = 8\,\mathrm{m}$) (See Fig. 1)
Group (4) Semi-exposed downtown park or residential area (10 sites with $z = 8$–$10\,\mathrm{m}$)
Group (5) Suburban/rural upwind and downwind (12 sites)
Group (6) Airports (3 sites at $z = 10\,\mathrm{m}$)

It is stressed that these anemometers were not originally sited with the idea that these groupings and spatial averages should be made. The authors have attempted to develop the spatial averages using the available data and the subjectively-defined groups.

The mean wind results generally are presented in tables as averages over all anemometers in a group and over the eight hour duration of the IOP. Obviously, there were variations in wind speeds and directions for the several anemometers in each group, and for the 15 or 16 30-min averages during any given IOP. This variability is not due solely to the urban influences, since stochastic variations occur even over flat uniform terrain, where it is primarily due to turbulence on the mesoscale. As an example of the variability, for Group 3 (street canyons downtown, shown in Fig. 1) and for a given 30-min period, the 20 anemometers are found to have an approximate 0.5–0.8 $\mathrm{m\,s^{-1}}$ spatial root mean square (RMS) difference in mean wind speed and a 100° spatial RMS difference in wind direction. The RMS difference in mean wind speed is about 0.4 times the mean scalar wind speed. The spatial RMS difference in wind direction is large because, in the street canyons, the wind direction depends strongly on the street orientation and nearness to tall buildings with recirculation zones. In contrast, for the building rooftop anemometers (Group 1a), the spatial variation in wind direction is much less, with an RMS of about 10°.

In addition to the spatial variability in the 30-min average wind speeds and directions within a group, there are also time variations for a given anemometer from one 30-min period to the next. The RMS difference due to time variations is less than that due to space variations for the JU2003 data.

Table 2 contains a summary of the mean (scalar) wind speed and wind direction results for each of the ten JU2003 IOPs for each of the seven groups of anemometers. Averages are also listed for all ten IOPs for each group, and for all seven groups for each IOP. The all-IOP and all-group average wind speed of 3.0 $\mathrm{m\,s^{-1}}$ and average wind direction of 191° are listed in the bottom right corner of Table 2.

There is seen to be a factor of 2.2 range (from 1.8 to 4.0 $\mathrm{m\,s^{-1}}$) in mean (averaged over the seven groups and over eight hours) wind speed and a 68 degree range (from 149 to 217 degrees) in mean (averaged over the seven groups and over eight hours) wind direction across the ten IOPs. These similar wind conditions were pre-ordained by the project team's desire to be sure that the tracer plume would be captured by the samplers.

Table 2 shows that there is a factor of eight difference between the overall mean (averaged over the ten IOPs) scalar wind speeds across the seven groups. An interesting general result for these ten days is that the average wind speed (5.0 $\mathrm{m\,s^{-1}}$) at the downtown building tops (group 1a) is approximately equal to the average wind speed (5.4 $\mathrm{m\,s^{-1}}$) at $z = 10\,\mathrm{m}$ at the airports outside the city. For any given IOP, the difference can be up to a factor of ±2 for these 8-h averages, and of course the difference would be larger for a given 30-min time period, as discussed above. The approximate agreement in the overall rooftop and airport means was also found by Hanna et al. (2003) for the SLC Urban 2000 field experiment, and is shown in Sect. 2.2 to be true for MSG05. The scientific reason for the agreement is more difficult to assess but could be studied with a fine scale three-dimensional meteorological model or a CFD model. It is obvious that the urban buildings should retard the wind flow in general, but the exact amount at rooftop is not easily estimated. The postulated relation between mean rooftop and airport wind speeds, though, could be useful for emergency response modeling, since, in most cities, the only observation of wind speed that is available is from the nearby airport.

In our initial analysis efforts, the low wind speeds (averaging 0.7 $\mathrm{m\,s^{-1}}$) were puzzling in Group 1b, which includes anemometers on low roofs in the downtown area. The investigators (e.g., M. Brown, private communication, 2006) who set up those anemometers have stated that some of the instruments were deliberately sited in sheltered locations and/or on the sides of buildings, with the intent to detect local circulations.

Table 2 Summary of observed wind speed (u) and wind direction (WD) during Joint Urban 2003 (JU2003) in Oklahoma City. Winds are averaged over each 8-h duration intensive operating period (IOP). Winds are also averaged within seven groups of similar types of anemometer locations

	Exposed bldg top downtown 7 sites DPG & PNNL ($z = 14$–$153\,m$)		Sheltered bldg tops in dense downtown area 14 LANL and 9 UOU sites $z = 19$–$47\,m$		Semiexposed downtown in bldgs but not street level 5 DPG sites $z > 10\,m$		Street canyon down-town 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 u	Avg
	u ($m\,s^{-1}$)	WD	u ($m\,s^{-1}$)	WD	u ($m\,s^{-1}$)	WD	u ($m\,s^{-1}$)	WD	u ($m\,s^{-1}$)	WD	u ($m\,s^{-1}$)	WD	u ($m\,s^{-1}$)	WD	($m\,s^{-1}$)	WD
Avg IOP01	3.4	201	0.5	236	1.8	177	1.0	189	1.5	164	3.0	207	1.5	16.0	1.8	170
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	193	0.7	222	2.7	174	1.5	198	2.1	184	3.7	196	5.4	174	3.0	192

Overall averages are given in the right two columns and in the bottom row

Another general result from Table 2 is that, for the limited ten day sample, the average scalar wind speeds (1.5 m s^{-1}) near street level in downtown street canyons (group 3) are about 1/3 of those at building rooftops (group 1a). This ratio of about 1/3 was also found for the Urban 2000 data (Hanna et al. 2003) and is later seen to be valid for MSG05, too. The physical reason for this particular ratio has not been completely formulated, but it is found consistently for the three urban field experiments. Of course, the 1/3 ratio would be expected to be more variable for a given pair of street-level and rooftop anemometer and for a given 30-min period.

According to Hanna and Chang (1992), the effects of stability are expected to be minimal in the downtown area because of the strong mechanical mixing forced by the buildings. They postulate that the magnitude of the Obukhov length, L, is unlikely to be less than about $3H$. The JU2003 data allow investigation of possible effects of stability because IOPs 01 through 06 were carried out in the daytime and IOPs 07 through 10 were carried out in the nighttime. Table 2 shows no noticeable variation between the wind data from the day and the night IOPs. The turbulent wind analysis (presented in the next subsection) also confirms this conclusion, using analyses of stability parameters such as the Obukhov length, L. At much larger heights above the ground (about 200 m and higher), where the boundary layer has been less affected by the urban surface, the stability effects may be more important (Lundquist and Mirocha 2006). Unfortunately, there were no vertical profiles of winds, turbulence, or temperature observed over the desired 100 or 200 m deep layer in the built-up downtown area in JU2003. The sodars and other vertical sounders were located just outside of the built-up area or in the suburbs. For example, there was a crane set up to measure vertical profiles, but it was about 1 km north of the built-up area.

The conclusions for the mean wind speeds and directions are generally based on averages over several anemometers and several 30-min time periods. As shown by the analysis of variations of wind speed and direction with space (for the different anemometers in a group) and with time (for the 16 different 30-min periods in each IOP), the wind speed and/or direction for a specific anemometer and a specific 30-min period could be different by about 0.5 or 1.0 m s^{-1} for wind speed, or by about 20° at rooftop or 100° at street level.

2.2 New York City Madison Square Garden 2005 (MSG05)

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 (Hanna et al. 2006). The average building heights ($H = 60$ m) in the MSG area in Manhattan are about three or four times what they are in JU2003, and Manhattan is about four or five times wider. The building morphology parameters, λ_f and λ_p, are relatively large (approaching about 0.5) in the MSG area, suggesting that relatively low values of u/u_* will occur and relatively large values of z_o/H, d/H, σ_u/u_*, σ_v/u_*, and σ_w/u_*. The two IOP days at 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 presents the locations on the MSG05 domain of the sonic anemometers (top panel) and an example of the observed wind vectors for the period from 0900 to 0930 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.

Besides the sonic anemometers shown in Fig. 2, several additional routine anemometers were available on tall buildings as part of a longer-term urban data collection effort. These locations included City College of New York (CCNY) in northern Manhattan, Environmental

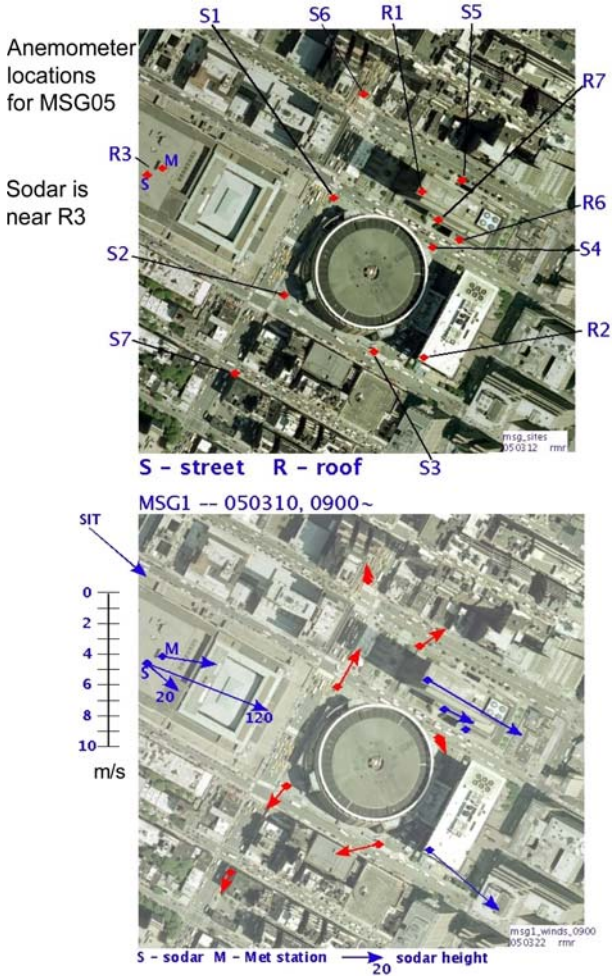


Fig. 2 View of area around Madison Square Garden (MSG) in Manhattan, where MSG is the round building and has diameter 130 m and height 50 m. The 229 m tall One Penn Plaza (OPP) building is to the NE of MSG and the 153 m tall Two Penn Plaza (TPP) building is to the ESE of MSG. Top: Anemometers used for 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 are shown for 0900 through 0930 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 south-west. 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.

Measurement Laboratory (EML) in Greenwich Village (about 2 km south of MSG), and Lehmann Brothers Building (LBR) in Times Square (1 km north of MSG). In addition, during the MSG05 IOPs, sodars were set up and operated on the Post Office roof just west of MSG, and on the Stevens Institute of Technology (SIT) campus to the west (upwind) in Hoboken, NJ. Winds from the major airports (JFK, LGA, and EWR) in the area were also available. The mean wind observations from the network of routine and intensive experiment anemometers are listed in Table 3.

Table 3 Summary of observed wind speed and wind direction during MSG 2005 field experiments IOP01 (51/2 H on 10 March 10) and IOP02 (51/2 H on 14 March). Locations of R (Rooftop) and S (Surface) sites are shown in Fig. 2 (top)

Site Label	Name	z (m) agl	IOP01 Wind speed $m\,s^{-1}$	IOP01 Wind direction deg	IOP02 Wind speed $m\,s^{-1}$	IOP02 Wind direction deg
R1	One Penn Plaza (OPP)	229	7.3	286	7.0	327
R2	Two Penn Plaza (TPP)	153	5.8	306	3.8	318
R3	Farley Post Office	34	3.6	281	3.9	269
CCNY	City College of New York	58	5.2	266	5.2	309
SIT	Stevens Inst of Tech	52	5.7	297	6.9	335
EML	Environ Monitor Lab	82	3.3	286	4.3	323
LBR	Lehmann Bros Bldg	160	4.7	286	3.6	308
JFK	Airport	3.4	6.2	290	6.5	320
S1	NW corner of MSG	3.0	3.0	212	2.7	187
S2	SW corner of MSG	3.0	1.7	27 steady	1.2	80 variable
S3	SE corner of MSG	3.0	3.3	76 steady	2.6	Variable W-E
S4	NE corner of MSG	3.0	1.6	Variable NNW-SSE	3.6	165 steady
S5	NW corner of OPP	3.0	2.6	238	1.7	292
S6	Front of New Yorker Hotel	5.0	1.2	162	–	–
S7	On 8th Ave S of MSG	3.0	1.2	17	2.0	28

As for the JU2003 rooftop anemometers, the siting during MSG05 represents a compromise among many considerations. For example, for safety purposes, none of the towers is mounted on a pole or tower higher than 10 m above the rooftop, raising the question that the wind sensor may be within the roof top displacement zone. However, analysis of the data suggests no obvious problems.

Based on wind observations at the airports and on the roofs of the tall buildings in Manhattan in Table 3, it can be concluded that both MSG05 IOPs were marked by similar wind speeds (about $5\,m\,s^{-1}$) and directions (WNW to NNW). Temperatures were also similar, slightly below 0°C, during both IOPs. Both experiments took place during the daytime, between 0700 and 1230 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 MSG05 wind observations from the seven tall buildings in Table 3 suggest that there is a range in wind speed of about a factor of two and in wind direction of about 40–60 degrees across the 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

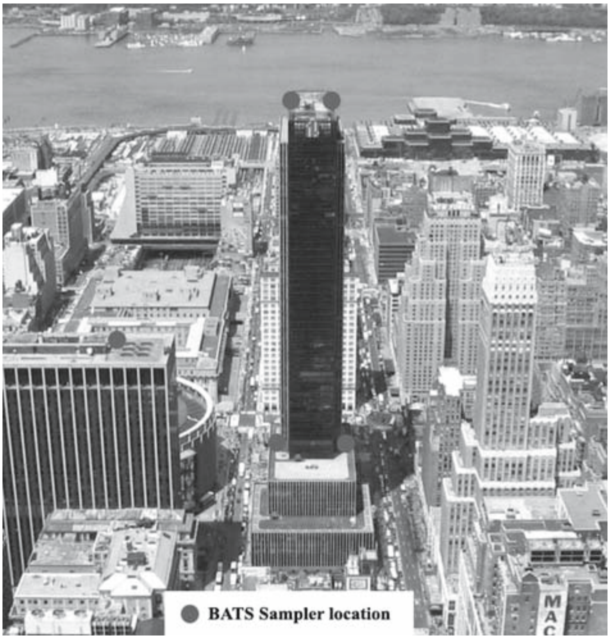


Fig. 3 View of MSG05 experiment area, looking towards the WNW from the Empire State Building. One Penn Plaza (OPP) is the tallest building (229 m). Two Penn Plaza (TPP) is the tall rectangular shaped building (153 m) to the left of OPP. Madison Square Garden (MSG) is the circular building barely visible behind TPP. BATS tracer sampler locations are shown on OPP and TPP building roofs as dots

ranges in wind speed and direction can be expected to be less than those on most days. It is tentatively concluded from these limited wind observations during MSG05 that, if a single anemometer on a tall building is used to determine the overall wind speed and direction, for say a plume transport and dispersion model, the minimum expected errors in the MSG area could be about a factor of two in cloud speed and 60 degrees in cloud direction. Table 3 does suggest that, for the rooftop anemometers, the winds from the very tall building (R1 at a height of 229 m on One Penn Plaza) are less susceptible to variations, and the winds from the lower buildings such as R3 on the Post Office exhibit the most variability (Fig. 3).

The MSG05 data confirm the finding at other cities, including JU2003 at Oklahoma City, that the observed wind speeds at the tall building tops (e.g., R1) average close to (within about 10–20 %) the observed wind speed at $z = 10$ m at a nearby airport (e.g., JFK). The wind directions are also similar (within about ten degrees).

Table 3 shows that the IOP-average wind speeds at the street level sites (at $z = 3$ m) average about 1/3 of those from the building-top anemometers. The street level wind directions are seen to be quite variable, clearly depending on their location (e.g., next to a building, in a street canyon, or in an intersection). For example, anemometer S7 is located in the street canyon of 8th Avenue, which is oriented towards 28 degrees (clockwise from north). The observed wind directions at that site are close to 28 degrees, implying the wind is channeled down the street canyon. As another example, anemometers S3 and S4 are located between the MSG and Two Penn Plaza buildings and are influenced by the frontal recirculation zone on the windward side of Two Penn Plaza. The observed directions are consistent with CFD model simulations of the MSG05 IOPs (Hanna et al. 2006).

3 JU2003 and MSG05 analysis of turbulent wind and temperature standard deviations and u_*, T_*, and L

The previous section presented results of mean wind speeds and directions. The current section presents turbulence results from sonic anemometers, which provide 10 Hz records of u (eastward directed), v (northward directed), and w (upward directed) wind components, and temperature T. These data have been used to calculate the following variables over averaging times, T_a, ranging from 5–60 min:

Mean wind components $<u>$, $<v>$, $<w>$
Mean temperature $<T>$
Mean scalar wind speed and vector wind speed
Mean wind direction
Standard deviations of wind component fluctuations σ_u, σ_v, and σ_w
Standard deviation of horizontal wind fluctuations $\sigma_h = (\sigma_u^2 + \sigma_v^2)^{1/2}$
$\mathrm{TKE} = (\sigma_u^2 + \sigma_v^2 + \sigma_w^2)/2$
Standard deviation of temperature fluctuations σ_T
Friction velocity u_*
Temperature scale $T_* = <w'T'> /u_*$
Obukhov length $L = (u_*^2/k)/((g/ <T>)T_*)$ with $k = 0.4$

The symbol $<>$ represents a time average. Note that the sonic anemometer data are not corrected to force $<w>$ to zero, since non-zero $<w>$ is expected in urban locations. The total horizontal velocity turbulent standard deviation, σ_h, is included in the analysis because of the large turbulent intensities in urban areas. A 30-min averaging time, T_a, is used in most of the analyses reported below.

3.1 JU2003 Calculations of turbulence variables for 20 sonic anemometers near street level

Summaries of the 30-min averaged variables defined above are given in Table 4 for JU2003 for the 20 DPG sonic anemometers (in Group 3 in Table 2), which were all in the downtown street canyons at heights of 8 m above ground and sited many metres from the nearest building (see Fig. 1 for locations). As stated earlier, the analysis is based on ten days of observations during periods with relatively persistent wind directions and moderate wind speeds. Complete sets of turbulence results for each 30-min period and each anemometer were calculated, but we give only the summary table. Note that the mean vector wind speed for the individual sonic anemometers is relatively light, ranging between 1.14 and 2.19 m s^{-1}. During these same time periods, the wind speed at the building tops ranged between 3.4 and 6.4 m s^{-1} (see Group 1a in Table 2). Unfortunately there were no sonic anemometer observations of turbulence on the exposed building tops during JU2003.

As explained earlier, the friction velocity, u_*, reported in the table is a “local” value, calculated from $u'w'$ and $v'w'$ at the specific sonic anemometer. The temperature scale, T_*, and the Obukhov length, L, are also local. The similarity relations in Table 4 are compared with those from MSG05 in Subsect. 3.3.

Table 4 Summary results of turbulence calculations for 20 DPG sonic anemometers in JU2003. All are at a height of 8 m in the downtown area (See Fig. 1 for locations). Each IOP has duration 8 h. 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	Time of day CST	Vector speed $m\,s^{-1}$	Scalar speed $m\,s^{-1}$	Vector dirctn deg	Scalar dirctn deg	σ_u $m\,s^{-1}$	σ_v $m\,s^{-1}$	σ_h $m\,s^{-1}$	σ_w $m\,s^{-1}$	σ_T °C	TKE $m^2\,s^{-2}$	u_* $m\,s^{-1}$	$-T_*$ (°C)	$-L$ (m)	σ_h/u_*	σ_w/u_*	$-\sigma_T/T_*$
1	08–16	1.14	1.46	150	163	0.75	0.76	1.09	0.5	0.31	0.82	0.33	0.16	147	3.3	1.5	1.89
2	08–16	1.49	1.91	213	202	0.99	1.04	1.47	0.65	0.49	1.36	0.41	0.22	1029	3.6	1.59	2.15
3	08–16	2.04	2.57	192	186	1.48	1.36	2.08	0.85	0.37	3.55	0.55	0.15	62.5	3.81	1.56	2.52
4	08–16	2.19	2.18	208	199	1.32	1.38	1.95	0.88	0.44	2.57	0.55	0.18	384	3.54	1.6	2.56
5	08–16	1.54	1.9	170	169	1.54	0.96	1.95	0.64	0.36	4.87	0.45	0.14	158	4.35	1.44	2.61
6	08–16	1.8	2.24	181	176	1.07	1.06	1.55	0.65	0.47	1.82	0.42	0.23	E+15	3.66	1.53	2.02
7	22-06	1.58	1.8	218	211	0.7	0.76	1.04	0.56	0.17	0.76	0.34	0.04	798	3.09	1.66	4.25
8	22-06	2.17	2.55	150	151	1.57	1.26	2.12	0.86	0.13	3.78	0.56	0.032	1260	3.81	1.55	4.06
9	22-06	1.69	2.05	177	171	1.13	1.06	1.62	0.69	0.17	2.57	0.44	0.036	573	3.67	1.57	4.72
10	20-04	1.63	1.9	199	195	0.85	0.89	1.26	0.6	0.21	1.36	0.36	0.037	971	3.47	1.65	5.67
avg	6 Day	1.7	2.13	186	183	1.03	1.09	1.68	0.7	0.41	2.5	0.45	0.18	Median 271	3.71	1.54	2.28
avg	4 Night	1.77	2.08	186	182	1.06	0.99	1.51	0.68	0.17	2.12	0.43	0.036	902	3.51	1.61	4.68
avg	All	1.73	2.11	186	183	1.05	1.05	1.61	0.69	0.31	2.34	0.44	0.12	Median 685	3.63	1.56	3.24

Note that $\sigma_h^2 = \sigma_u^2 + \sigma_v^2$

The mean and turbulent wind speed components and u_* in Table 4 are averaged separately and are listed near the bottom of the table for the daytime IOPs (1 through 6) and the night-time IOPs (7 through 10). There is generally less than a 10% difference between the values for the day and night IOPs during JU2003. For example, the averaged daytime and nighttime u_* are 0.45 and 0.43 m s^{-1}, respectively. These results suggest that there is not a significant variation in the near-surface wind speed and turbulence with day and night.

The standard deviation of temperature fluctuations, σ_T, is also listed in Table 4, and averages 0.3°C across all IOPs. The temperature scale, T_*, is seen to average about −0.12°C, leading to the ratio σ_T/T_* averaging −3.24. However, unlike the mean and turbulence wind data, the temperature data do reflect a difference between the day and night IOPs. For example, it is found that σ_T averages 0.41 and 0.17°C during the day and night, respectively. T_* shows a factor of five difference (−0.18 during the day vs. −0.036°C during the night). The negative value of T_* at night suggests a positive (upward) sensible heat flux near street level, probably due to the effects of anthropogenic heat fluxes and the storage and release of daytime heat from the concrete and asphalt. The ratio, σ_T/T_*, shows less day–night variation, averaging −2.28 during the day and −4.68 at night. As seen in Table 1, values of σ_T/T_* of about −2 to −5 are expected for very-nearly neutral conditions on a similarity plot of σ_T/T_* versus z/L. 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, with magnitudes ranging from −0.5 to −3.5. However, many of Roth's data were taken when conditions were moderately unstable. Roth (2000) lists a few theoretical formulae for $\sigma_T/T_*(z/L)$, and the formulae generally agree that the limit as z/L approaches 0 (neutral conditions) is about −3.0, which is within 10% of the averaged σ_T/T_* value in Table 4 for JU2003. The relatively large magnitudes of the JU2003 σ_T/T_* observations at a height of 8 m are further evidence that the urban boundary layer near street level may be close to neutral conditions, day or night.

A primary measure of stability is L, which is also listed in Table 4. It can be very large when the temperature scale (proportional to the sensible heat flux) is very small (nearly neutral). It is seen that the average L over all sonic anemometers and time periods in each IOP ranges from about −63 m for IOP03 to effectively infinity for IOPs 05 and 06. The nighttime IOPs (07-10) have L ranging from −573 to −1270 m. The median L over all sonic anemometers is −685 m. The daytime IOPs have a median L of −271 m and the nighttime IOPs have an average L of −902 m. Of course there are also large ranges in L for the 20 anemometers during a given 30-min period and for the 15 30-min averages for a given anemometer during a given IOP. The RMS differences and ranges are not listed because L has a tendency to approach infinity (plus or minus) at some times and locations. These very large but negative Ls in Table 4 suggest that slightly unstable conditions are seen day or night during JU2003.

In addition to the sonic anemometer data reported in Table 4, the turbulent velocities, as indicated by the lateral component, σ_v, have been analyzed from some of the routine anemometers (i.e., cup anemometers or aerovanes), which produce outputs of σ_θ (the standard deviation of wind direction fluctuations) as well as mean winds. JU2003 observations of mean wind speed, u, from these anemometers, can be combined with measurements of the standard deviation of wind direction fluctuations, σ_θ, to calculate $\sigma_v = u[\tan(\sigma_\theta)]$. Preliminary results suggest that, for the routine anemometers in the urban groups in Table 2, the turbulence σ_v estimated from $u[\tan(\sigma_\theta)]$ is fairly constant, at a value of about 1 m s^{-1}, which agrees well with the sonic anemometer observations, which average 1.05 m s^{-1} in Table 4. In contrast, for the suburban/rural group in Table 2, the observed lateral turbulence σ_v from $u[\tan(\sigma_\theta)]$ is about 1/3 of that for the urban groups.

An important result indicated by the JU2003 data in Table 4 is that the IOP-averaged turbulent speeds are much more constant or "robust" than the mean wind speeds, which can sometimes have very small magnitudes at street level. Britter and Hanna (2003) and Venkatram et al. (2002, 2004) suggest that, once the averaged turbulent speeds are known in an urban area, then the values can be assumed to apply throughout the urban canopy. There may be factor of two variations, due both to decreases in turbulent speeds as height decreases, and to variations due to the effects of nearby individual buildings.

As an additional exercise with the JU2003 turbulence data, the turbulence time scale, T_t, has been estimated using a method based on the observed variation of horizontal turbulent fluctuations, $\sigma_h^2 = \sigma_u^2 + \sigma_v^2$, with averaging time T_a (5, 10, 15, 30, and 60 min in our case). The method is derived from a set of analytical equations suggested by Pasquill (1974). Assuming an exponential autocorrelogram and the implied Markov shape for the energy spectrum, the following equation can be derived for the ratio of the variance, σ_h^2, for averaging time, T_a, to the variance, σ_h^2, for very large averaging time:

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

It is assumed in the derivation of Eq. 1 that σ_h^2 for $T_a = 60$ min captures all of the turbulence and represents the "very large" averaging time. Given the JU2003 observations of the variances for various T_a, then Eq. 1 can be solved for T_t. This approach has been applied to the JU2003 turbulence observations from IOP02, resulting in T_t calculated to be about 20 s for averaging times of 5, 10, 15, and 30 min. Assuming a mean wind speed u of about 2 m s^{-1}, this implies an integral turbulent length scale $L_t = uT_t = 40$ m, which is reasonable in an urban downtown area where the street canyons have that approximate width.

3.2 MSG05 calculations of turbulence variables for sonic anemometers near street level and at rooftop

Following the same format used in Table 4 for presenting the JU2003 results, Table 5 contains the calculations based on the observations during MSG05. The results (averaged over the $5\frac{1}{2}$ h for each IOP) are presented for seven sonic anemometers (R1 and R2 on tall building rooftops, and S1, S4, S5, S6, and S7 at $z = 3$ m near street level). The data from sonic anemometers S2 and S3, seen in Fig. 2 to be located on the south-west and south-east corners of MSG, respectively, had problems and were not analyzed. 30-min averaging periods are used as the basis in both Table 4 (for JU2003) and Table 5 (for MSG05).

The similarity relations (e.g., σ_w/u_*) derived from the MSG05 data in Table 5 will be discussed in Subsect. 3.3, along with those from JU2003.

The averaged data in Table 5 support the general conceptual model that the turbulence at the rooftops is larger than that near street level. On average, Table 5 shows that the street-level ($z = 3$ m) TKE (one half of the sum of the squares of σ_u, σ_v, and σ_w) during MSG05 is about 0.30 times that at rooftop, the street level σ_h is about 0.53 times that at rooftop, and the street level σ_w is about 0.63 times that at rooftop. As suggested by Britter and Hanna (2003), the difference between street level and rooftop may be larger for the horizontal than the vertical fluctuations because of the inhibiting effect of the buildings on horizontal wind fluctuations near street level. Also, it is noted that these differences found in one of the largest cities in the world are still less than those found for dense vegetative canopies (Finnigan 2000).

Table 5 Summary results of turbulence for seven MSG05 sonic anemometers in New York City. R1 and R2 are on one Penn Plaza (OPP) and Two Penn Plaza TPP) rooftops at heights of 223 m and 153 m, respectively. S1, S4, S5, S6, and S7 (all at $z = 3$ m) are on the NW corner of MSG, the NE corner of MSG, the NW corner of OPP, along 8th Ave north of OPP, and along 8th Ave to the south of MSG, respectively (see Fig. 2, Top Panel). Each IOP has duration 51/2 h. The means and turbulence are calculated for 30-m periods

IOP	Site	Vect speed $m\,s^{-1}$	Scalar speed $m\,s^{-1}$	Vect dir deg	Scal dir deg	σ_u $m\,s^{-1}$	σ_v $m\,s^{-1}$	σ_h $m\,s^{-1}$	σ_w $m\,s^{-1}$	σ_T °C	TKE $m^{-2}\,s^{-2}$	u_* $m\,s^{-1}$	$-T_*$ (°C)	$-L$ (m)	σ_h/u_*	σ_w/u_*	σ_T/T_*
1	R1 OPP	6.38	6.8	293	283	2.72	2.13	3.47	1.16	0.91	6.78	0.79	0.05	–17	4.39	1.47	18.2
2	R1 OPP	6.32	6.75	324	307	1.92	2.78	3.38	1.23	1.09	6.61	0.68	0.36	123	4.97	1.81	3.03
1	R2 TPP	4.8	5.4	306	275	2.95	2.35	3.78	1.14	0.79	7.84	0.6	0.22	1190	6.3	1.9	3.59
2	R2 TPP	3.16	4	322	245	2.52	2.57	3.6	1.17	0.76	7.22	0.54	0.44	94.6	6.67	2.17	1.73
1	S1	2.39	2.76	202	208	1.2	1.34	1.81	0.77	0.44	1.94	0.61	0.12	232	2.97	1.26	3.67
2	S1	2.48	2.86	185	185	1.49	1.41	2.01	0.78	0.58	2.35	0.66	0.16	208	3.04	1.18	3.62
1	S4	1.34	2.67	280	246	1.43	2.02	2.47	0.7	0.44	3.45	0.61	0.14	291	4.04	1.15	3.14
2	S4	3.82	4	165	165	0.94	1.71	1.95	0.8	0.43	2.27	0.7	0.1	–412	2.79	1.14	4.3
1	S5	2.41	2.89	249	248	1.07	1.72	2.03	0.69	0.54	2.31	0.45	0.21	74.8	4.51	1.53	2.57
1	S6	1.74	1.74	161	161	1.06	1.31	1.69	0.83	1.01	1.8	0.53	0.21	31.5	3.19	1.57	4.8
1	S7	0.95	1.51	22	123	0.8	1.22	1.46	0.61	0.56	1.25	0.5	0.21	106	2.92	1.22	2.6
2	S7	1.95	2.28	29	79	0.97	1.38	1.68	0.69	0.55	1.68	0.47	0.13	166	3.57	1.47	4.23
avg	R1 OPP	6.35	6.78	309	295	2.32	2.45	3.42	1.19	1	6.69	0.73	0.2	53.4	4.68	1.63	10.6
avg	R2 TPP	3.98	4.7	314	260	2.74	2.46	3.69	1.15	0.78	7.53	0.57	0.33	645	6.48	2	2.66
avg	S1	2.48	2.81	193	196	1.35	1.38	1.91	0.77	0.51	2.14	0.64	0.14	220	3	1.2	3.65
avg	S4	2.58	3.33	224	205	1.19	1.86	2.21	0.75	0.44	2.86	0.65	0.12	–60.9	3.41	1.15	3.72
avg	S5	2.41	2.89	248	248	1.07	1.72	2.03	0.69	0.54	2.31	0.45	0.21	74.8	4.51	1.53	2.57
avg	S6	1.74	1.74	161	161	1.06	1.31	1.69	0.83	1.01	1.8	0.53	0.21	31.5	3.19	1.57	4.8
avg	S7	1.45	1.9	26	101	0.89	1.3	1.57	0.65	0.55	1.47	0.49	0.17	136	3.22	1.33	3.42
avg	Roof	5.16	5.74	311	278	2.53	2.46	3.56	1.17	0.89	7.11	0.65	0.26	349	5.58	1.81	6.63
avg	Street	2.13	2.53	Var	Var	1.11	1.51	1.88	0.74	0.61	2.12	0.55	0.17	87.2	3.47	1.36	3.63
avg	All	3.65	4.14	Var	Var	1.82	1.98	2.72	0.96	0.75	4.61	0.6	0.21	174	4.52	1.59	5.08

Note that $\sigma_h^2 = \sigma_u^2 + \sigma_v^2$

The $5\frac{1}{2}$ h average standard deviation of turbulent temperature fluctuations, σ_T, is usually in the range from about 0.4 to about 1.1°C for the seven sonic anemometers and the two IOPs. The average σ_T at street level is 0.61°C, which is about 49% larger than the value of 0.41°C observed for the daytime JU2003 IOPs. The magnitude of σ_T at street level is about 0.68 times that at rooftop during MSG05.

The $5\frac{1}{2}$ h average friction velocity, u_*, shows less variation with height than some of the other turbulence quantities. The ratio of street level to rooftop u_* is about 0.82. Since the momentum flux (and the drag) are proportional to u_*^2, this implies that the multi-hour average momentum flux at street level is about 0.74 times that at rooftop. The magnitude of the average temperature scale, T_*, at street level is 0.67 times that at rooftop. Since the vertical sensible heat flux is proportional to $-u_*T_*$, this implies that, on average, the sensible heat flux at street level is about 0.56 times that at rooftop.

A few other simple preliminary relations are suggested by the data. For example, the average friction velocity near street level is about 1/10 of the average wind speed at rooftop, and is about 1/5 of the average wind speed at street level. The average σ_h at street level is about 1/3 of the average rooftop wind speed and the average σ_w is about 1/8 of the average rooftop wind speed. These relations could tentatively be used to estimate u_*, σ_h, and σ_h when sonic anemometers are not available.

Of course, the above preliminary conclusions are based on averages over all instruments and hours. Nevertheless the general conclusions may be useful in generating an understanding of the processes. Individual sites and time periods show more variability. For example, at a similar field experiment in Manhattan five months after MSG05 and a few blocks towards the Midtown area, 12 street-level sonic anemometers showed a relative spatial variation (RMS deviation in space divided by the mean) of about 0.3 for scalar wind speed and about 0.3 for σ_v (Hanna and Zhou 2007). This experiment was named Midtown 2007 (MID07). The corresponding relative variation in time (over a $7\frac{1}{2}$ h IOP) was about 0.1 or 0.2. The relative variation in space of 0.3 is about 1/2 of the relative variations (σ_u/u and σ_v/u) observed during MSG05 for the averaged 30-min turbulence data reported in Table 6. It can be concluded that, even though the turbulence values reported in the tables do have a variation in space and time, the variation is about 1/2 of the σ_u averaged over all anemometers and time periods.

3.3 Comparisons of JU2003 and MSG05 turbulence observations with similarity relations observed and postulated in references

Table 1 has presented a set of similarity relations observed in other cities and postulated by some references for turbulent variables in urban areas. Table 6 extracts some observations of dimensional and nondimensional standard deviations and u_* from the calculations listed for JU2003 and MSG05 given in Tables 4 and 5, respectively, and compares the JU2003 and MSG05 observations with the relations in Table 1. Columns 2, 3, and 4 in Table 6 present the hypothesized relations from Table 1, the JU2003 observations, and the MSG05 observations, respectively. The observations given for the field experiments represent averages over all IOPs and all sonic anemometers near street level. As discussed in the previous section, there is some variation in the turbulence variables from site to site and from time period to time period, but it is generally about 1/2 of the averaged values reported in Table 6.

It is seen in Table 6 that the turbulence averages are very similar for JU2003 and MSG05. The averaged dimensionless variables from JU2003 and MSG05 are within 20% of each other. This in itself implies a consistency from one urban area to another and suggests that similarity relations may be valid.

Table 6 Comparison of JU2003 and MSG05 mean turbulence observations with summary results from the literature in Table 1 for urban canopies (UCs). H is the mean building height

Turbulence quantity	Table 1 Recs from Britter & Hanna (2003) and References	JU2003 Obs	MSG05 Obs
σ_u/u_*	1.6 in UC	2.36	2.74
	2.4 near & above H		
σ_u/u	0.45	0.50	0.44
σ_v/u_*	1.4 in UC	2.36	2.02
	1.9 near & above H		
σ_v/u	0.39	0.50	0.60
σ_h/u_*	2.1 in UC	3.63	3.47
	3.1 near & above H		
σ_w/u_*	1.1 in UC	1.56	1.36
	1.3 near & above H		
σ_w/u	0.31	0.33	0.29
TKE/u_*^2	2.87 in UC	12.1 (mean of all *TKE*)	7.01 (mean of all *TKE*)
	5.53 near & above H	6.9 (using mean σ_u etc.)	6.7 (using mean σ_u etc.)
σ_T/T_*	−3	−3.24	−3.63
u_*/u	0.28 in UC for downtown area	0.25	0.22
σ_h m s^{-1}		1.61	1.88
σ_w m s^{-1}		0.69	0.74
u_* m s^{-1}		0.44	0.60

It is also seen in Table 6 that the observations of scaled (dimensionless) horizontal wind standard deviations (e.g., σ_u/u_*, σ_v/u_*, and σ_h/u_*) from JU2003 and MSG05 in the UC tend to be consistently higher, by about 50–80 %, than postulated by Britter and Hanna (2003). Perhaps this discrepancy is because few of the references took as extensive observations as JU2003 and MSG05 of turbulence near street level. Or, the difference may partially be due to the value of u_* being used for scaling, since the local u_* is used rather than a bulk value representative of the surface drag. Furthermore, the time series of turbulent speeds from JU2003 and MSG05 do verify that the presence of a building often causes an increase in horizontal fluctuations as the wake of the building fluctuates in size and position.

The scaled (dimensionless) vertical turbulent speed, σ_w/u_*, is observed to be about 20 or 30% larger than the value of 1.1 postulated in Table 1.

The observed JU2003 and MSG05 temperature fluctuations, σ_T, divided by the scaling temperature, T_*, can also be compared with the published similarity relations. The average values of σ_T/T_* at JU2003 and MSG05 at street level are about −3.24 and −3.63, which correspond to the value postulated by the references for nearly neutral conditions, on the slightly unstable side. The calculated Obukhov length, L, is typically negative with magnitude of a few hundred metres, which supports the concept that stabilities are typically near-neutral or perhaps very slightly unstable close to street level. These findings are consistent with the known daytime weather conditions during the field experiments. Even for the nighttime experiments in JU2003, the T_* and L values indicate slightly unstable conditions near street level.

Table 6 also includes scaling of the turbulent variables by the average scalar wind speed, u. Britter and Hanna (2003) point out that, for dense built-up areas, the characteristic wind speed, u, in the urban canopy layer (at $z < H$) is rather constant over much of the mid and lower layers, and propose a simple formula for u_*/u that is a function of the building morphology parameter, λ_f. For dense building coverages typical of the downtown areas during JU2003 and MSG05, λ_f is calculated to be greater than 0.2, and hence u_*/u is expected to be about 0.28, based on the Britter and Hanna (2003) formula. This value is close to the observed averaged values of 0.25 and 0.22 in JU2003 and MSG05, respectively.

Assuming $u_*/u = 0.28$, the postulated values of σ_u/u, σ_v/u, and σ_w/u are 0.45, 0.39, and 0.31, respectively. Table 6 shows that the observed values are close to these postulated values. In fact, the proposed values for turbulence scaled by u are in better agreement with the observations than the proposed values for turbulence scaled by u_*.

4 Tracer concentrations in Oklahoma City JU2003

The OKC JU2003 and MSG05 field experiments included continuous releases of SF_6 and perfluorocarbon tracer (PFT) gases, respectively, from a point source near street-level in the downtown areas. The JU2003 tracer data placed in the data archive at DPG (2005) have been used in this analysis. The MSG05 tracer data have just been distributed and their analysis has not been completed. The focus of the discussion below is on the maximum 30-min average concentrations on sampling arcs at various downwind distances during JU2003.

During each of the ten IOPs in JU2003, three continuous releases of SF_6 of duration 30 min were made at two-hour intervals. Instantaneous (puff) releases of SF_6 were made at other times, but are not discussed or analyzed here. IOPs 01 through 06 took place during the day and IOPs 07 through 10 took place during the night. Samplers were set out on a rectilinear grid in the downtown area at distances less than 1 km from the source, and on three concentric arcs (at 1, 2, and 4 km) to the north of the downtown area. Figure 4 shows the sampler set-up for IOP04. The sampler positions were somewhat different for each IOP in order to conform to the expected wind directions and release locations. Three optional release locations were used (Botanical Garden, Westin, and Park Avenue). The averaging time for the samplers was adjustable and was generally set to 5, 15, or 30 min. Some of the samplers were always set for 30 min averages and others were always set for a shorter period. In the downtown area, where the samplers were on a rectangular grid, the authors subjectively assigned each sampler to one of four effective "arc" distances—0.2, 0.37, 0.62, and 0.85 km. In addition a few rooftop samplers were employed in the downtown area in order to assess the amount of vertical dispersion that was occurring.

As an example of the observed time variability of concentrations, Figure 5 presents the time series of 15-min averaged maximum concentrations for IOP09 for the seven sampler arcs, and for rooftop samplers. The concentration rise and fall for the three release periods (i.e., trials) can clearly be seen, and a slight delay in the arrival of the tracer cloud can be seen at the farthest arcs. The amount of delay is approximately consistent with the observed average wind speed of about 3 m s^{-1} (see Table 2). At that speed, it would take the cloud about 20 min to travel to the 4 km arc.

The following analysis focuses on the maximum 30-min averaged concentration, C_{max}, observed for a given release by the set of samplers on a given distance arc. Hanna et al. (2003), Venkatram et al. (2002, 2004), Batchvarova and Gryning (2006), Britter (2005), and Neophytou and Britter (2004) have suggested the following dimensionless similarity relation

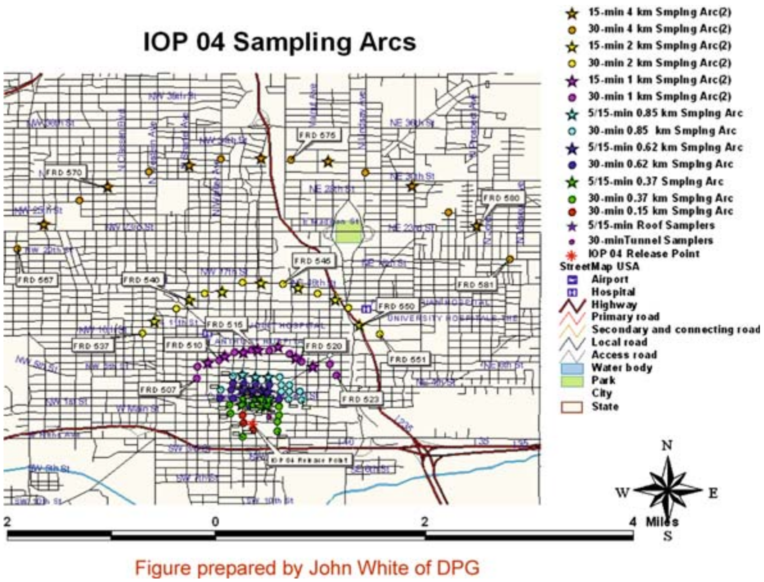


Fig. 4 Map of downtown Oklahoma City, site of Joint Urban 2003 (JU2003) field experiment. Locations of NOAA Air Resources Laboratory Field Research Division (ARLFRD) SF_6 samplers are shown, as used in IOP04. Data from these samplers were analyzed to generate the summary results for continuous releases in this paper

for continuous releases near street level in downtown areas with many tall buildings covering an area of 1 km^2 or larger:

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

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 $A(x/H)^{-2}$ for x/H < about 50, where A is a "constant" of order 10. The H cancels out and it follows that $C_{max} u/Q = Ax^{-2}$. Hanna et al. (2003) suggest a slightly more complicated, but still analytical, formula for F for the Salt Lake City Urban 2000 observations, which cover distances out to 6 km (about $300H$).

It is assumed in Eq. 2 that the morphology parameter, λ_f, is relatively large (greater than about 0.2) and the generalized function, F, does not depend on λ_f,.

Table 7 contains the observed $C_{max} u/Q$ on each distance arc for the 29 sets of continuous release trials (10 IOPs and three releases or trials each IOP, except for two releases during IOP01). The source location is also given in the table. IOPs 01–06 and 07-10 occur during the day and night, respectively. We have found that the first two trials of IOP05 are more representative of the night, though, since they occur during the early morning and the mixing depths are observed to be relatively low (less than 200 m) due to the presence of thunderstorms in the area. Thus IOP05 trials 1 and 2 are included in the nighttime category in the plots discussed below.

Figure 6a, b present summary plots of $C_{max} u/Q$ versus x for each release trial in JU2003 for daytime and nighttime trials, respectively. In all cases, the wind speed, u, is assumed to be the average over all of the anemometers, as listed at the right-hand side of Table 2. The

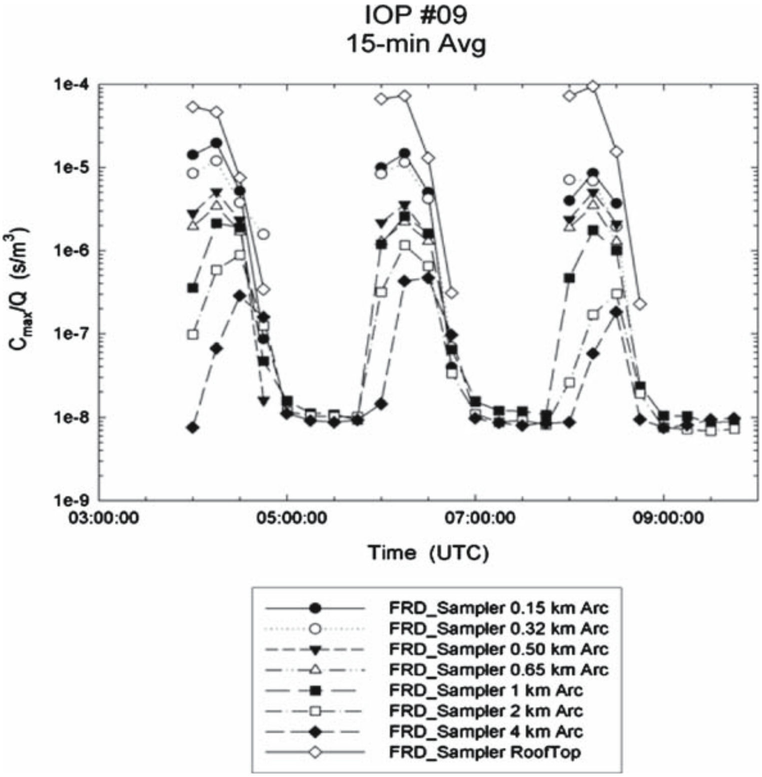


Fig. 5 Time series of observed 15-min averaged C_{max}/Q (s m^{-3}) for JU2003 IOP 9. C_{max} is the observed maximum during the 15-min period at the samplers at a given arc distance. The "rooftop samplers" include several scattered around the downtown area

DAPPLE observations, which were taken in London during the daytime (Neophytou and Britter 2004; Britter 2005), are included in Fig. 6a. The Urban 2000 observations, which were taken in Salt Lake City (SLC) during the nighttime (Hanna et al. 2003), are shown in Fig. 6b. The points for the SLC Urban 2000 SF_6 tracer data were originally plotted by Hanna et al. (2003) on a similar diagram. The mean building height, H, is about 19 m for Urban 2000, 27 m for JU2003, and 22 m for DAPPLE.

The line, $Cu/Q = 10/x^2$, is plotted on Fig. 6a and b. Neophytou and Britter's (2004) suggested limit for this formula ($x <$ about 50 H) is approximately 1000 m for these experiments.

In Fig. 6a, for daytime conditions, the JU2003 $C_{max}u/Q$ data for individual trials are seen to agree well with the trend with distance, x, of the averaged DAPPLE data. The x^{-2} relation appears to be approximately followed out to distances of 4 km during the daytime. However, the "constant" A in the x^{-2} relation is closer to 3 than to 10. The scatter of the data from the individual JU2003 trials about the best fit line is approximately $\pm$ a factor of three (including about 90% of the points).

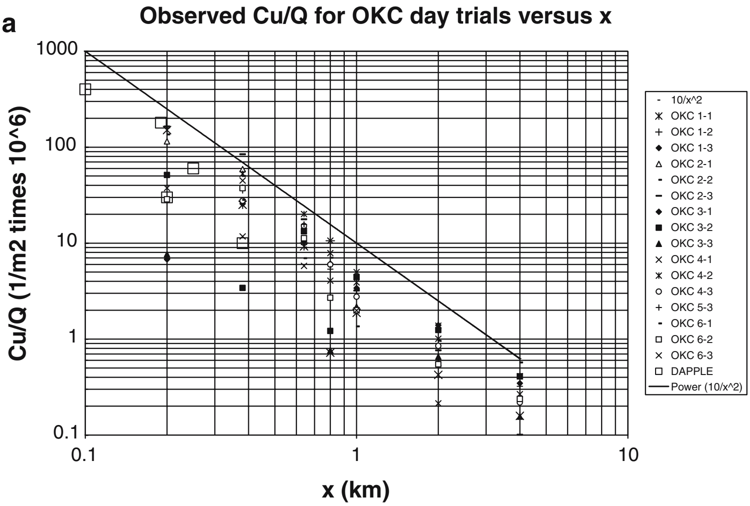
In Fig. 6b, for nighttime conditions, the SLC Urban 2000 averaged $C_{max}u/Q$ data are quite close to the median of the JU2003 data. There are 14 nighttime trials during JU2003. The JU2003 points on the 0.2 km arc are slightly lower in magnitude than those on the 0.38 km arc. The reason for the lower C_{max} values on the closer arc may be that there many fewer

Table 7 Observed 30-min $C_{max}u/Q$ in m^{-2} Times 10^6 at JU2003. The wind speed, u, is the average over all groups of anemometers (see Table 2). Missing data indicate that the observations did not pass quality control standards or were below the threshold

IOP	Source Location	Trial	Start time UTC	arc 1 0.2 km	arc 2 0.38 km	arc 3 0.64 km	arc 4 0.8 km	arc 5 1 km	arc 6 2 km	arc 7 4 km
1	Westin	1	1600	150.8	25.1	9.23	0.72	1.87	0.42	0.16
1		2	1800		28.2	22.8	10.59	3.94	1.99	0.82
2	Westin	1	1600	114.9	59.1	10.3				
2		2	1800	135.8	50.0	7.0		1.35		
2		3	2000	164.3	84.2	17.7		3.20	0.76	0.10
3	Botanical	1	1600	6.8	25.7	10.3	6.11	3.40	1.39	0.35
3		2	1800	51.4	3.4	13.2	1.22	4.43	1.24	0.41
3		3	2000	7.7	38.0	15.2	0.76	2.17	0.65	0.16
4	Botanical	1	1600		44.9	11.2	10.64	4.99	1.01	0.27
4		2	1800		52.9	20.1	7.88	3.90	1.38	0.41
4		3	2000		27.6	15.1	5.98	2.76	0.85	0.22
5	Botanical	1	1400	18.7	189.6	17.2	17.92	9.46	8.96	6.94
5		2	1600		254.9	26.4	26.99	10.55	4.91	2.21
5		3	1800	158.9	35.4	15.7	5.35	3.19	0.53	0.32
6	Botanical	1	1400	6.9	28.3	9.0	7.02	3.30	0.96	0.57
6		2	1600	28.6	37.4	11.2	2.70	2.00	0.55	0.24
6		3	1800	37.5	11.7	5.8	4.06	1.98	0.21	0.08
7	Botanical	1	400	9.0	31.0	15.7	7.17	4.91	2.51	1.74
7		2	600		167.7	50.5	15.12	7.14	4.51	2.88
7		3	800		330.7	20.7	30.92	15.59	6.94	2.29
8	Westin	1	400	88.6	52.7	34.4	16.80	11.83	5.31	2.25
8		2	600	131.8	67.5	25.6	10.47	10.47	6.32	0.94
8		3	800	256.7	98.8	35.8		12.05	4.66	1.93
9	Park	1	400	102.3	63.2	24.5		10.85	3.94	2.57
9		2	600	78.9	63.2	18.3		12.18	4.74	1.83
9		3	800	26.5	43.7	23.3		10.70	4.37	1.98
10	Park	1	200	57.7	45.5	13.0		6.75	2.29	1.14
10		2	400	23.8	27.0	17.6		7.82	3.66	1.32
10		3	600	228.8	8.1	13.3		6.66	3.52	2.97

samplers on the 0.2 km arc, this allowing the tracer cloud to sometimes not have its C_{max} captured. The points on Fig. 6b tend to verify the $C_{max}u/Q = Ax^{-2}$ relation, with A equal to about 10, for distances less than and equal to 1 km. The data tend to be above the $10x^{-2}$ line by about a factor of two at $x = 2$ km and a factor of four at $x = 4$ km. The discrepancy is likely due to the inhibited vertical mixing at night as the cloud passes into the residential areas.

As seen in Fig. 6a and b, the observed concentration data can be fit by the line $C_{max}u/Q = 3x^{-2}$ during the daytime and by the line $C_{max}u/Q = 10x^{-2}$ during the nighttime. Thus there is a factor of about three difference between daytime and nighttime $C_{max}u/Q$, despite the



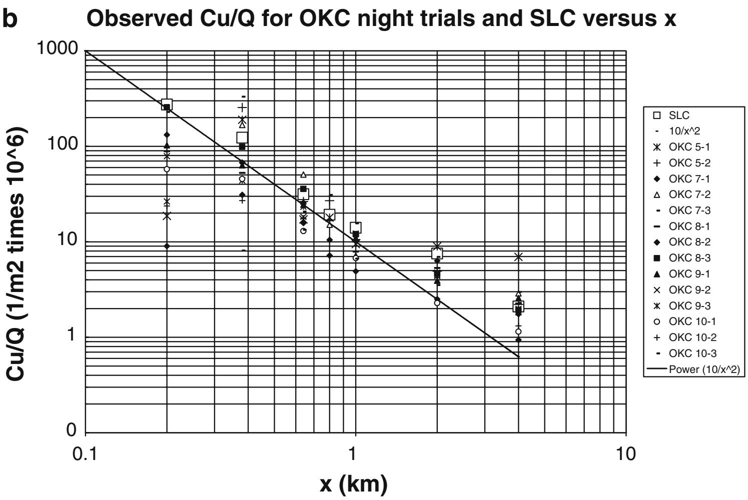


Fig. 6 (**a**)Summary plot of observed of Cu/Q versus x for daytime trials during JU2003 and observed average for DAPPLE. (**b**) Summary plot of observed of Cu/Q versus x for nighttime trials during JU2003 and observed average values for Urban 2000. C is the maximum 30-min averaged concentration observed 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 $x < 1$ km when mean building height, H, is 20 m

fact that the street-level turbulence observations indicated little day–night difference and similar slightly unstable values of σ_T/T_* and L. The reason for the day–night difference in $C_{max}u/Q$ is probably due to the fact that there are stable conditions aloft over the built-up Oklahoma City urban area at night (Lundquist and Mirocha 2006). Note that the $C_{max}u/Q$ data from other cities (London DAPPLE and Salt Lake City Urban2000) plotted on Fig. 6a and b confirm this day–night difference of about a factor of three. We stress that these results are for near-surface continuous releases of non-buoyant tracers.

5 Conclusions

This paper presents some results of preliminary analyses of the JU2003 and the MSG05 observations of fast response wind and temperature data, as well as the JU2003 observations of tracer concentrations. These data are unique because the focus was on turbulence and dispersion near street level in the built-up downtown areas. The results are encouraging in the sense that similar scientific relations appear to be evident in more than one city.

The original analysis produced 30-min averages of winds, turbulence, and concentration for many individual anemometers and concentration samplers and for many 30-min periods. For our purposes, in order to present the main results in the available space, the focus is usually on the averages over many anemometers and many time periods. However, we have also presented summaries of the variations in space and time of the 30-min averages. In general, the magnitudes of the variations in space and time are less than half the magnitudes of the averaged values of the winds, turbulence and concentrations that are presented.

The following tentative conclusions have been reached for the averages over space and time.

5.1 Mean winds and turbulent variances and fluxes

Wind data from three cities (SLC, OKC, and NYC) suggest that the mean scalar wind speed and direction on the tops of tall downtown buildings, at heights of 100–300 m, are approximately equal to winds observed near the surface at a nearby airport, and that the mean wind speed at street level is about 1/3 of the mean wind speed at the tops of tall downtown buildings. We realize that these results should ideally be cast in terms of dimensionless or scaled variables, and that there should be a satisfactory theory to explain the results, but we mention the dimensional relations because they are so clear.

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. The wind directions at the tops of tall buildings are much more consistent, as expected, even though they show a variability of $\pm$ about 30 degrees.

Calculations from sonic anemometer observations of wind and temperature fluctuations in downtown areas suggest that turbulence quantities such as σ_u, σ_w, σ_T, and u_* are fairly robust. Nondimensional relations such as $\sigma_w/u_* = 1.5$ and $u_*/u = 0.25$ are seen to be valid for these urban data, on average. Turbulence integral time scales near street level in downtown areas are found to equal about 20 s (corresponding to an integral length scale of about 40 m).

Only small differences are seen in the results for day versus night (i.e., stability) for these urban downtown wind and turbulence relations, where most of the observations are from near street-level. On average, daytime heat fluxes are slightly unstable and nighttime heat fluxes are very slightly unstable, as shown by the values of the Obukhov length. This effect is likely due to the combined effect of the anthropogenic positive heat flux to the atmosphere, as well as the strong mechanical mixing caused by the buildings.

5.2 Dispersion of continuous releases of tracer gas from point sources near street level

The JU2003 concentration observations from the continuous SF_6 release trials have been analyzed and compared with observations from two other urban field experiments (SLC Urban 2000 and London-DAPPLE). In all three experiments, the tracer gas was released from a point source near street-level in the downtown area. When the maximum concentration, C_{max}, on a sampling arc is considered, the daytime observations of $C_{max}u/Q$ versus distance, x, are similar for JU2003 and DAPPLE. The relation $C_{max}u/Q = 3/x^2$ is valid during the daytime over the range of distances from about 0.1 km to 4 km, and the data points from the individual JU2003 trials have a scatter about the line of about ±a factor of three. The nighttime observations of $C_{max}u/Q$ versus distance, x, are found to be similar for JU2003 and Urban 2000. However, there is a larger "constant" in the relation ($C_{max}u/Q = 10/x^2$ is more appropriate for the nighttime data), and is valid only to distances of about 1 km. As for the daytime trial, the data points from the individual JU2003 nighttime trials have a scatter about the line of about ±a factor of three. Neophytou and Britter (2004) postulate that the downwind distance limit to the formula is about $50H$, and the observed 1000 m limit is consistent with this postulate, since H is about 20 m. During the nighttime, the stability is near-neutral in the built-up downtown area but stable conditions redevelop as the air passes over residential areas. At $x/H > 50$, a similarity relation is still valid but the exponent in the x/H term slowly decreases to about -1.5, due to reduced vertical dispersion in the more stable air.

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