9.1 SIMILARITY RELATIONS SEEN IN MANHATTAN TURBULENCE OBSERVATIONS

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ABSTRACT

Extensive sonic anemometer observations of micrometeorological variables near street-level and at roof-top in built-up downtown areas in Manhattan have been analyzed. The Madison Square Garden–2005 (MSG05) experiment, in March, collected data from five street-level sites and two roof-top sites in the 500 m by 500 m area around MSG on two well-mixed days with moderate winds. The Midtown-2005 (MID05) experiment, in August, involved 10 street-level sites and five roof-top sites in an approximate 1 km by 1 km area south of Central Park on six days with light-to-moderate winds. There are many tall buildings in both domains, with average heights of about 60 m and a few buildings near 250 m. The results of the sonic anemometer analyses in Manhattan are compared with the results reported by the authors of similar sonic anemometer observations made during the Joint Urban 2003 (JU2003) experiment in Oklahoma City, and with urban similarity relations found by others in other cities. It is found that the turbulent standard deviations and the similarity relations (e.g., σ_u/u^*) are fairly consistent from one city and one field experiment to another. For example, near the surface, σ_u is typically about 0.5 to 1 m/s and σ_T is about 0.5 °C. The local σ_w/u^* is about 1.6 and the local u^*/u is about 0.24 at the sites. The ratio σ_T/T^* in the street-canyons is about -2 to -5 at the three sites, even at night during JU2003. These values of σ_T/T^* are consistent with similarity theory for very-slightly unstable conditions and with the observed Monin-Obukov lengths (on the order of -100 m). The analysis of the surface and rooftop data suggests that most of the turbulent speed standard deviations at the surface are about 40 or 50 % of their values at the rooftops.

In addition, the variations at MID05 in the 30-minute mean turbulence values with time (i.e., 15 30-min time periods each IOP) and with site (i.e., 12 surface sites) were calculated in order to estimate their magnitude compared to the 30 min averages of σ_u etc. It is found that the space and time variations are generally less than 50 % of the 30 min averages analyzed above.

1. INTRODUCTION

This paper expands upon the comprehensive analysis by Hanna et al. (2007) of meteorological observations obtained in short-term intensive urban field studies in Oklahoma City (OKC), known as the Joint Urban 2003 (JU2003) experiment, and in Manhattan, known as the Madison Square Garden 2005 (MSG05) experiment. The current analysis adds data from a second field study in Manhattan, known as the Midtown 2005 (MID05) experiment. Data are available from near-street-level and from the rooftops of tall buildings in the built-up downtown area. The focus is on turbulence observations from networks of sonic anemometers. The goal is to identify areas where a consensus can be reached concerning the vertical variation of turbulent energy or the agreement with similarity relations such as σ_w/u^* = constant. Formulas and parameterizations of urban turbulence in the literature are tested.

Clarke et al. (1987) measured turbulence over St. Louis in the mid-1970's and showed the presence of large increases in the turbulent velocities over the urban area, with the difference accentuated at night. Oke (1987) reviews the state of the science of urban meteorology as of about 1986 and Rotach (1996) provides a review as of about 1995. In the past 10 years, there have been extensive new experiments and analyses of urban wind and turbulence profiles, and results are presented in several papers, including those by Roth (2000), Macdonald (2000), Britter and Hanna (2003), and Kastner-Klein and Rotach (2004). Urban meteorology and dispersion field experiments in Europe include the Zurich urban experiment (Rotach, 1995), the Basel Urban Boundary Layer Experiment (BUBBLE) (Rotach et al., 2005), the Marseille field experiment (Grimmond et al. 2004; Mestayer et al., 2005), and the London field experiment known as Dispersion of Air Pollutants and their Penetration in Local Environments (DAPPLE) (Britter, 2005). In the U.S., urban field experiments in the past five years include Joint Urban 2003 in Oklahoma City (Allwine et al., 2004) and the Urban Dispersion Program (UDP) experiments in Manhattan in 2005 (Allwine and Flaherty, 2006 and 2007);

Britter and Hanna (2003) point out that the friction velocity, u*, is an important scaling parameter for urban wind and turbulence, and 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 square root of the sum of 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 an anemometer (usually a sonic anemometer in the current paper) in the eastward, northward, and up

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directions, respectively., and are usually based on averaging times of about 10 to 60 minutes. A 30 minute averaging time is used in the current paper.

Some suggested similarity relations and other variables for urban winds and turbulence are listed by Hanna et al. (2007), based on some of the urban observations and analyses in the set of references that has been surveyed. These relations are tested with the JU2003, MSG05, and MID05 data in later sections. Britter and Hanna (2003) base their recommendations on a survey of many observations and on similarity analyses. In addition, Rotach (1995) studied observations in Zurich, and Macdonald (2000) studied observations in small scale field experiments and fluid modeling experiments. Grimmond et al. (2004) focused on results from the field experiment in Marseille. Roth (2000) investigated turbulence data from 14 cities. Kastner-Klein and Rotach (2004) studied a wind tunnel simulation of Nantes.

2. MSG05 AND MID05 DESCRIPTIONS

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 in the U.S. is addressing flow and dispersion in cities with large built-up areas containing at least five or ten tall ($z > 100$ m) buildings. Most of the observations in these field experiments are made at street level deep within urban street canyons and/or near very tall buildings. The JU2003 (Allwine et al., 2004), MSG05 (Allwine and Flaherty 2006, Hanna et al., 2006 and 2007), and MID05 (Allwine and Flaherty, 2007) 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 DHS and DTRA 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 Operating Period (IOP) days, during which a number of tracer releases took place over several hours, with detailed meteorological observations.

Sonic anemometers are necessary in urban street canyons, where wind speeds are generally low and an anemometer is needed that can measure down to a few cm s^{-1}. However, 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.

For anemometers near street level, placement in a street canyon can predetermine the dominant local wind directions and the variation of the wind speed with 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.

The following paragraphs describe the MDG05 and MID05 experiments, with emphasis on the sonic anemometer observations. PFT tracer was released during MSG05 and PFT and SF6 tracers were released during MID05 and were sampled at a grid of monitors. The current paper does not address the tracer data.

The JU2003 turbulence data are included in some of the tables below. That experiment has been described in detail in previous papers (e.g., Allwine et al., 2004; Hanna et al., 2007) and the reader is referred to those papers.

The text below discusses the numbers of sonic anemometers and other details. Table 1 summarizes this information in a side-by-side table to aid comparisons.

2.1 MSG05

The science goals for MSG05, which took place during 5 ½ hour time periods (from 7:00 am through 12:30 pm) on 10 and 14 March 2005, were to increase understanding of flow and dispersion in deep urban canyons and of rapid vertical transport and dispersion in recirculating eddies adjacent to very tall buildings in a large urban area (Allwine et al, 2006, Hanna et al., 2006 and 2007). 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 minimum values of u/u^* will occur and maximum values of σ_u/u^*, σ_v/u^*, and σ_w/u^*. The two IOP days at MSG05 included many meteorological measurements, such as seven sonic anemometers at street level (at $z = 3$ m) and two on 10 m towers on top of very tall buildings (at $z > 150$ m). Figure 1 presents the locations on the MSG05 domain of the sonic anemometers. Unlike JU2003, there were sonic anemometers in MSG05 on the roofs of the skyscrapers, as well as at street level. This paper uses data from five of the street-level (surface) and two of the rooftop anemometers (see Table 1). Surface anemometers were at a height of 3 m. Rooftop anemometers were on the One Penn Plaza (OPP at 233 m) and Two Penn Plaza (TPP at 153 m) buildings, at a height of 5 to 10 m above the rooftop.

The siting 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.

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

2.2 MID05

The MID05 field experiment was a larger field experiment than MSG05 (Allwine and Flaherty, 2007). It took place on six days in August 2005, on a larger domain centered about two km to the northeast of MSG, covering the so-called Midtown area of Manhattan. Figures 2 and 3 show the domain and the locations of the 12 street-level (surface) anemometers and some of the rooftop anemometers. Table 1 summarizes the main characteristics of the sonic anemometers. The surface anemometers were at a height of 3 m. The rooftop anemometers were on the Met Life (MetL1 at 247 m), OPP (233 m), McGraw-Hill (MGH1 at 208 m), General Motors (GM1 at 225 m), and Park Plaza (PPZ at 182 m) buildings, at a height of 5 to 10 m above the rooftop.

Each of the six IOPs lasted for 7 ½ hours, from 5:00 am through 12:30 pm. Wind speeds were generally lighter than during MSG05, and wind directions differed for the six IOPs.

3. ANALYSIS OF TURBULENT WIND AND TEMPERATURE STANDARD DEVIATIONS AND u*, T*, AND L

The 10 Hz records from the sonic anemometers have been used to calculate the following variables over a 30 min averaging times for this analysis:

Mean wind components <u>, <v>, <w>
Mean temperature <T>
Mean scalar 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 $\sigma_h = (\sigma_u^2 + \sigma_v^2)^{1/2}$
$TKE = (\sigma_u^2 + \sigma_v^2 + \sigma_w^2)/2$
Standard deviation of temp fluctuations σ_T
Friction velocity $u^* = (\langle u'w' \rangle + \langle v'w' \rangle)^{1/2}$
Temperature scale $T^* = \langle w'T' \rangle / u^*$
Monin-Obukhov length
$L = (u^{*2}/0.4)/((g/\langle T \rangle)T^*)$

The symbol < > represents an average over time. The total horizontal velocity turbulent standard deviation, σ_h, is used because of the large turbulent intensities in urban areas.

3.1 MSG05 Calculations of Turbulence Variables for Sonic Anemometers Near the Surface and at Rooftop

Table 2 contains a summary of the calculations based on the sonic anemometer observations during MSG05. The similarity relations (e.g., $\sigma_w/u^* = 1.36$ at the surface) derived from the data will be further discussed in Subsection 3.3, along with those from JU2003 and MID05. The data in Table 2 are presented for each instrument and each IOP, as well as for averages over both IOPs and over groups of similar locations. It is seen that the magnitudes of the turbulence variables (e.g., σ_h, σ_w and σ_T) at the surface are about one-half of their magnitudes at rooftop. The average friction velocity, u*, shows less variation with height. The ratio of surface to rooftop u* is about 0.82.

Of course, the above preliminary conclusions are based on averages over all instruments and hours. Individual sites and time periods show more variability. The discussion of the MID05 data will expand on this issue.

3.2 MID05 Calculations of Turbulence Variables for Sonic Anemometers Near the Surface and at Rooftop

Table 3 contains the average values of the wind temperature, and turbulence variables for the five individual rooftop sites and the 12 individual surface sites for MID05. The averages (and ranges) for the rooftop sites combined and the surface sites combined are listed at the bottom of the table. The wind speed data indicate that the average scalar wind speeds during MID05 are about ½ of their values during MSG05. The MID05 experiment took place during typical mid-summer conditions with light to moderate winds, whereas the MSG05 experiment took place during post-frontal windy periods in March. During both experiments, the average scalar wind speed at the surface is about 0.4 times that at the rooftops.

In agreement with the results from MSG05, the magnitudes of the turbulence variables (e.g., σ_h, σ_w and σ_T) at the surface are about one-half of their magnitudes at rooftop. The ranges in the averages over the several anemometers are similar at the surface and at the rooftops, with a typical range of about ±20% to 40%.

The similarity relations and comparisons with MSG05 and JU2003 data are given in Section 3.3.

3.3 Comparisons of JU2003, MSG05, and MID05 Turbulence Observations with Similarity Relations from References

Hanna et al. (2007) discuss a set of similarity relations observed in other cities and postulated by some references for turbulent variables in urban areas. The first section of the current paper has reviewed some of these references. Table 4 extracts some observations of dimensional and dimensional and nondimensional standard deviations and u* and T* from the calculations listed for MSG05 and MID05 given in Tables 2 and 3, respectively, includes the same data from JU2003, and compares the observations at the three sites with the relations suggested in the references. Column 2 in Table 4 presents the hypothesized relations from the literature (summarized by Hanna et al., 2007). Columns 3, 4, and 5 present the corresponding JU2003, MSG05, and MID observations, respectively. Column 6 presents the average over the three field experiments. The observations given for the field experiments represent averages over all IOPs and all sonic anemometers, separated by day and night for JU2003 and by surface and rooftop for MSG05 and MID05.

The last eight rows of the table present the average values of the dimensional variables (except the median is given for T* and L). The turbulent speeds and u* obviously scale with wind speed, u, as expected. The temperature standard deviation, σ_T, is in the range from about 0.4 to 0.6 °C and the temperature scale, T*, is about 0.2 °C at the surface during the day at the three sites. The median Monin-Obukhov length, L, is negative and with relatively large magnitude, day and night, at the surface and the rooftops, suggesting persistent slightly-unstable conditions in the built-up downtown areas. Since $L = u^{*2}/(0.4(g/T)T^*)$, and T* is about -0.2 °C, then L equals about - 400 u^{*2} in these three urban downtown areas.

It is seen in Table 4 that, for daytime conditions, and for either surface or rooftop anemometers, most of the dimensionless turbulence averages are very similar for JU2003, MSG05, and MID05. The averaged dimensionless variables from JU2003 and MSG05 are within 20 % of each other.

The table includes use of both u* and u to normalize the turbulent velocities. The average ratio u*/u is about 0.24 for the surface measurements and about 0.13 for the rooftop measurements. The surface value of 0.24 agrees fairly well with the postulated value of 0.28. The observed average and values of σ_u/u, σ_v/u, and σ_w/u near the surface are 0.50, 0.56, and 0.31, which are within 40 % of the postulated values of 0.45, 0.39, and 0.31, respectively.

When u* is used for scaling, the observations of scaled horizontal wind speed standard deviations (e.g., σ_u/u^*) from the three sites near the surface tend to be consistently higher, by about 50 to 80 %, than postulated by Britter and Hanna (2003). The observed TKE is about 3 times larger than the postulated values.

The observed JU2003, MSG05, and MID05 temperature fluctuations, σ_T, divided by the scaling temperature, T*, can also be compared with published similarity relations. The average values of σ_T/T^* at JU2003, MSG05, and MID05 at the surface are about -3.24, -3.63, and -1.95, which correspond to the value postulated by the references for nearly neutral conditions, on the slightly-unstable side. 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.

4. VARIATION OF TURBULENCE IN TIME AND SPACE

The analysis of observed 30-minute averaged urban turbulence in Section 3 dealt with average values over time or over a group of similar locations. The urban domain, more so than any other domain, is likely to show variations in time and in space due to the influence of the buildings. This effect is investigated in this section and the results are presented in Tables 5 and 6. In general it is found that the contribution of the time and space variations to the total standard deviation is less than 50 % of the standard deviation quoted in Section 3. This is encouraging, since it verifies that the conclusions in section 3 are generally valid and are not overwhelmed by site-to-site variations or time variations from one 30 min average to the next.

Table 5 contains values of the standard deviation (STD) of the set of values of the turbulence variables measured near the surface during MID05. Table 6 contains the same information for the rooftop anemometers. Row 1 lists the means, which are identical to what is found in Table 3. STD are calculated in three different ways: Space and Time (s&t) variations based on the 15 30 min averages during an IOP and the 12 sites (at the surface) or 5 sites (at the rooftops). Thus there is a maximum of 15x12 = 160 numbers at the surface and 15x5 = 75 numbers at the rooftops for calculating STD. Then the STDs for the six IOPs are averaged to give the numbers in the table. The space (s) variations are based on the STD over the 12 (surface) sites during each 30 min period. The time (t) variations are based on the STD for each site over the 15 30-min periods during each IOP. Tables 5 and 6 first list the STD and then the STD/mean. Typically, for the surface anemometers, the magnitude of STD(s) is about 90% of the magnitude of STD (s&t) and the magnitude of STD (t) is about 70 % of the magnitude of STD (s&t). The 70 % ratio between STD (t) and STD (s&t) is valid for the rooftop anemometers, too.

As mentioned earlier, the relative value of STD (s&t)/mean is usually about 0.3 or 0.4 for the turbulent speeds. The three ratios listed beneath Tables 5 and 6 are the ratios of the STD of a mean variable (WS, w, and T) to the mean 30-min average turbulent standard deviation of that variable. Thus STD(WS)/σ_h is about 0.4 or 0.5, STD(w)/ σ_w is about 0.4, and STD(T)/ σ_T is about 3.8 at the surface and 2.4 at rooftop. The relatively large value of STD(T)/ σ_T indicates that the variability of the mean temperature in space and time is larger than the turbulent variability within a 30-min averaging period. This may be due partly to the fact that a sonic anemometer measures the temperature fluctuations more accurately than the mean temperature, and partly to the fact that, on a sunny day in an urban area, some anemometers are in the sun and others are in the shade.

5. CONCLUSIONS

Some results are given of analyses of the JU2003, MSG05, and MID05 observations of fast response winds and temperatures. These urban data are unique because the focus was on turbulence near street level (i.e., the surface) in the built-up downtown areas. The results are encouraging in the sense that similar scientific relations appear to be evident in three experiments.

The following tentative conclusions have been reached:

Calculations from sonic anemometer observations of wind and temperature fluctuations in downtown areas during JU2003, MSG05, and MID05 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 $u^*/u = 0.24$ are shown to be valid for these urban data.

Only small differences are seen in the results for day versus night (i.e., stability) for these urban downtown turbulence relations. Daytime heat fluxes are slightly unstable and nighttime heat fluxes are very slightly unstable, as shown by the values of the Monin-Obukhov length.

The variations between the surface and rooftops could be investigated using the Manhattan MSG05 and MID05 data, showing that most of the turbulent speed standard deviations at the surface are about 40 or 50 % of their values at the rooftops.

In addition, the variations at MID05 in the 30-minute mean turbulence values with time (i.e., 15 30-min time periods each IOP) and with site (i.e., 12 surface sites) were calculated in order to estimate their magnitude compared to the 30 min averages of σ_u etc. It is found that the space and time variations are generally less than 50 % of the 30 min averages analyzed above.

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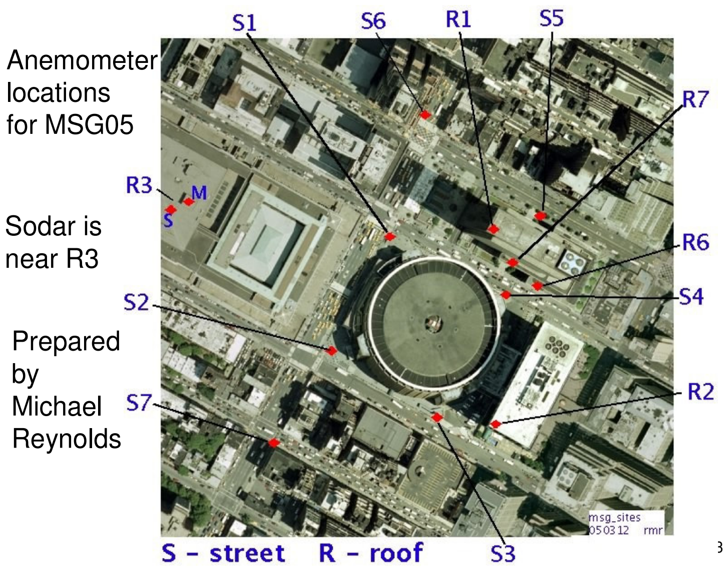

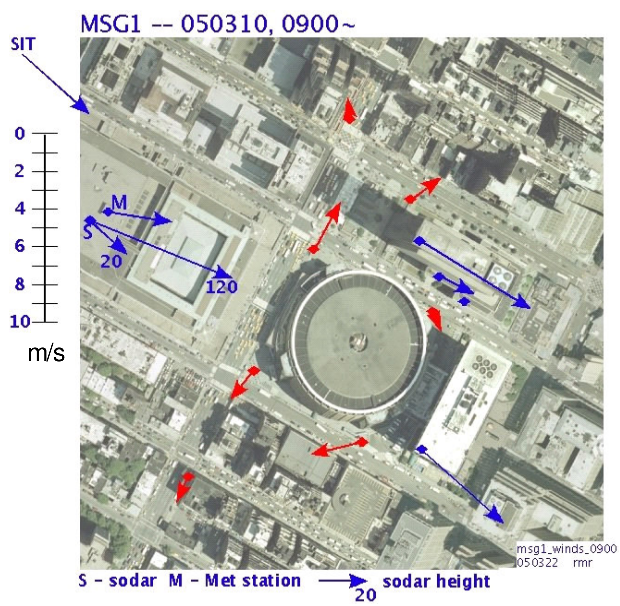

Figure 1 – View of area around Madison Square Garden (MSG) in Manhattan, where MSG is the round building and has diameter 130 m and height 50 m. The 229 m tall One Penn Plaza building is to the NE of MSG and the 153 m tall Two Penn Plaza building is to the ESE of MSG. Top: Anemometers used for wind observations 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

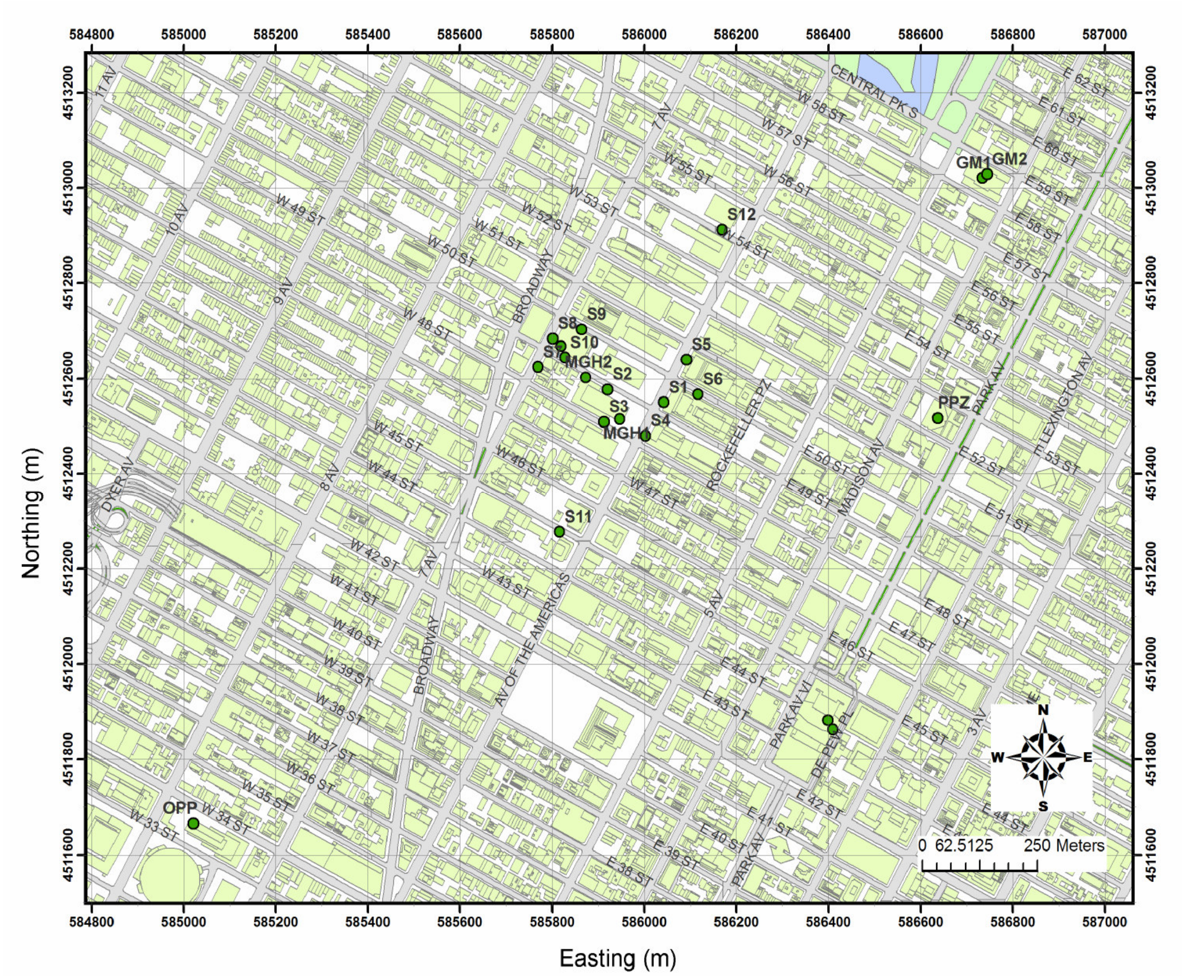

Figure 2 – View of area around the Midtown (MID) area in Manhattan, showing locations of sonic anemometers used in MID05. The letter S refers to "surface" (actually at about z = 3 m agl), and the other letters refer to "rooftop" sites (from 150 to 250 m agl). Note that MSG is the round building in the lower left corner of this map. The OPP rooftop anemometer (near MSG) is used in both MSG05 and MID05. Figure provided by Julia Flaherty, Pacific Northwest Laboratory.

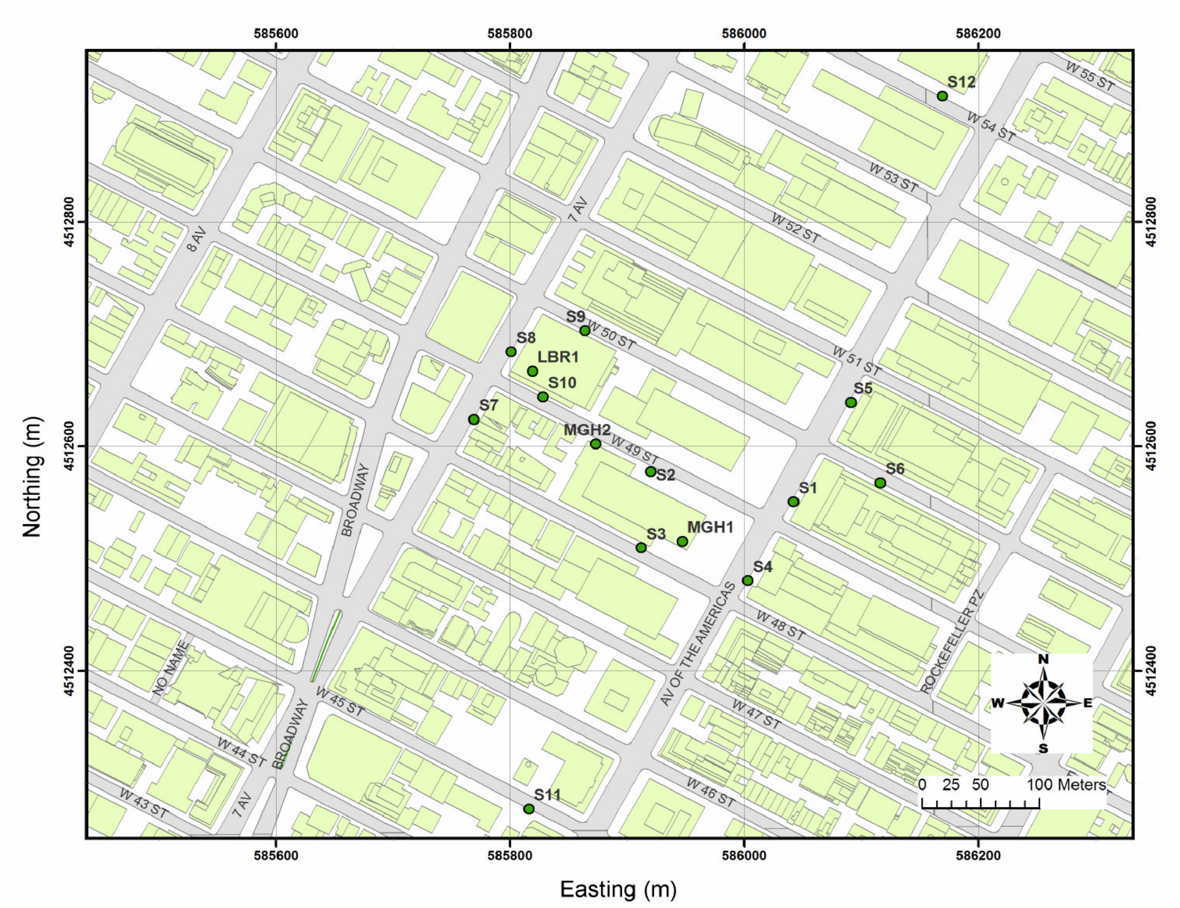

Figure 3 – Zoom view of the MID05 area, showing details of locations of sonic anemometers in the central area of the study where the most intense observations were made. The letter S refers to "surface" (actually at about z = 3 m agl), and the other letters refer to "rooftop" sites (from 150 to 250 m agl). Note that MSG is in the lower left corner of this map. Figure provided by Julia Flaherty, Pacific Northwest Laboratory.

Table 1. Summary of sonic anemometers analyzed

Field Experiment	Numbers of sonic anemometers	Height of instrument	Number of IOPs and time of year and duration	IOP breakdown by day-night and timing
JU2003 (Oklahoma City)	20 surface	8 m	10 (summer, 8 hr)	6 day, 4 night
MSG05 (Manhattan)	5 surface, 2 rooftop	3 m	2 (winter, 5 ½ hr)	Day (morning from 7:00 to 12:30 pm)
MID05 (Manhattan)	12 surface, 5 rooftop	3 m	6 (summer, 7 1/2 hr)	Day (morning from 5:00 am to 12:30)

Table 2. 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 N of OPP, and along 8th Ave to the S of MSG, Respectively (see Figure 1, Top Panel). Each IOP has Duration 5 1/2 Hrs. The Means and Turbulence are Calculated for 30 Min Periods. Note that $\sigma_h^2 = \sigma_u^2 + \sigma_v^2$.

IOP	Site	Vect speed m s^{-1}	Scalar speed m s^{-1}	Dir deg	σ_u ms^{-1}	σ_v ms^{-1}	σ_h ms^{-1}	σ_w ms^{-1}	σ_T °C	TKE $m^2 s^{-2}$	u* ms^{-1}	-T* (°C)	-L (m)	σ_h/u*	σ_w/u*	σ_T/T*
1	R1 OPP	6.38	6.80	293	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	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	4.80	5.40	306	2.95	2.35	3.78	1.14	0.79	7.84	0.60	0.22	1190	6.30	1.90	3.59
2	R2 TPP	3.16	4.00	322	2.52	2.57	3.60	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	1.20	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	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	1.43	2.02	2.47	0.70	0.44	3.45	0.61	0.14	291	4.04	1.15	3.14
2	S4	3.82	4.00	165	0.94	1.71	1.95	0.80	0.43	2.27	0.70	0.10	-412	2.79	1.14	4.30
1	S5	2.41	2.89	249	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	1.06	1.31	1.69	0.83	1.01	1.80	0.53	0.21	31.5	3.19	1.57	4.80
1	S7	0.95	1.51	22	0.80	1.22	1.46	0.61	0.56	1.25	0.50	0.21	106	2.92	1.22	2.60
2	S7	1.95	2.28	29	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	2.32	2.45	3.42	1.19	1.00	6.69	0.73	0.20	53.4	4.68	1.63	10.6
avg	R2 TPP	3.98	4.70	314	2.74	2.46	3.69	1.15	0.78	7.53	0.57	0.33	645	6.48	2.00	2.66
avg	S1	2.48	2.81	193	1.35	1.38	1.91	0.77	0.51	2.14	0.64	0.14	220	3.00	1.20	3.65
avg	S4	2.58	3.33	224	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	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	1.06	1.31	1.69	0.83	1.01	1.80	0.53	0.21	31.5	3.19	1.57	4.80
avg	S7	1.45	1.90	26	0.89	1.30	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	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	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	1.82	1.98	2.72	0.96	0.75	4.61	0.60	0.21	174	4.52	1.59	5.08

Table 3 Summary Results of Turbulence for 15 MID05 Sonic Anemometers in New York City. Each of the six IOPs has Duration 7 1/2 hrs. The Means and Turbulence are Calculated for 30 Min Periods. Medians are listed at the bottom for T*, L, and σ_T/T*. Note that $\sigma_h^2 = \sigma_u^2 + \sigma_v^2$.

Anemometer location	Scalar wind speed m/s	T ℃	σu m/s	σv m/s	σh m/s	σw m/s	TKE m^2/s^2	σT ℃	u* m/s	T* ℃	L m	σu/u*	σv/u*	σw/u*	σh/u*	σT/T*	TKE/u*^2
Rooftop:																	
GM1	2.59	296.1	1.18	1.44	1.89	0.68	2.14	1.54	0.44	0.52	-111	2.98	3.53	1.66	4.67	-2.26	11.11
METL1	3.50	295.2	1.41	1.44	2.04	0.59	2.47	0.44	0.35	-0.11	-147	4.62	4.50	1.89	6.52	-1.95	19.70
MGH1	3.23	296.2	1.56	1.46	2.15	0.71	2.84	0.44	0.58	-0.13	-534	2.88	2.69	1.30	3.97	-3.65	8.51
OPP	3.34	296.8	1.54	1.89	2.47	0.78	3.65	0.38	0.65	-0.10	1612	2.68	3.22	1.37	4.23	31.37	8.54
PPZ	2.39	294.7	1.29	1.37	1.90	0.67	2.11	0.49	0.53	-0.15	-409	2.56	2.66	1.29	3.72	-6.01	7.62
Surface:																	
s1	1.35	300.8	0.71	0.91	1.16	0.40	0.80	0.62	0.24	-0.34	-22	3.15	4.01	1.79	5.12	-2.54	13.76
s2	0.94	301.8	0.60	0.64	0.88	0.30	0.47	0.42	0.18	-0.23	-51	3.68	3.88	1.82	5.38	-1.93	15.13
s3	1.30	297.1	0.65	0.60	0.89	0.39	0.53	0.34	0.19	-0.14	39	3.91	3.51	2.23	5.28	-0.18	14.40
s4	1.33	299.7	0.70	0.89	1.13	0.43	0.76	0.89	0.31	-0.57	-19	2.50	3.17	1.52	4.04	-1.85	7.91
s5	1.33	300.7	0.65	0.80	1.03	0.38	0.63	0.59	0.26	-0.32	-22	2.74	3.31	1.61	4.31	-1.90	9.35
s6	0.73	302.8	0.45	0.40	0.61	0.27	0.23	0.47	0.13	-0.32	-14	4.18	3.53	2.42	5.51	-2.21	14.47
s7	0.96	301.1	0.51	0.61	0.80	0.35	0.40	0.53	0.20	-0.40	-11	2.85	3.44	1.97	4.48	-1.41	9.96
s8	1.30	296.2	0.61	0.73	0.95	0.36	0.55	0.50	0.26	-0.21	-30	2.66	3.23	1.66	4.21	-1.22	7.84
s9	1.14	298.7	0.79	0.56	0.98	0.40	0.60	0.60	0.31	-0.17	-27	2.89	2.15	1.46	3.61	-4.61	6.36
s10	1.01	297.5	0.63	0.50	0.81	0.38	0.43	0.49	0.21	-0.31	-5	3.26	2.51	1.93	4.13	-1.63	9.42
s11	1.31	297.2	0.65	0.50	0.83	0.34	0.42	0.41	0.23	-0.22	-35	2.92	2.25	1.52	3.71	-2.48	7.85
s12	1.20	296.4	0.77	0.60	0.98	0.39	0.58	0.45	0.23	-0.27	-49	3.66	2.86	1.85	4.68	-2.29	10.94
rooftop avg	3.01	295.8	1.40	1.52	2.09	0.69	2.64	0.66	0.51	-0.11	-147.0	3.15	3.32	1.50	4.62	-2.26	11.10
rooftop range	2.39-3.50	294.7-296.8	1.29-1.56	1.37-1.89	1.89-2.47	0.67-0.78	2.11-3.65	0.38-1.54	0.35-0.65			2.56-4.62	2.66-4.50	1.29-1.89	3.72-6.52		7.62-19.7
surface avg	1.16	299.2	0.64	0.65	0.92	0.37	0.53	0.53	0.23	-0.25	-24.0	3.20	3.15	1.81	4.54	-1.91	10.61
surface range	0.94-1.35	296.2-302.8	0.45-0.79	0.40-0.91	0.61-1.16	0.27-0.43	0.23-0.80	0.34-0.89	0.13-0.31			2.50-4.18	2.15-4.01	1.46-2.42	3.61-5.51		6.36-15.1

Table 4. Comparison of JU2003, MSG05 and MID05 Mean Turbulence Observations with Summary Results from the Literature for Urban Canopies. "Sfc" is at height 3 to 8 m. "Roof" is at rooftop of tall buildings (typical heights of 100 to 250 m). All Measurements are Local. If no "day-night" or "sfc-roof" breakdown is given, the difference is less than 2 or 3 %.

Turb Quantity	*Recs from Literature*	*JU2003 Obs (all at surface)*	*MSG05 Obs (all during daytime)*	*MID05 Obs (all during daytime)*	*Avg over Three Field Experiments*
$\sigma_u/u*$	1.6 sfc, 2.4 roof	2.36	2.00 sfc, 3.90 roof	3.12 sfc, 3.44 roof	2.49 sfc, 3.69 roof
σ_u/u	0.45	0.50	0.44	0.55 sfc, 0.47 roof	0.50 sfc, 0.45 roof
$\sigma_v/u*$	1.4 sfc, 1.9 roof	2.36	1.71 sfc, 3.78 roof	3.18 sfc, 3.49 roof	2.42 sfc, 3.65 roof
σ_v/u	0.39	0.50	0.60 sfc, 0.43 roof	0.57 sfc, 0.50 roof	0.56 sfc, 0.44 roof
$\sigma_h/u*$	2.1 sfc, 3.1 roof	3.63	3.47 sfc, 5.58 roof	4.50 sfc, 4.96 roof	3.87 sfc, 5.27 roof
$\sigma_w/u*$	1.1 sfc, 1.3 roof	1.56	1.36 sfc, 1.81 roof	1.80 sfc, 1.60 roof	1.57 sfc, 1.70 roof
σ_w/u	0.31	0.33	0.29 sfc, 0.20 roof	0.32 sfc, 0.23 roof	0.31 sfc, 0.22 roof
$TKE/u*^2$	2.87 sfc, 5.53 roof	6.9	7.01 sfc, 16.8 roof	10.12 sfc, 11.73 roof	8.01 sfc, 14.3 roof
$\sigma_T/T*$	-3	-2.28 day, -4.68 night	-3.63 sfc, -6.63 roof	-1.95 sfc, -2.12 roof	Daytime -2.62 sfc, -4.38 roof
$u*/u$	0.28 sfc downtown	0.25	0.27 sfc, 0.11 roof	0.20 sfc, 0.16 roof	0.24 sfc, 0.13 roof
σ_h (m/s)		1.61	1.88	0.94 sfc, 2.09 roof	
σ_w (m/s)		0.69	0.74 sfc, 1.17 roof	0.37 sfc, 0.68 roof	
TKE (m^2/s^2)		2.32	2.12 sfc, 7.11 roof	0.53 sfc, 2.04 roof	
σ_T (°C)		0.41 day, 0.17 night	0.61 sfc, 0.89 roof	0.53 sfc, 0.66 roof	
u (m/s)		2.11	2.53 sfc, 5.74 roof	1.18 sfc, 2.99 roof	
u* (m/s)		0.44	0.55 sfc, 0.65 roof	0.24 sfc, 0.49 roof	
T* (°C)		-0.18 day, -0.04 night	-0.17 sfc, -0.26 roof	-0.25 sfc, -0.49 roof	
L (m) median		-270 day, -900 night	-130 sfc, -100 roof	-28 sfc, -147 roof	

Table 5 – Variability in time and space for 12 MID05 surface anemometers. STD is the standard deviation of a set of N 30-minute averages of the variable listed, over space and time (s & t) for a given IOP and then averaged over all IOPs, over space (s) for a given 30 minute time period and then averaged over all time periods and IOPs, and over time (t) for a given anemometer location and IOP, and then averaged over all locations and IOPs.

Statistic	**Scalar wind speed WS m s^{-1}**	**T (°K)**	**σ_u ms^{-1}**	**σ_v ms^{-1}**	**σ_h ms^{-1}**	**σ_w ms^{-1}**	**TKE** $m^2 s^{-2}$	**σ_T °C**	**u* ms^{-1}**	**-T* (°C)**	**σ_u/u***	**σ_v/u***	**σ_w/u***	**σ_h/u***	**TKE/u^{*2}**
Mean	1.16	299.2	0.64	0.65	0.92	0.37	0.53	0.53	0.23	0.29	3.20	3.15	1.81	4.54	10.61
STD (s & t)	0.38	2.05	0.17	0.22	0.25	0.08	0.27	0.22	0.09	0.23	1.28	1.37	0.74	1.78	5.18
STD (s)	0.36	1.76	0.15	0.21	0.22	0.07	0.23	0.20	0.09	0.21	1.19	1.28	0.66	1.65	4.36
STD (t)	0.25	1.21	0.13	0.13	0.18	0.06	0.18	0.14	0.07	0.15	1.01	1.03	0.57	1.41	4.09
STD (s&t) /mean	0.33		0.27	0.33	0.27	0.21	0.49	0.41	0.40	0.76	0.41	0.43	0.41	0.40	0.51
STD(s) /mean	0.31		0.22	0.31	0.23	0.19	0.42	0.38	0.38	0.52	0.38	0.40	0.37	0.37	0.43
STD (t) /mean	0.22		0.21	0.21	0.19	0.15	0.35	0.27	0.30	0.53	0.32	0.33	0.31	0.31	0.37

[STD (s & t) of WS]/σ_h = 0.41; [STD (s & t) of w]/σ_w = 0.35; [STD (s & t) of T]/σ_T = 3.79

Table 6 – Variability in time and space for five MID05 rooftop anemometers. STD is the standard deviation of a set of N 30-minute averages of the variable listed, over space and time (s & t) for a given IOP and then averaged over all IOPs, and over time (t) for a given anemometer location and IOP, and then averaged over all locations and IOPs. The STD over space is not listed because the number of sites is at most 5 and is often less than 5.

Statistic	**Scalar wind speed WS m s^{-1}**	**T (°K)**	**σ_u ms^{-1}**	**σ_v ms^{-1}**	**σ_h ms^{-1}**	**σ_w ms^{-1}**	**TKE** $m^2 s^{-2}$	**σ_T °C**	**u* ms^{-1}**	**-T* (°C)**	**σ_u/u***	**σ_v/u***	**σ_w/u***	**σ_h/u***	**TKE/u^{*2}**
Mean	3.01	295.8	1.40	1.52	2.09	0.69	2.37	0.66	0.51	-0.11	3.15	3.32	1.50	4.62	11.10
STD (s & t)	1.17	1.67	0.44	0.50	0.62	0.18	1.74	0.87	0.21	0.56	1.58	1.59	0.64	2.17	6.70
STD (t)	0.93	1.42	0.35	0.41	0.50	0.15	1.31	0.48	0.16	0.31	1.11	1.10	0.45	1.49	5.39
STD (s&t) /mean	0.39		0.31	0.34	0.30	0.27	0.64	1.22	0.42	5.09	0.46	0.45	0.39	0.44	0.57
STD (t) /mean	0.31		0.25	0.27	0.24	0.22	0.49	0.71	0.37	2.82	0.35	0.33	0.30	0.32	0.48

[STD (s & t) of WS]/σ_h = 0.56; [STD (s & t) of w]/σ_w = 0.45; [STD (s & t) of T]/σ_T = 2.35