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Along-wind dispersion of puffs released in a built-up urban area

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Abstract The SF_6 gas tracer observations for puffs released near the ground during the Joint Urban 2003 (JU2003) urban dispersion experiment in Oklahoma City have been analysed. The JU2003 observations, at distances of about 100–1,100 m from the source, show that, at small times, when the puff is still within the built-up downtown domain, the standard deviation of the concentration time series, σ_t, is influenced by the initial puff spread due to buildings near the source and by hold-up in the wakes of large buildings at the sampler locations. This effect is parameterised by assuming an initial σ_{to} of about 42 s, leading to a comprehensive similarity formula: $\sigma_t = 42 + 0.1t$. The second term, $0.1t$, is consistent with an earlier similarity relation, $\sigma_t = 0.1t$, derived from puff observations in many experiments over rural terrain. The along-wind dispersion coefficient, σ_x, is assumed to equal $\sigma_t u$, in which u is the puff speed calculated as the distance from the source to the sampler, x, divided by the time after the release that the maximum concentration is observed at the sampler. σ_x can be expressed as $\sigma_x = \sigma_{xo} + 0.14x$, with the initial σ_{xo} of 45 m. This initial σ_{xo} agrees with the suggestion of an initial plume spread of about 40 m, made by McElroy and Pooler from analysis of the 1960s' St. Louis urban dispersion experiment. The puff speeds, u, are initially only about 20% of the observed wind speed, averaged over about 80 street-level and rooftop anemometers in the city, but approach the mean observed wind speed as the puffs grow vertically. The scatter in the σ_t data is about ± a factor of two or three at any given travel time. The maximum σ_t is about 250 s, and the maximum duration of the puff over the sampler, Dt, sometimes called the retention time, is about 1,100 s or 18 min for these puffs and distances.

Keywords Alongwind dispersion · Puff transport and dispersion · Similarity formula · Urban dispersion

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1 Introduction

The dispersion of air pollutants in cities with tall buildings and street canyons is not yet thoroughly understood, even though many serious air pollution problems occur in urban areas (Molina and Molina 2004), and about half of the world's population lives in cities. Nearly all of the earlier dispersion experiments were conducted over relatively flat terrain in rural areas (Draxler 1984). A better understanding of atmospheric flow and dispersion in cities is essential for both emergency response (in case of toxic release) and public health planning (through better characterisation of population exposure).

Several urban meteorology and dispersion field experiments have been carried out in recent years in the U.S., such as the Joint Urban 2003 (JU2003) study in Oklahoma City (Allwine et al. 2004) and in European cities, such as the Dispersion of Air Pollution and its Penetration into the Local Environment (DAPPLE) study in London (Arnold et al. 2004). The purpose of these field experiments has been to improve characterisations of urban wind fields and pollutant dispersion. These urban field data have been used to develop and test urban dispersion models (Chang et al. 2005; Hanna et al. 2003).

A relevant early urban dispersion experiment was the St. Louis tracer experiment carried out by the predecessor of the U.S. Environmental Protection Agency (U.S. EPA) in 1963–1965 (McElroy and Pooler 1968). Tracer gas was continuously released from point sources near ground level and sampled by a network extending several kilometres downwind. The St. Louis experiment led to relations for the lateral and vertical dispersion coefficients (σ_{y} and σ_{z}) in urban areas that later became known as the "urban curves" in the widely used Industrial Source Complex (ISC) dispersion model recommended and distributed by the U.S. EPA. For the purpose of the current study, it is important to note that the original McElroy and Pooler (1968) dispersion curves derived from this experiment suggested use of an "initial" σ_{y} and σ_{z}, for the same reasons as described below for JU2003. Namely, the plots of observed σ_{y} or σ_{z} versus distance, x, are "best fit" by assuming an initial spread (at $x = 0.0$). The initial σ_{yo} was suggested to be about 40 m, which will be seen in later sections to be close to the best-fit value for the (JU2003) along-wind dispersion data.

The current study focuses on the instantaneous puff releases during the JU2003 tracer experiment, which was conducted in Oklahoma City between June 28 and July 31 of 2003 (Allwine et al. 2004). Ten intensive operation periods (IOPs) of 8 h each were completed during this period, and detailed meteorological, turbulence and tracer measurements were made.

There were both continuous and instantaneous releases of SF_6 tracer gas during JU2003. Although both types of releases are being studied by the authors, the current paper addresses the instantaneous (puff) releases, which were generated by bursting a balloon filled with SF_6 at a height of about 1.5 m above local ground level. The initial diameter of the puff was about 1 m. The focus is on the along-wind size of the puff, which influences the maximum concentration in the puff and its duration over a receptor. For emergency response decisions, the duration of time that the puff exceeds some critical concentration is of importance. In a comprehensive analysis of several field experiments involving puffs over rural terrain, (Hanna and Franzese 2000) considered extensive sets of observations of puffs over a wide range of travel times, t. They demonstrated that the standard deviation, σ_{t}, of the concentration distribution at a given location, is satisfactorily parameterised by the relation $\sigma_{\mathrm{t}} = 0.1t$.

There have been few observations of along-wind dispersion in urban areas, where there is likely to be additional along-wind puff spread due to two effects, (1) the initial spread at the source location if there are buildings nearby, and (2) the spread due to hold-up at a sampler location if the sampler is near the wake of a large building or group of buildings.

The current study analyses 167 puff-sampler time series from the JU2003 field experiment. This set comprises about 2/3 of the total number of puff-sampler observations available. The other data did not pass quality control tests or did not contain useful information, defined as concentrations above background. In addition to an investigation of σ_{t}, we also include analysis of several other variables, such as the standard deviation, σ_{x}, of the along-wind concentration as a function of distance, x, at a given time, t. The variation of puff travel speed, u, with x and t is also investigated.

The study of concentration time series at a sampler at a fixed position is influenced by the fact that, for puffs over any type of surface, the trailing part of the puff (at times after the maximum concentration is observed) has a much longer tail than the leading part (at times prior to when the maximum concentration is observed). This can be explained simply because the puff is always growing, so has a smaller size (as indicated by σ_{x}) when its centre first approaches a sampler than when its centre is past the sampler. For the field data over flat rural surfaces discussed by Hanna and Franzese (2000), the ratio of the size of the trailing part of the puff to the leading part is about 2 or 3, consistent with a $\sigma_{\mathrm{t}} = 0.1t$ relation. The ratio of 2 or 3 is consistent with the median calculated from the JU2003 data and listed later. Note that, in any light-wind environment, as the turbulence intensity, $\sigma_{\mathrm{u}}/\mathrm{U}$, approaches unity or larger, the puff may disperse backwards faster than its centre is being transported forwards, so the concentration may not reach zero until several hours have passed at a given receptor location. σ_{u} is the standard deviation of the fluctuations in along-wind speed and U is the observed mean wind speed. The variable u is reserved for the puff speed. In addition to the puff dispersion, the building wake holdup further increases the ratio of the size of the trailing edge of the puff to the leading edge of the puff in an urban environment.

A separate and independent analysis of the JU2003 puff data has been recently published (Doran et al. 2006). Their approach was different from ours in many aspects. For example, they analysed a smaller number of puff-sampler time series, because their acceptance criteria for puff-sampler data were slightly more restrictive than ours. In addition, they focused on the retention time or the total duration of a puff over a sampler, because of the importance to emergency response planning. They investigated the lateral spread of the puff, to the extent that it could be determined by cross-wind transects through the puff by a mobile van with a sampler. Their results did not reveal the agreement with similarity relations for σ_{t} and σ_{x}, as well as the variation with distance of the ratio of cloud speed to wind speed, possibly because they used a wind speed observation at a single site and we used an average wind speed over many sites. Following discussion, they also used an initial plume spread to obtain a better fit to the data.

2 Description of JU2003 field experiment and fast-response tracer data

During JU2003, there were three to six puff releases made during each of the 10 IOPs (Allwine et al. 2004). Except for the first IOP, release intervals of 20 min were used, with the expectation that the first puff would clear the sampling network (extending about 1 km from the source) before the next puff was released. This philosophy was successful most of the time, but, for a few of the puff releases, the first puff had not completely cleared the area before the next puff was released. The release location during each IOP was fixed, but sometimes changed from one IOP to the next. Three different release locations were used during the 10 IOPs—one in front of the Westin Hotel, one near the Myriad Botanical Gardens, and one on Park Avenue midway between Broadway and Robinson Avenues. These three locations are referred to as the “Westin”, “Botanical”, and “Park” releases and are shown in

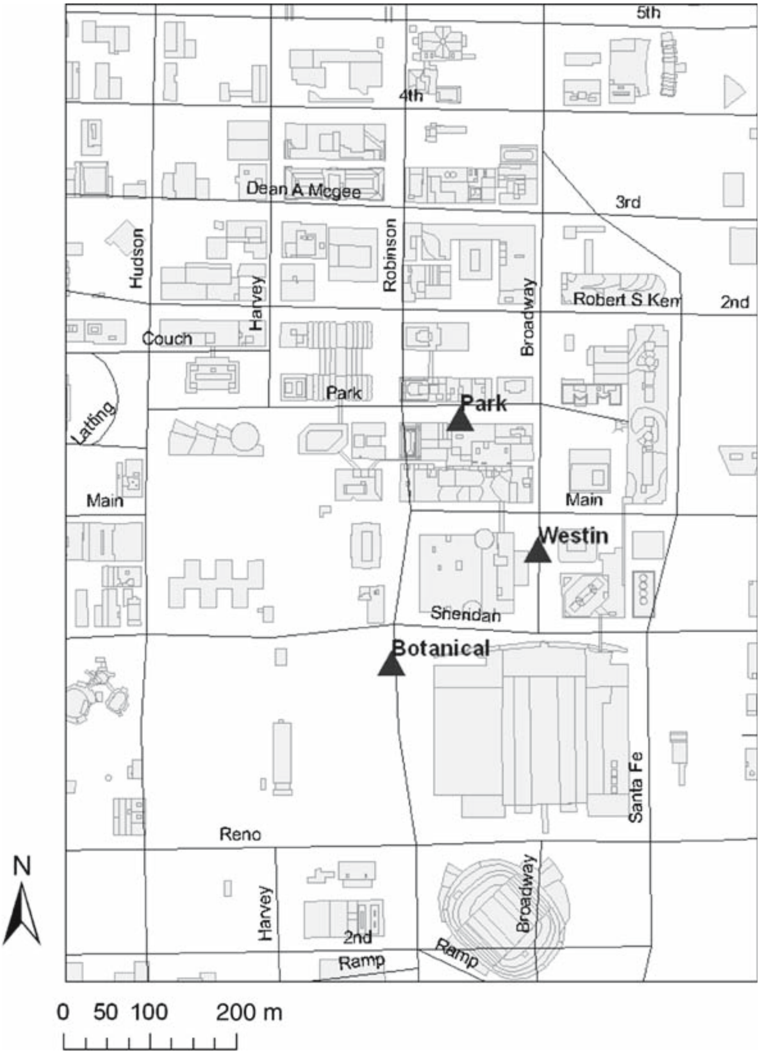

Fig. 1 Three release locations (marked by triangles) used during JU2003

Fig. 1. The choice of "Westin" or "Botanical Garden" release locations was dependent on the wind direction, so as to optimise the probability that the tracer cloud (plume or puff) would pass through the area of tall buildings and over the network of tracer samplers. The "Park" release allowed the investigation of local street canyon effects in more detail (Allwine et al. 2004). The Westin and Park release locations were in the midst of tall buildings, while the Botanical Garden release location was surrounded by grass and trees in a park just upwind of the area of tall buildings.

During each IOP, nine real-time fast-response (0.5 s) SF_6 samplers were placed in fixed locations downwind of the release. These samplers were in or near the downtown central business district (CBD) in Oklahoma City, at distances ranging from about 100 m to about 1,200 m from the release point. Figure 2 provides a two-dimensional (2D) view of Oklahoma

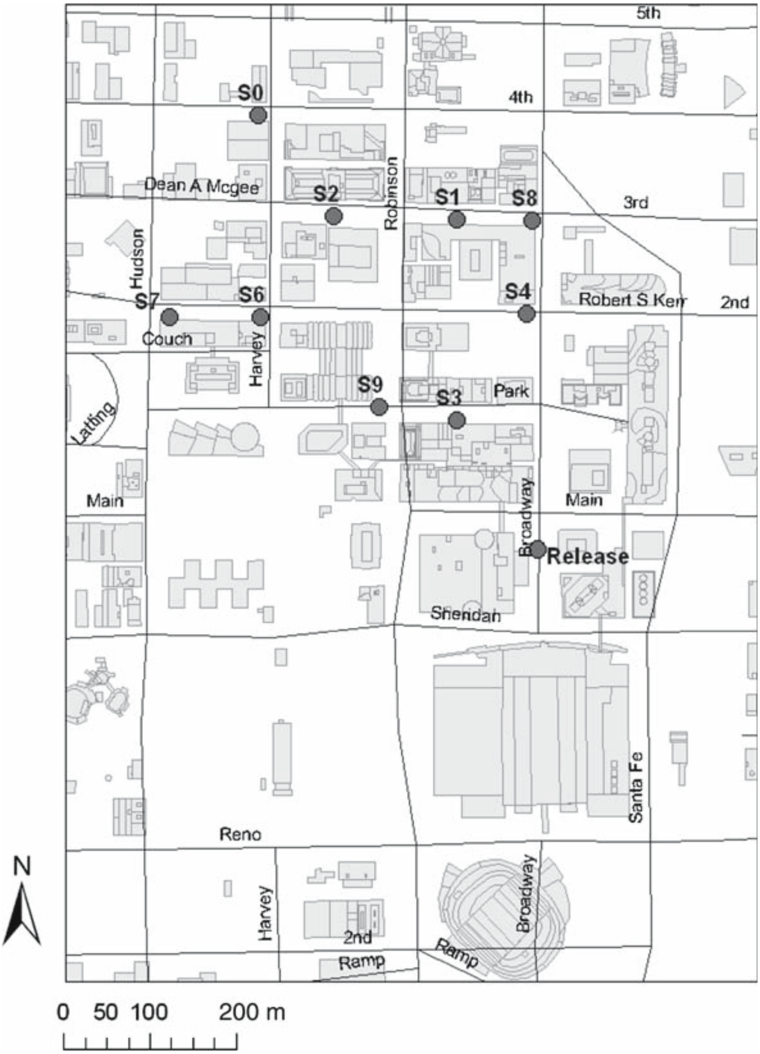

Fig. 2 Locations of release site (Westin) and fast-response samplers during IOP 8 and view of streets and buildings in Oklahoma City

City streets and building locations as well as an example of the release and sampler locations during IOP 8. Figure 3 is a three-dimensional (3D) view of Oklahoma City buildings from the south. A more detailed description of the tracer gas field experiment can be found elsewhere (Clawson et al. 2005).

Dugway Proving Ground (DPG, 2005) maintains the JU2003 data archive (https://ju2003-dpg.dpg.army.mil) and performed the initial processing of the 2 Hz (0.5 s) concentration data from the fast response samplers. If every sampler had collected valid data, there would be 360 (i.e., nine samplers during ten IOPs with an average of four puffs per IOP) sets of concentration time series data available for analysis. In our analysis, a set of puff data is used only if the "quality control (QC) flag" is 0 (meaning good data). Another limitation is

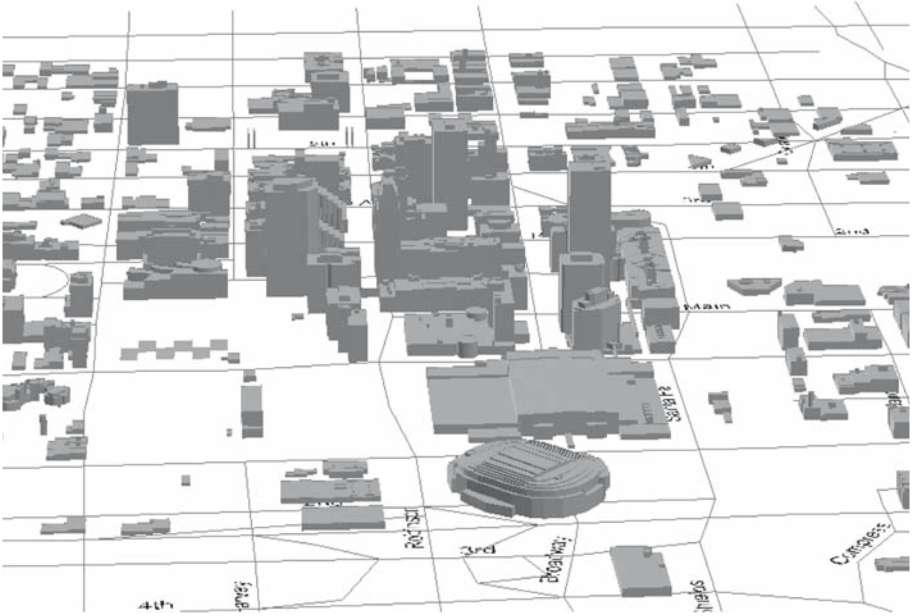

Fig. 3 3D view (from the south) of Oklahoma City buildings

that not all samplers were “hit” by the puff. More than half collected either no data or very low scattered concentration data. For example, no time series data from IOP2 were chosen for analysis, since five of the nine samplers collected no data and the other four samplers collected data that were barely above the instrument detection limit, which is five parts per trillion by volume (pptv). A total of 167 concentration time series were suitable for analysis, based on the QC flag being equal to 0 and the concentration being larger than the detection limit.

Extensive meteorological data were also collected during JU2003 from many fixed anemometers and from radiosondes and remote sounders such as sodars (Allwine et al. 2004). A previous study (Hanna et al. 2007) has analysed these data in order to estimate the average wind speed, turbulence, and stability in the Oklahoma City urban area. Some of these averaged data are useful for analyzing the puff tracer data. Table 1 contains a summary of some of the key averaged meteorological observations for each IOP, such as average wind speed (U) and wind direction (WD) for urban street-level locations and for all 80 anemometers averaged; lateral and vertical turbulence standard deviations, σ_v and σ_w, and friction velocity u_* at street level; and the Obukhov length, L, at street level. L can be considered to be a measure of stability. Wind speeds are seen to be consistently moderate and from the southerly quadrant, and Obukhov lengths are typically large and negative, suggesting slightly unstable conditions.

Urban modellers often use building morphology parameters. For example, in the built-up downtown area of JU2003, the building morphology parameters λ_p and λ_f are both about 0.3; λ_p is the dimensionless plan area, defined as the average plan area of the buildings divided by the total lot area, λ_f is the dimensionless frontal area, defined as the average frontal (i.e., facing the wind) area of the buildings divided by the total lot area (Macdonald 2000).

Table 1 Some key meteorological observations at JU2003. The term "street level" refers to 20 sonic anemometers in the downtown area. The term "80-anemometer" refers to many anemometers at street level and on building tops, as well as in the suburbs and nearby airports

IOP	Time of day CST	Street level scalar wind speed U ($\mathrm{m\,s^{-1}}$)	80-anem. avg U ($\mathrm{m\,s^{-1}}$)	Street level wind wind directnWD (degree)	80-anem. avg WD (Degree)	Street level σ_{V} ($\mathrm{m\,s^{-1}}$)	Street level σ_{W} ($\mathrm{m\,s^{-1}}$)	Street Level u_* ($\mathrm{m\,s^{-1}}$)	Street level −L (m)
1	0800–1600	1.46	1.8	150	170	0.76	0.50	0.33	147
2	0800–1600	1.91	2.8	213	216	1.04	0.65	0.41	1029
3	0800–1600	2.57	3.7	192	196	1.36	0.85	0.55	62.5
4	0800–1600	2.18	4.0	208	199	1.38	0.88	0.55	384
5	0800–1600	1.90	2.8	170	191	0.96	0.64	0.45	158
6	0800–1600	2.24	3.1	181	194	1.06	0.65	0.42	1000000
7	2200–0600	1.80	2.5	218	217	0.76	0.56	0.34	798
8	2200–0600	2.55	3.8	150	157	1.26	0.86	0.56	1260
9	2200–0600	2.05	3.2	177	177	1.06	0.69	0.44	573
10	2000–0400	1.90	2.4	199	200	0.89	0.60	0.36	971
avg	6 Day	2.13	3.0	186	194	1.09	0.70	0.45	Median 271
avg	4 Night	2.08	3.0	186	188	0.99	0.68	0.43	902
avg	All	2.11	3.0	186	192	1.05	0.69	0.44	Median 685

The average building height, H, is about 27 m. The surface roughness length, z_o, can be estimated as 2 m, and the displacement length, d, as 22.5 m, based on relations suggested by Britter and Hanna (2003).

3 Results

The results of several types of analyses are listed in this section. However, much variability is found, since each single puff is just one member (realisation) of an ensemble of similar puffs, and there were only about 40 puffs released in the entire JU2003 experiment, including three release locations and day, night, and morning transition periods. An ensemble could be defined as a group of puffs released during similar meteorological conditions (e.g., wind speed and direction, turbulence, stability, etc.).

The following subsections tabulate the main characteristics of the puff releases and summarise the findings for parameters such as cloud speed (u), along-wind dispersion in time (σ_t) and distance (σ_x), and other derived measures of the concentration time series. Graphs are presented for the three variables where similarity relations are derived (u/U versus x, σ_t versus t, and σ_x versus x).

3.1 General characteristics of the puff data

Table 2 summarises the general characteristics of the puff releases for the 167 concentration time series analysed in this study, including puff release time and location, the tracer sampler numbers (0–9, with never any data for sampler 5), and the average observed wind speed (WS) and direction (WD) over the 80 anemometers (from Table 1) for each IOP. Note that IOPs 1 through 6 took place during the day, while IOPs 7 through 10 took place during the night.

3.2 Summary statistics

Table 3 lists some summary statistics for the 167 fast response time series. Figure 4 is used to help explain some of the parameters in Table 3, since that figure, for sampler 7 during IOP 9, is a representative example of a concentration time series.

Four fundamental "times" are used to characterise the observed SF_6 time series:

(1) The travel time, t, is the difference between the time when the 0.5 s C_{max} is reached and the release time. For the example in Fig. 4, C_{max} is reached at point 3 (about 1023) and the release time is 1020. Therefore the travel time t is about 3 min. In Table 3, t ranges from 62 s to 709 s (about 1–12 min) for the 167 puff-sampler time series, with an average of 271 s (about 4.5 min).

(2) $Time_{total}$ (the time duration of concentration >0.0) is defined as the time between when the concentration first rises from zero and last drops to zero. For the example in Fig. 4, $Time_{total}$ is the time difference between points 1 and 5, which is about 10 min. In Table 3, $Time_{total}$ ranges from about 2–24 min with an average of about 9 min.

For the JU2003 puff data, $Time_{total}$ will seldom exceed 20 min because, in most cases, another puff was released after 20 min. It is not possible to distinguish the SF_6 tracer from the first puff from the SF_6 from the second puff.

(3) Dt (the time duration of concentration $>0.1C_{max}$) is defined based on the requirement that C exceeds $C_{max}/10$. Hanna and Franzese (2000) found that Dt was a much more robust measure than $Time_{total}$, which can sometimes be overly influenced by small outliers. For the example in Fig. 4, Dt is the time difference between points 2 and 4

Table 2 Basic information for the 167 fast response concentration time series from JU2003. Wind speed and direction are observed averages over all fixed anemometers (Hanna et al. 2006)

IOP	PUFF	Release time (CDT)	Samplers analysed	Release location	Wind speed (WS) (U) ($\mathrm{m\,s^{-1}}$)	Wind direction (WD)
1	1	0900	4	Westin	1.8	149
1	2	0910	4, 6	Westin	1.8	149
1	3	0920	4	Westin	1.8	149
1	4	0930	4	Westin	1.8	149
1	5	0945	4	Westin	1.8	149
1	6	1000	4	Westin	1.8	149
3	1	0900	0,1,3,4,6,7,8	Botanical	3.7	196
3	2	0920	0,3,4,6,7	Botanical	3.7	196
3	3	0940	0,1,3,4,6,7,8,9	Botanical	3.7	196
3	4	1000	0,1,3,6,7,8	Botanical	3.7	196
4	1	0900	3,4,6,7	Botanical	4.0	199
4	2	0920	0,3,4,6,7	Botanical	4.0	199
4	3	0940	4	Botanical	4.0	199
5	1	1500	0,2,4,8,9	Botanical	2.8	191
5	2	1520	0,2,4,6,7,8,9	Botanical	2.8	191
5	3	1540	0,2,4,6,7,8,9	Botanical	2.8	191
5	4	1600	2,4,8	Botanical	2.8	191
6	1	1500		Botanical	3.1	194
6	2	1520	0,1,2,3,6,7,8	Botanical	3.1	194
6	3	1540	2,3,6,7	Botanical	3.1	194
6	4	1600	0,1,2,3,6,7,8	Botanical	3.1	194
7	1	0500	0,1,2,3,4,6,7,8,9	Botanical	2.5	217
7	2	0520	0,1,2,3,4,6,7,8,9	Botanical	2.5	217
7	3	0540	0,1,3,4,6,7,8,9	Botanical	2.5	217
7	4	0600	0,1,3,4,6,7,8,9	Botanical	2.5	217
8	1	0500	0,1,2,3,4,6,8,9	Westin	3.8	157
8	2	0520	0,1,2,3,4,6,8	Westin	3.8	157
8	3	0540	0,1,2,3,4,6,8,9	Westin	3.8	157
8	4	0600	0,1,2,3,6,8,9	Westin	3.8	157
9	1	0500	1,2,7,8	Park	3.2	177
9	2	0520	1,2,7,8	Park	3.2	177
9	3	0540	1,7,8	Park	3.2	177
9	4	0600	1,7,8	Park	3.2	177
10	1	0300	2,4	Park	2.4	200
10	2	0320	2,4	Park	2.4	200
10	3	0340	2,4	Park	2.4	200

(about 5 min). Dt ranges from about 1 to 18 min in Table 3 with an average of about 5 min. As mentioned for $\mathrm{Time_{total}}$, the maximum value of Dt is capped by about 20 min, which is the time interval between puff releases.

(4) The total time duration of concentration $>0.1\mathrm{C_{max}}$, Dt, is the sum of the two time durations, $\mathrm{Dt_a}$ and $\mathrm{Dt_d}$, which are defined as the time difference, between the time of $\mathrm{C_{max}}$ and the time when the concentration is greater than or equal to $\mathrm{C_{max}}/10$ for the first and last time, respectively. For the example in Fig. 4, $\mathrm{Dt_a}$ is the time difference between points 3 and 2 (about one minute) and $\mathrm{Dt_d}$ is the time difference between points 4 and 3 (about 4 min). In Table 3, Dt_a has a range from 2.5 s to 7.5 min with an average of about 73 s, while $\mathrm{Dt_d}$ has a range from 46 s to 1,020 s (17 min) with an average of nearly 240 s (4 min). No significant correlation was found between $\mathrm{Dt_a}$ and $\mathrm{Dt_d}$ in these data.

Table 3 Summary statistics for the 167 fast response concentration time series

Variable	Unit	Mean	Median	SD	Min	Max	Note
t (travel time)	s	271	231	127	62	709	Time from release to max concentration at sampler
c_{max}(0.5 s)	ppt	9606	8397	7416	426	24009	Instantaneous (0.5 s) max concentration
x (distance)	m	418	383	236	98	1127	Distance between release point and sampler
u (cloud speed)	$m\,s^{-1}$	1.61	1.63	0.66	0.25	3.69	Distance x divided by time t
Ratio of cloud speed (u) to wind speed (U)		0.52	0.51	0.22	0.14	1.32	Cloud speed (u) divided by average wind speed (U)
Time_{total}	s	530	512	245	137	1412	Time between when $C > 0$ was first and last observed
Dt	s	309	283	163	62	1087	Time between when Cmax/10 was first and last observed
σ_t	s	71.9	65.8	37.9	14.4	252.67	Standard deviation of the concentration time series, calculated as Dt/4.3
σ_x	m	109	99	59	21	275.60	Alongwind dispersion coefficient, calculated as $\sigma_t\ u$
Dt_a	s	73.8	64.0	59.2	2.5	450.00	Time between when Cmax/10 was first observed and C_{max}(0.5 s)
Dt_d	s	235	217	152	46	1008.00	Time between when C_{max}(0.5 s) and when C_{max}/10 was last observed
Dt_d to Dt_a ratio		8.49	3.14	17.31	0.40	127.88	$\mathrm{Dt}_d/\mathrm{Dt}_a$

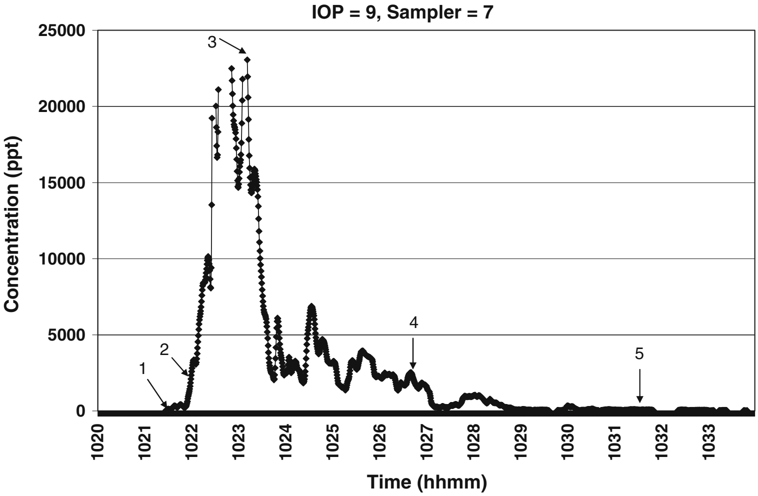

Fig. 4 Concentration time series from fast response sampler 7 during IOP 9. The numbers 1 through 5 indicate key points used to derive puff statistics

The time duration, $\mathrm{Dt} = \mathrm{Dt_a} + \mathrm{Dt_d}$, is sometimes referred to as retention time (Doran et al. 2006), since it is a measure of the time period over which concentrations are maintained at significant levels. Among the 167 concentration time series, there are six with Dt (retention times) greater than 10 min, with a maximum of almost 20 min. The six highest retention times occurred during IOP 7 (sampler 6) and IOP 8 (sampler 3, 6 or 9), and all seemed to be from samplers located near tall buildings. However, the apparent strong relationship between large Dt and nearness to buildings is not consistent and there are some exceptions.

In addition, the ratio of $\mathrm{Dt_d}$ to $\mathrm{Dt_a}$ is calculated and listed in Table 3. The ratio is a measure of the non-symmetry of the observed concentration time series. The ratio has a mean of 8.5 and a median of about 3, meaning that the durations of the trailing edges of the puffs are found to be several times larger than the durations of the leading edges. Such non-symmetry is due to both the normal turbulent puff dispersion and the building wake holdup. For a Gaussian puff with σ_x equal to about $0.1x$, it is expected that the median of $\mathrm{Dt_d}/\mathrm{Dt_a}$ would be about 2 or 3, independent of any building wake hold-up effects.

A summary of the distances, x, between the release point and the sampler locations is also listed in Table 3. This distance ranges from about 100 m to 1,100 km with an average of 418 m. The cloud (puff) speed, u, is calculated as the ratio of the distance, x, to the travel time, t. The speed, u, is the average cloud speed over its trajectory from the source position to the sampler position (or the effective speed at which the puff is moving), and is not the instantaneous cloud speed at x. The ratio of cloud speed, u, to wind speed, U, is also listed in Table 3. The cloud speed is found to be, on average, about half of the wind speed averaged over the city. The detailed analysis in the next section will show how the ratio, u/U, increases with x.

The standard deviation of the concentration time series (σ_t) is calculated in two different ways. Both methods are based on the total distribution and do not separately account for the fact that the trailing edge of the puff has a longer tail (i.e., $\mathrm{Dt_d} > \mathrm{Dt_a}$). The first method is a robust method (less susceptible to outliers) used by Hanna and Franzese (2000) in their analysis of rural puffs. The robust method uses the times at the leading and trailing edges of the puff when $C = 0.1C_{max}$ occurred. This time duration is Dt defined earlier. The method then assumes the relation, valid for a normal distribution, that σ_t equals Dt/4.3. The value 4.3 comes from the fact that for a normal distribution, the probability at the mean time (t_{mean}) is 10 times the probabilities at times of either $t_{mean} - 2.15\sigma_t$ or $2.15\sigma_t - t_{mean}$. The second method for calculating σ_t uses the standard second-moment technique, which is not as robust as the first method and could be dominated by one or two outliers. The σ_t statistics listed in Table 3 are calculated using method 1 (the robust method). For example, the mean σ_t is 72 s. For comparison, the second method gives a mean of 92 s. The alongwind dispersion coefficients (σ_x) listed in Table 3 are calculated as σ_t times the cloud speed, u, with a mean value of 109 m.

3.3 Analysis of variations of puff parameters with time and distance

In addition to the summary statistics described in Sect. 3.2, the variations of the derived puff parameters in Table 3 with travel time, t, or distance, x, were also analysed. However, note that, the variation with t or x is usually not found by following a specific puff as it moves. Very few of the data would allow this, since the samplers seldom line up exactly along the puff trajectory. Instead, the points on the plot represent a random sampling of many puffs at various x and t.

3.3.1 Ratio of cloud speed u to observed average wind speed U

It is expected that the cloud speed, u, will increase with x or t because, for a release near the ground, the top of the puff is continually dispersing upward into regions with higher wind speeds. Figure 5 contains a plot of the ratio of cloud speed, u, to observed average wind speed, U, as a function of downwind distance, x. As expected, the data in Fig. 5 verify that smaller u/U ratios (about 0.2 or 0.3) occur at the smaller distances (about 100–300 m), while the ratios level off and gradually approach unity at the larger distances (greater than 500 m). The data in the figure can be approximately fit by the equation:

$$\mathrm{u/U} = 0.3 + 0.7x/1{,}200 \tag{1}$$

(for $x < 1,200$ m).

Doran et al. (2006) also investigated the relation between puff speed, u, and wind speed, U, but based their analysis on the U observed at a single observing site. Our analysis uses an average U calculated over many observing sites in the urban domain, and thus is expected to be more robust, and lead to a more consistent relation between u/U and distance.

3.3.2 Analysis of variations of σ_t with time of travel, t

Figure 6 contains a plot of the observed σ_t versus the time of travel, t, for the 167 points. The points for different IOPs or for day versus night IOPs are not differentiated because the data show insignificant differences between IOPs and between day and night. The points can be fit by the following linear relation:

$$\sigma_t = 42 + 0.1t \tag{2}$$

(with an R^2 of 0.21) where σ_t and t have units of seconds.

The intercept, 42 s, at $t = 0.0$, can be primarily explained as a measure of initial puff size as a result of the influence of buildings around the source location. As noted in the

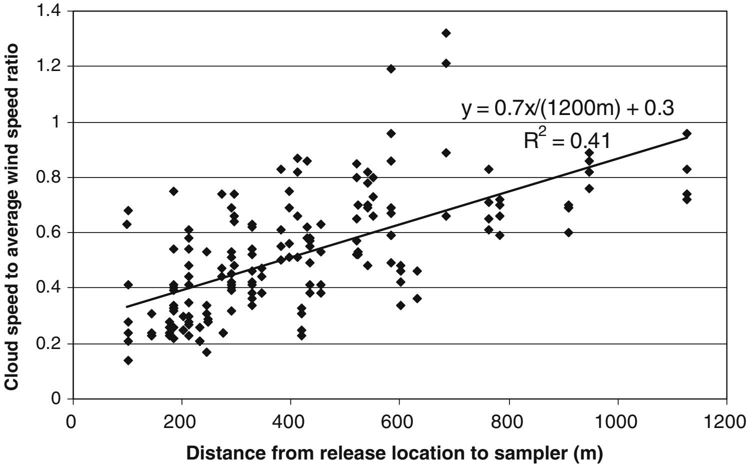

Fig. 5 Cloud speed (u) to average wind speed (U) ratio vs. distance (x) from release location to sampler

introduction, McElroy and Pooler (1968) suggested use of an intercept term for σ_y and σ_z (lateral and vertical plume spreads) to better fit their urban dispersion tracer data from a field experiment in St. Louis. For both the JU2003 and the St. Louis experiments, the source was near the ground and had initial dimensions of less than 1 or 2 m.

The along-wind spread σ_x is related to σ_t through the local puff speed, u. The effective intercept term for σ_t in Eq. 2 is also influenced by puff hold-up in the wakes of large buildings upwind of the sampler locations. This hold-up is more effective for puffs that are relatively narrow and shallow (i.e., at small t), since, as time increases, the width and depth of the puff increase so that the puff extends to the sides and above the building wakes.

Equation 2 asymptotically approaches the linear relation, $0.1t$, reported by Hanna and Franzese (2000) as providing a best-fit over a wide range of travel times for many experiments involving puff observations over rural terrain. Because the slope of the curves from the current urban experiment agree well at large t with the slope from the many rural experiments, it can

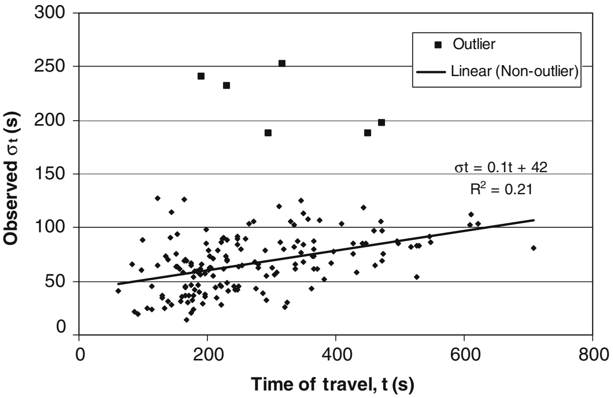

Fig. 6 Observed σ_t versus time of travel, t

be concluded that the rate of along-wind puff dispersion in urban areas follows a similarity relation after the initial dilution phase.

3.3.3 Dependence of intercept term on release location

The intercept term in Eq. 2 is related to the typical separation of buildings and the local wind speed, and is expected to vary somewhat as building separation and wind speed vary. To further refine the intercept term, the JU2003 concentration time series were separated into two groups based on release location. Data from the "Park" and "Westin" release sites are combined into one group as they are both in the midst of tall buildings, while data from the "Botanical" release site are placed in another group since the site was in a park upwind of the area of tall buildings. The resulting best-fit curves are:

$$\sigma_{\mathrm{t}} = 35 + 0.09t \tag{3}$$

(Botanical Release Site)

$$\sigma_{\mathrm{t}} = 45 + 0.13t \tag{4}$$

(Westin and Park Release Sites)
where σ_{t} and t have units of seconds. The 30% difference in the intercept terms follows expectations and demonstrates that release locations surrounded by more buildings tend to have a larger intercept (initial spread).

3.3.4 Analysis of variations of σ_{x} with distance, x

Figure 7 contains a plot of the JU2003 along-wind dispersion coefficient, σ_{x}, versus distance, x, for the 167 points. σ_{x} is calculated as $u\sigma_{\mathrm{t}}$, where u is the average puff speed over the trajectory between the source and the distance, x. The observations support the similarity relation in the following equation:

$$\sigma_{\mathrm{x}} = 45 + 0.14x \tag{5}$$

(R^2 of 0.39) where σ_{x} and x have units of m. The term R^2 is the square of the correlation coefficient and can be thought of as the fraction of the variance that is explained by the equation. Similar to the discussion about σ_{t}, it is reasoned that the puff has an initial spread, parameterised by an initial intercept or along-wind dispersion coefficient of 45 m. This can be thought of as the initial cloud size. When the puff is first released near the surface, its actual size is only about 1 m. The 45 m initial spread is also called the intercept, and is in agreement with the initial plume spread reported by McElroy and Pooler (1968) for the tracer experiment in St. Louis. The initial plume spread should be proportional to the typical distance between buildings near the source.

It is possible to derive Eq. 5 for σ_{x} from Eq. 2 for σ_{x} through use of Eq. 1 for u/U and assuming that the overall average observed U is $3\,\mathrm{m\,s^{-1}}$, as listed in Table 1. Rewrite Eq. 2 as $\sigma_{\mathrm{x}}/u = 42 + 0.1x/u$. Then replace u using Eq. 1 as $= 0.3\mathrm{U} + 0.7x\mathrm{U}/1,200$. The result, $\sigma_{\mathrm{x}} = 38 + 0.17x$, is close to Eq. 5.

It is important to recognise that the actual initial puff size (about 1 m) in JU2003 is much less than the derived initial σ_{x} of about 40 m in the best-fit equation. These equations should be used only for initial puff sizes less than about 40 m.

Several other plots were tried using various combinations of the observed variables and x and t. In most cases there was the usual scatter but no clear trend. The discussions above

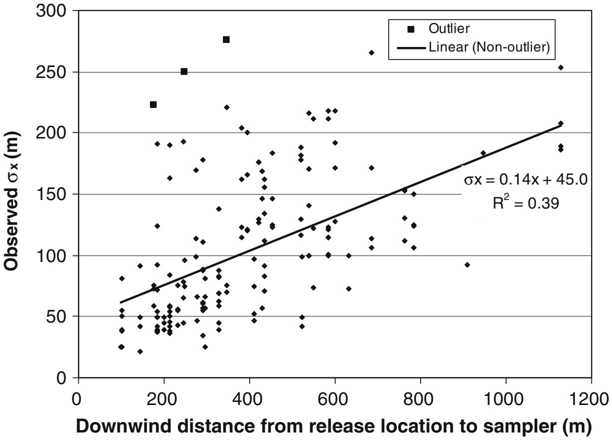

Fig. 7 Along-wind dispersion coefficient σ_x vs. distance from release location to sampler

present the plots where the more clear relations were evident (for σ_t versus t, for σ_x versus x, and for u/U versus x. Generally it is possible to use Eqs. 1 through 5 to derive an explanation for the lack of a relation in a particular plot. Much of the observed behaviour is caused by the factor of three increase of u/U with x across the sampling domain.

3.3.5 Analysis of outliers seen on the figures

There is a factor of two or three scatter of the observed points about the fitted curves for σ_t and σ_x in Figs. 6 and 7. This is partly due to the fact that each puff observation is a single realisation in an ensemble, and it is expected that the members of an ensemble would have scatter. But the scatter is also due to differences in source and sampler locations with respect to buildings. And some of the scatter may also be due to day night differences, since the incoming boundary layer is stable at night and unstable or neutral in the day, even if the boundary layer is near-neutral at street level in the downtown areas. One study (Grimmond et al. 2004) analysed micrometeorological data from the suburbs of Oklahoma City during JU2003 and report that stable conditions existed in those areas at night. Another study (Lundquist and Mirocha 2006) describe vertical profiles of temperatures and winds in the surroundings of Oklahoma City and also show the presence of stable conditions and low-level jets.

To further investigate the scatter of the 167 points used in the σ_t versus t plot, the data were ordered from high to low based on σ_t. It is found that there are six "outlier" points with relatively high σ_t greater than 150 s. The six outliers are identified as concentration time series from puff 2 from sampler 3, puff 1 from sampler 9, and puffs 3 and 4 from sampler 6 during IOP 8; and puffs 3 and 4 from sampler 6 during IOP 7. In contrast to the relatively smoothly varying concentration time series shown in Fig. 4, there is more than one peak in the time series for the puffs and samplers and IOPs when these six outliers occurred. The presence of multiple peaks could be due to several phenomena, such as building wake hold-up caused by buildings with large recirculating wakes, large turbulence intensities near the sampler locations, or meandering of the wind field. When deriving the best fit curve in Fig. 5, these six outliers were not considered. However, they are obviously important when making emergency response decisions, since they define the maximum retention time of tracer material at a location.

The six outliers mentioned above are found to involve samplers that are indeed located near to and/or behind large buildings. These buildings are likely to have large recirculating wakes that can cause “wake hold-up” and increase the retention time. This effect is enhanced in IOP08 because the south-east wind direction causes the puffs to pass through the middle of the built-up downtown area. Another outlier is Sampler 6 in IOP07. That sampler is on the downwind side of two tall buildings. During that same IOP, there were low σ_{t} values observed at Sampler 9, which was located in an open area, beyond the downwind edge of the city.

Despite the success of the theory in explaining some of the high and low observed σ_{t} values, further study of all 167 puffs reveals that there are many exceptions that occur. For example, even though there are high σ_{t} values at sampler 6 for two puffs released during IOP7, there is a relatively low σ_{t} value for another puff at that same sampler. In general, the theoretical findings and hypotheses seem to be valid for perhaps 70% or 80% of the puffs in a group.

The same type of inconsistent result is found in the day versus night analysis. Looking at the highest 25 σ_{t} observations, about 75% of them occur during the night IOPs (7, 8, 9, and 10), Looking at the lowest 25 σ_{t} observations, about 75% of them occur during the day IOPs (1 through 6). Consequently there is a possible suggestion that the higher σ_{t} values may occur during the night and the lower values during the day. But again there are exceptions, since about 25% of the data do not conform to the rule.

4 Summary

The instantaneous release (puff) data from the JU2003 urban dispersion experiment have been analysed and some simple relations developed based on straight lines best-fit to the data. The puffs are released near the ground and have an initial size of about 1 m. It is found that the results are consistent with McElroy and Pooler’s (1968) suggestion that there is an initial cloud size of about 40 or 50 m in an urban area. The initial cloud size depends on the typical building spacings and street widths in that city. The results are also consistent, at larger times and distances, with the similarity relation, $\sigma_{\mathrm{t}} = 0.1t$, for along-wind dispersion found by Hanna and Franzese (2000) based on puff observations in many experiments over rural terrain. The JU2003 σ_{t} observations show that $\sigma_{\mathrm{t}} = 42 + 0.1t$, where the first term is an indication of the initial cloud size and the second term is the general relation approached at larger times as the puff departs the built-up downtown area. The along-wind dispersion coefficient, σ_{x}, can be expressed as a function of downwind distance, x, using the best-fit formula, $\sigma_{\mathrm{x}} = \sigma_{\mathrm{xo}} + 0.14x$, where this initial σ_{xo} is 45 m. The equations for σ_{t} and σ_{x} are valid only for puffs whose actual size at release, $\sigma_{\mathrm{xactual}}$, as measured by the standard deviation of the initial actual concentration distribution in space, is smaller than or approximately equal to the intercepts σ_{to} and σ_{xo}. For larger actual initial puff sizes, the value of $\sigma_{\mathrm{xactual}}$, could be substituted for σ_{xo} in the formula for σ_{x}, and the value of $\sigma_{\mathrm{xactual}}/\mathrm{U}$ could be substituted for σ_{to} in the formula for σ_{t}.

The puff speed, u, is calculated as the distance from the source to the sampler position, x, divided by the time, t, between the release time and the time when the maximum concentration is observed at that sampler. The puff observations confirm that the puff accelerates with time, due to the fact that its top is dispersing upwards into layers with higher wind speeds. The puff speed, u, increases by an average factor of three or four as it passes the samplers at distances ranging from about 100 m to about 1,200 m. At a distance of 1,200 m, the puff speed, u, is approximately equal to the observed average wind speed, U, calculated over about 80 anemometers across the Oklahoma City area.

The derived similarity relationships could be considered for use in applied air dispersion modelling systems such as HPAC/SCIPUFF (DTRA 2004), QUIC-PLUME (Williams et al. 2004) and computational fluid dynamics (CFD) models. These models can in turn help us gain a better understanding of atmospheric flow and dispersion in built-up urban areas.

There is a typical scatter of ± a factor of two or three in the observations when compared with the best-fit lines. A few of the points with larger σ_t (up to 250 s) have been identified as cases where the sampler was in the wake of a large building and the puff was "held-up" for a longer time by entrainment in the building wake. For emergency planning, the total maximum $\sigma_t$is about 250 s (about 4 min), or the total maximum Dt (retention time) is about 18 min for these JU2003 puffs.

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