AE International – North America

Atmospheric Environment 37 (2003) 5069–5082

ATMOSPHERIC ENVIRONMENT

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# A baseline urban dispersion model evaluated with Salt Lake City and Los Angeles tracer data

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Received 6 March 2003; accepted 9 August 2003

**Abstract**

A simple baseline urban dispersion model is suggested for use in simulating near-surface releases of tracer chemicals in the urban canopy layer. The model is based on the Gaussian plume or puff model, accounting for low wind speeds, nearly neutral stabilities, large turbulence intensities, and large initial mixing in urban areas. The performance characteristics of this baseline model can be easily determined and used for comparisons with more complex models. Two urban tracer data sets are used to demonstrate the baseline model's performance—the Salt Lake City (SLC) Urban 2000 data set, and the Los Angeles (LA) 2001 data set. The focus of the comparisons is on the maximum concentration, $C_{\max}$, on a given monitoring arc, normalized by the emission rate, $Q$. The $C_{\max}/Q$ observations follow some straightforward similarity relations, such as a decrease with downwind distance, $x$, raised to the power $-1.5$ to $-2.0$, and a lack of dependence on wind speed during nighttime light wind scenarios when wind speeds are less than about 1.5 m/s. The predictions of the simple baseline model are shown to agree with the observations from the 30 experimental trials in SLC and LA within a factor of about two to three.


*Keywords:* Urban dispersion; Urban meteorology; Turbulence and dispersion; Air pollution modeling

## 1. Introduction

There is much research underway on flow and dispersion in urban areas, spurred by environmental issues and by the need to estimate the effects of releases of chemical and biological (CB) agents by terrorists. As an example of a large urban research study, Allwine et al. (2002) describe the extensive tracer and meteorological data base known as "Urban 2000" obtained in the Salt Lake City (SLC) area. Rappolt (2001) discuss a similar tracer experiment in 2001 in the Los Angeles (LA) downtown area. Both of these studies were motivated by concerns about possible CB agent effects. Venkatram et al. (2002) carried out a tracer experiment in San Diego and showed how the observations agree with a straightforward urban dispersion model based on knowledge of urban turbulence intensities. The San Diego experiment was initiated because of "environmental justice" issues, where there is a concern with possible excessive environmental effects in disadvantaged neighborhoods.

Over 30 years earlier, McElroy and Pooler (1968) took similar tracer observations in the St. Louis downtown area and fit some simple power-law formulas to the plume spread observations. Based on the St. Louis data and other urban data, Hanna (1971) and Briggs (1973) developed simple Gaussian-plume-based urban dispersion models. Since that time, several additional field experiments and model development activities have occurred, such as the Urban 2000 experiment mentioned above, and it is possible to use this information to develop an updated simple urban dispersion model.

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1352-2310/$ - see front matter 
doi:10.1016/j.atmosenv.2003.08.014

Towards this goal, Hanna and Britter (2002) and Britter and Hanna (2003) have proposed a straightforward set of formulas for estimating wind flow, turbulence, and dispersion in urban and industrial obstacle arrays. Based on some of those recommendations, a simple operational baseline model for dispersion in urban areas was developed and is described in this paper and results are given of tests of the model with the recent tracer data from SLC and LA. The current model is based on the Gaussian plume and puff formulas and emphasizes specification of the turbulence in the urban canopy.

## 2. Baseline model assumptions

It is assumed that the concentration resulting from continuous releases in the urban canopy layer is represented by the standard Gaussian formula:

$$C/Q_c = (1.0/(2\pi u\sigma_y\sigma_z)) \times \exp(-(y-y_0)^2/(2\sigma_y^2))(\exp(-(z-h_e)^2/(2\sigma_z^2)) + \exp(-(z+h_e)^2/(2\sigma_z^2))), \quad (1)$$

where $C$ is the concentration (g/m$^3$), and $Q_c$ is the continuous mass emission rate (g/s). $u$ is the wind speed (m/s) representing the speed of the plume over its trajectory. $\sigma_y$ and $\sigma_z$ are the standard deviations of the concentration distributions in the lateral and vertical directions, and increase with downwind distance, $x$, $y$ and $z$ are the lateral and vertical positions where the concentration is being calculated, and $y_0$ and $h_e$ are the lateral and vertical positions of the plume centerline. Often $h_e$ is considered to be the initial elevation of the plume. The final exponential term in Eq. (1) is the standard "reflection term". All variables and parameters represent averages over about a one-h time period.

When the release is instantaneous with total mass, $Q_i$, in grams, the effects of along-wind dispersion should be included. The concentration, $C$, due to an instantaneous release is given by the equation:

$$C/Q_i = (1.0/((2\pi)^{3/2}\sigma_y\sigma_z\sigma_x))\exp(-(x-x_0)^2/(2\sigma_x^2)) \times \exp(-(y-y_0)^2/(2\sigma_y^2)) \times (\exp(-(z-h_e)^2/(2\sigma_z^2)) + \exp(-(z+h_e)^2/(2\sigma_z^2))), \quad (2)$$

where $x$ is the downwind position of interest and $x_0$ is the distance where the center of the cloud or puff is located (generally, $x_0$ equals the wind speed, $u$, times the travel time, $t$). $\sigma_x$ is the standard deviation of the concentration distribution in the downwind direction. The variables and parameters in Eq. (2) represent time averages of only a few seconds but are considered to be ensemble means. An ensemble mean is defined as the mean over a large number of realizations carried out under nearly identical release scenarios and meteorological scenarios.

To be strictly correct, $\sigma_x$, $\sigma_y$, and $\sigma_z$ are slight functions of averaging time. However, for the purposes of the simple baseline urban model in this paper, the same $\sigma_x$, $\sigma_y$, and $\sigma_z$ values are assumed for all averaging times ranging from a few minutes to 1 h.

In many of the applications of these equations and in the performance evaluations in this paper, the focus is on the maximum near-ground-level concentration, $C_{max}$, on the plume or puff centerline (i.e., at $x = x_0$, $y = y_0$, and $z = h_e$). If the release height, $h_e$, is close to the ground, then, for downwind distances where $\sigma_z \gg h_e$, it can also be assumed that the plume or puff center is at the ground (i.e., $h_e = 0.0$). In this case, the maximum concentration, $C_{max}$, on the plume or puff center at any downwind distance $x$ is given by

Continuous release :

$$C_{max}/Q_c = 1.0/(\pi u\sigma_y\sigma_z) \text{ (on centerline of plume)}, \quad (3)$$

Instantaneous release :

$$C_{max}/Q_i = 1.0/(2^{1/2}\pi^{3/2}\sigma_y\sigma_z\sigma_x) \text{ (on center of puff)}, \quad (4)$$

where, as mentioned earlier, the dispersion coefficients $\sigma_y$, $\sigma_z$, and $\sigma_x$ are all prescribed functions of downwind distance, $x$.

The above equations are based on the Cartesian coordinate system, where $x$, $y$, and $z$ are orthogonal axes. For light winds, when $\sigma_y/x$ may be of order unity, and the standard deviation of wind direction fluctuations, $\sigma_\theta$, is also large, the plumes can be very broad and may spread out towards all points of the compass. In this situation, the polar coordinate system should be used to calculate off-centerline concentrations, where $R$ is the radial distance from the source and $\theta$ is the angular direction in radians. The plume centerline is located at $\theta_0$ (equivalent to $y_0$). The Gaussian "$y$" term in the above equations should be rewritten as

$$(1.0/((2\pi)^{1/2}\sigma_y))\exp(-(y-y_0)^2/(2\sigma_y^2)) = 1.0/((2\pi)^{1/2}\sigma_\theta R))\exp(-(\theta-\theta_0)^2/(2\sigma_\theta^2)), \quad (5)$$

where it is assumed that $\sigma_y = \sigma_\theta R$.

An implication of light winds and large $\sigma_\theta$ (as expressed in Eq. (5)) is that upwind dispersion is possible near the source. This effect was not treated in the current paper, since the focus is on the maximum concentration, $C_{max}$, on a given monitoring arc, and except for the 156 m arc at SLC, there were no monitors in the upwind direction.

An additional calculation is sometimes needed because most practical releases are not instantaneous but instead have a finite time duration, $T_d$, that is of the same order as the travel time to the receptors of interest. For example, the SLC Urban 2000 and the LA field experiments used $T_d$ of 60 and 5 min, respectively. In both of these experiments the monitoring distances were placed such that, for travel times exceeding $T_d$, the tracer cloud was still on the monitoring network. A common approach is to simulate these finite duration releases as a series of instantaneous puff releases. However, in keeping with our desire for a simple analytical model, we use the rough rule for finite duration releases suggested by Britter and McQuaid (1988). They propose that the "continuous plume" formula should be used for $x \ll uT_d$ and the "instantaneous puff" formula (with $Q_i = Q_c T_d$) should be used for $x \gg uT_d$. At intermediate distances larger than $0.5uT_d$ and less than about $5uT_d$, the following "finite duration" correction could be applied to the continuous plume Eqs. (1) or (3):

$$C/(C(\text{Eq. (1) or (3)})) = 1 \quad \text{for } x < uT_d/2, \tag{6}$$

$$C/(C(\text{Eq. (1) or (3)})) = 0.5uT_d/x \quad \text{for } uT_d/2 < x. \tag{7}$$

At $x \gg 0.5uT_d$, Eq. (7) is not appropriate because it is simply an empirical correction to the continuous plume formula and will eventually lead to large underpredictions compared to the solution for an instantaneous source given by Eqs. (2) or (4). Consequently, the general recommendation is made that, for finite duration releases at $x > 0.5uT_d$, the concentration be calculated as follows:

$$\text{At } x > 0.5uT_d: \quad C = \max(\text{Eq. (2) or (4), Eq. (7)}). \tag{8}$$

This set of finite duration correction equations is tested later with the LA tracer data.

As with most analytical Gaussian plume and puff models, the simple baseline model assumes that the cloud speed, $u$, is constant over its trajectory. Furthermore, the speed, $u$, should be a vector average (as opposed to a scalar average). In the case of urban canopy releases while the bulk of the cloud is in the canopy layer, the wind or cloud speed, $u$, should be representative of the canopy layer. There are some measurements by anemometers of the wind speed in the urban canopy layer in SLC and LA, and these observations are used in our later evaluations. In case there are no measurements of wind speed in the urban canopy, Bentham and Britter (2003) have analyzed several data sets and suggest a characteristic urban canopy wind speed, $u_c$, given by the equation,

$$u_c = u^*(2/\lambda_f)^{1/2}, \tag{9}$$

where $u^*$ is the friction velocity representative of the total drag of the urban surface and $\lambda_f$ is an urban morphology parameter equal to the ratio of the total frontal area of the obstacles to their total lot area, over a typical domain of about 1 km$^2$ or more. It is found that $\lambda_f = 0.3$ for the SLC and LA downtown areas. Eq. (9) should be used from ground level to the height, $z_c$, above which $u_c$ is less than the wind speed given by the standard log profile for neutral conditions:

$$u = (u^*/0.4)\ln((z-d)/z_0), \tag{10}$$

where $z_0$ is the surface roughness length and $d$ is the displacement length. Due to the strong generation of mechanical turbulence, nearly neutral stabilities are usually found over urban areas at heights less than about two times $H_b$, which is defined as the average height of the buildings. Combining Eqs. (9) and (10), it is seen that $z_c = z_0 \exp(0.4(2/\lambda_f)^{1/2}) + d$. For $z > z_c$, Eq. (10) should be used to calculate $u$. Given a wind speed measurement or prediction at some height above $H_b$ but $<2$ or $3H_b$, another option for estimating $u^*$ is to use Eq. (10). As an example of the application of the above wind profile equations, for typical built-up downtown areas where $\lambda_f > 0.3$, Hanna and Britter (2002) suggest that the roughness length, $z_0 = 0.15H_b$ and the displacement length, $d = 0.5H_b$. If the wind speed is observed at a height of $2H_b$, then $u^* = 0.17u(2H_b)$ and $u_c = 0.45u(2H_b)$. Or, if the wind speed is observed at a height of $H_b$, then $u^* = 0.33u(H_b)$ and $u_c = 0.86u(H_b)$.

Sometimes the wind speed is observed only at a nearby airport or sometimes it is available only from a mesoscale meteorological model, which requires other approximations based on standard wind profile theory and described by Hanna and Britter (2002).

The standard deviations of the concentration distributions (i.e., the dispersion coefficients $\sigma_x$, $\sigma_y$, and $\sigma_z$) are assumed to be given by the Briggs (1973) urban dispersion formulas. These urban formulas, also listed by Hanna et al. (1982), have been fit to the so-called McElroy and Pooler (1968) urban curves determined from the St. Louis tracer experiments, and account for enhanced turbulence and modified stabilities in urban areas. These urban curves account for the large turbulence velocities generated by mechanical mixing in urban areas, and reflect the tendency for urban stabilities to be close to neutral or adiabatic. Venkatram et al. (2002) suggest that it is best if the turbulence velocities are observed in the urban canopy by instruments such as sonic anemometers, and that these measurements should be used directly in the dispersion models. However, if these instruments are not available, it is usually necessary to parameterize the enhanced turbulence over urban areas.

In order to account for the large initial mixing of plumes due to the presence of nearby building obstacles, the assumption is made in the simple baseline urban dispersion model that the initial plume is mixed uniformly behind the obstacles, which can be approximated by $\sigma_{x0} = \sigma_{y0} = \sigma_{z0} = H_b/2$. This strong initial mixing, valid for source release heights at or below $H_b$, is noted by Allwine et al. (2002) in their preliminary analyses of the Urban 2000 data. Future models might also consider including the effect of $\lambda_f$, as suggested by Hanna and Britter (2002).

A further modification to the Briggs urban curves is made in order to account for known large turbulence intensities during light winds, caused by horizontal meandering eddies with time scales of a few minutes, which occur over all types of surfaces, and are observed to have magnitudes in the range from about 0.1–1.0 m/s for 1-h averaging times (Hanna, 1990). Our analysis of the SLC Urban 2000 wind data suggest that a minimum value of turbulent velocity $\sigma_v = \sigma_u = 0.25\,\mathrm{m/s}$ is appropriate. Thus, the lead coefficients in the $\sigma_y$ and $\sigma_x$ equations, which can be considered to be equivalent to the turbulence intensities, $\sigma_v/u$ and $\sigma_u/u$, are not allowed to drop below $(0.25\,\mathrm{m/s})/u$. This condition is found to be triggered for most of the trials at SLC and LA, due to the fact that wind speeds in the downtown urban area seldom exceed 1.5 m/s.

As mentioned above, most analyses of boundary layers and dispersion in built-up downtown urban areas suggest that stabilities are nearly neutral. Venkatram et al. (2002) find this in their field studies, and the concept is used in the Briggs (1973) urban dispersion curves. Our analyses of SLC data (all nighttime) and the LA data (split between night and day), suggest that nearly neutral conditions can usually be assumed. However, some of the LA data suggest that slightly unstable conditions may be more appropriate for summer days, since observed normalized concentrations ($C/Q$) appear to be about three times less in the afternoon than at night. Without doubt, the influence of stability will increase in less built-up urban areas and in suburban and rural areas, where there is less generation of turbulence by mechanical mixing by the obstacles. For the purposes of this simple urban baseline model, it is assumed that conditions in urban areas are nearly always nearly neutral, and the evaluations in Sections 4 and 5 use this assumption.

Considering the above discussions, the following formulas are used in the baseline urban dispersion model for the dispersion coefficients $\sigma_x$, $\sigma_y$, and $\sigma_z$:

Use the following formulas for the nearly neutral conditions that are assumed to apply most of the time except for slightly unstable summer days:

$$\sigma_z = \sigma_{z_0} + 0.14x/(1.0 + 0.0003x)^{1/2}, \tag{11}$$

$$\sigma_y = \sigma_{y_0} + \max(0.16, (0.25\,\mathrm{m/s})/u)x/(1.0 + 0.0004x)^{1/2}. \tag{12}$$

Use the following formulas for slightly unstable sunny summer days:

$$\sigma_z = \sigma_{z_0} + 0.24x(1.0 + 0.001x)^{1/2}, \tag{13}$$

$$\sigma_y = \sigma_{y_0} + \max(0.32, (0.25\,\mathrm{m/s})/u)x/(1.0 + 0.0004x)^{1/2}. \tag{14}$$

As in Eqs. (1)–(4), the wind speed in Eqs. (12) and (14) represents the effective cloud speed. This would be the mid-canopy wind speed for releases below $H_b$, which was the case in SLC and LA.

It should be noted that, at $x$ larger than about 100 m and wind speeds less than about 1.5 m/s, the inclusion of the $(0.25\,\mathrm{m/s})/u$ term in Eqs. (12) and (14) causes the wind speed to "drop out" of the continuous plume Eqs. (1) or (3). This leads to the conclusion that, on the plume centerline near the ground, the maximum concentration, $C_{\max}$, is independent of wind speed, $u$, for low wind speeds and $x > 100\,\mathrm{m}$. This low-wind condition is found for about 60–80% of the tracer experiments at SLC and LA, since wind speeds in the urban canopy were light.

$\sigma_x$ has the same formulation for all stability conditions:

$$\sigma_x = \sigma_{x_0} + \max(0.25, (0.25\,\mathrm{m/s})/u)x. \tag{15}$$

For instantaneous sources, $\sigma_{x_0}$ is assumed to equal $H_b/2$, just as for $\sigma_{y_0}$ and $\sigma_{z_0}$. In addition, as mentioned in the discussion around Eqs. (7) and (8), it is necessary to account for the fact that most "real" sources have a finite duration, $T_d$. In this case, at large distances (much greater than about $uT_d/2$) from the source, the effect of the finite duration of the release produces a relatively long cigar-shaped slug of material. The effect of the long slug on the total initial $\sigma_{x_0}$ can be accounted for using Hanna and Britter's (2002) simple approximation at large $x \gg 0.5uT_d$:

$$\sigma_{x_0} = H_b/2 + 0.5uT_d. \tag{16}$$

In the tracer experiments such as SLC and LA (see below), the release rate $Q_c$ is maintained fairly constant (within about 5%) over the entire time duration $T_d$. This is the optimum situation for application of the finite duration terms in Eqs. (7) and (16). However, a "real" release is more likely to be highly time-variable, and in that case it may be more appropriate to model the release as a time series of many puffs with differing source terms. The concentration at any location and time period would then be estimated by summing the contributions of the individual puffs.

For the purposes of the simple urban baseline model, it is assumed that the $\sigma_x$, $\sigma_y$, and $\sigma_z$, and the minimum turbulent velocity (0.25 m/s) for a finite duration release are the same as those for a continuous plume with an averaging time, $T_a$, of about 1 h. In reality, these quantities vary roughly as $T_a^{0.2}$ (Hanna et al., 1982), and future revisions to the urban model may account for this variation as additional supporting observations are collected in urban field experiments.

## 3. Comparisons with SLC data

The Department of Energy (DOE) and collaborating organizations carried out the Urban 2000 flow and dispersion experiment in the SLC area in September and October, 2000 (Allwine et al., 2002). All $SF_6$ releases were during the night and were of duration 1 h from a point source or a ''short'' 30 m line source near street level in the downtown area, as seen in Fig. 1, which covers a 14 km$^2$ area and shows the release point marked by a star near the middle of the domain and the $SF_6$ monitors as black dots. Three sampling arcs are visible at distances of about 2, 4, and 6 km to the northwest of the release point. In addition, in the 1.3 km$^2$ square area known as the ''Downtown Domain'', there were grids of monitors located on block intersections and midway along the blocks. These monitors were used to define four additional arcs at distances from about 0.15 to 1 km. Some of the meteorological monitors are also shown. The SLC National Weather Service (NWS) anemometer is at the airport in the northwest corner of the figure. The N01 surface anemometer and the N02 and N03 sodar sites are located in a suburban area about 6 km upwind of the urban area. The M02 anemometer is at the top of a 121 m building, and the D11 square marks a sodar at the top of a 36 m building. Average building height, $H_b$, is about 15 m and $z_0$ is estimated to be about $0.15H_b = 2.25$ m.

All source releases were maintained at a constant rate for 1 h. For all but Intensive Operating Period 09 (IOP09), the release rate was about 1 g/s, beginning at 0, 2, and 4 MST. For IOP09, the release rate was 2 g/s beginning at 21, 23, and 1 MST. $SF_6$ concentrations were reported in a data file for 30 min averages over a 6-h period during each night, allowing sufficient time for concentration data from all three releases to be captured. Observed wind speeds were very light (about 0.2–0.5 m/s) at street level (1.5 m height) and were about 1–2 m/s at a height of 50 m for most IOPs. Wind speeds were higher (about 1 m/s at street level and 4–5 m/s at 50 m) for IOPs 09 and 10.

### 3.1. Wind observations

A summary of the average wind observations below and above the urban canopy layer during each IOP of Urban 2000 is given in Table 1, where the locations of most of the 12 anemometers were shown on Fig. 1. The four ''G'' instruments in Table 1 are all sonic anemometers and are mounted at a height of 1.5 m in the area around a large building (the Heber-Wells building) just downwind of the source location. All

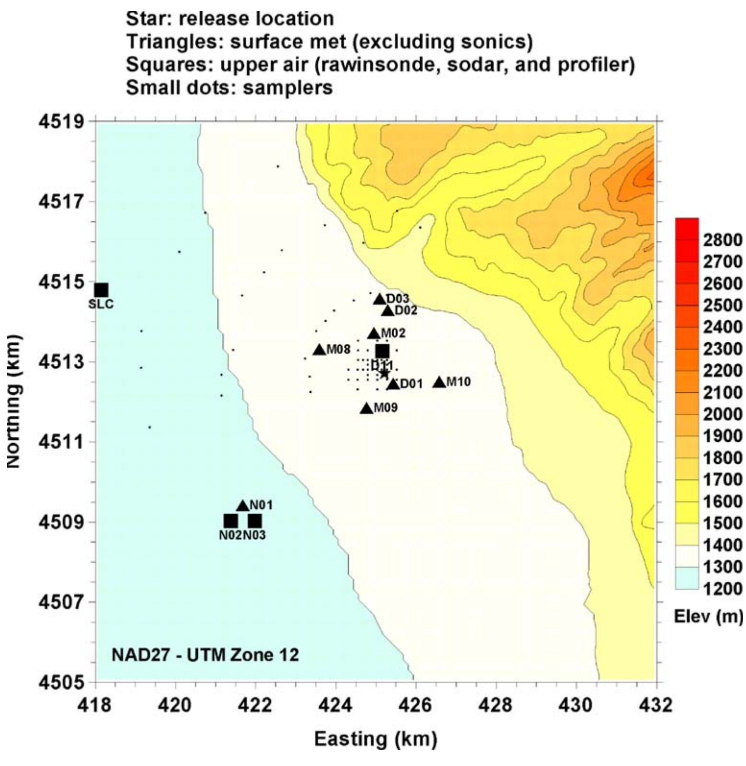


Fig. 1. Map of Salt Lake City domain used in the Urban 2000 study, showing the locations of the release, the surface meteorological monitors, the upper air sites, and the $SF_6$ samplers. (Map prepared by Joseph Chang.)

Table 1
Observed wind speeds in m/s from fixed anemometer sites at Salt Lake City Urban 2000, averaged over each IOP and all IOPs for each anemometer, and averaged over monitors D01, D03, M02, M08, M09, and M10 for each IOP. See Fig. 1 for locations

| | Wind station, Height (m agl) | | | | | | | | | | | | Average $u$ (m/s) over D's and M's |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D01, 9 | D03, 12 | G01, 1.5 | G02, 1.5 | G04, 1.5 | G06, 1.5 | M02, 124 | M08, 23 | M09, 7 | M10, 11 | N01, 10 | SLC, 10 | |
| IOP02 | 0.29 | 0.60 | 0.15 | 0.30 | 0.12 | 0.21 | 1.06 | 1.28 | 0.46 | 0.52 | 1.15 | 2.57 | 0.70 |
| IOP04 | 0.44 | 1.26 | 0.30 | 0.50 | 0.21 | 0.25 | 1.43 | 1.67 | 0.59 | 0.77 | 1.60 | 3.57 | 1.03 |
| IOP05 | 0.42 | 1.65 | 0.37 | 0.21 | 0.27 | 0.33 | 0.63 | 1.27 | 0.53 | 0.44 | 1.12 | 2.71 | 0.82 |
| IOP07 | 0.42 | 1.33 | 0.32 | 0.39 | 0.27 | 0.35 | 1.32 | 1.77 | 0.78 | 0.77 | 1.22 | 3.43 | 1.07 |
| IOP09 | 1.33 | 2.43 | 0.73 | 1.29 | 0.66 | 0.49 | 5.45 | 3.64 | 1.91 | 1.11 | 4.47 | 7.38 | 2.64 |
| IOP10 | 0.75 | 1.56 | 0.51 | 0.67 | 0.57 | 0.41 | 3.40 | 2.75 | 1.27 | 0.73 | 3.37 | 6.00 | 1.72 |
| Average | 0.63 | 1.51 | 0.38 | 0.52 | 0.33 | 0.33 | 2.29 | 2.10 | 0.95 | 0.73 | 2.18 | 4.31 | 1.37 |

speeds and directions are vector averages. The last column in the Table lists the average wind speed used in subsequent analysis, based on the two "D" anemometers and the four "M" anemometers. There are a few major conclusions that can be drawn from the wind data in Table 1:

- IOPs 02, 04, 05, and 07 have similar low wind speeds, averaging from 0.70 to 1.07 m/s.
- IOPs 09 and 10 have moderate wind speeds, with IOP 09 averaging 2.64 m/s and IOP 10 averaging 1.72 m/s.
- The sonic anemometers (the four "G" monitors located around the Heber-Wells building just north of the source release position) at a height of 1.5 m consistently yield low wind speeds—about 0.1–0.5 m/s for IOPs 02, 04, 05, and 07, and about 0.4–1.3 m/s for IOPs 9 and 10.
- Monitor N01, at the Raging Waters suburban site upwind of the city, has wind speeds about twice as large as those at the same elevation in the urban area.
- Monitor SLC is the NWS anemometer at SLC Airport, located in flat open terrain, and consistently has wind speeds about twice as large as at N01 and about three times as large as in the urban area.

The hourly average of the standard deviation of wind direction fluctuations, $\sigma_\theta$, was also reported in the data archive for each of the anemometers discussed above. As expected for the turbulent light-wind urban canopy region, $\sigma_\theta$ is relatively large, with a median over all trials of about 40°. $\sigma_\theta$ decreases to about 20° for the moderate-wind period, IOP09, consistent with the known behavior inversely proportional to $u$. Note that these observed $\sigma_\theta$ for the wind direction fluctuations should be nearly the same as the observed $\sigma_\theta$ for the lateral distribution of $SF_6$ concentrations, which is used in Eq. (5).

Fig. 2 contains observed and theoretical wind profiles (from Eqs. (9) and (10)) in part (a) for "all six IOP averages", and in part (b) for a 1 h average at time ending 00 MST in IOP09. IOP09 is the test case with the highest wind speeds. The wind observation from the D11 sodar (located at the top of a 36 m tall downtown building) at a height above the surface of about 120 m is used to define $u^*$ for both parts of the figure. A roughness length, $z_0$, of $0.15H_b = 2.25$ m, and a displacement length, $d$, of $0.5H_b = 7.5$ m, are assumed in order to calculate the theoretical wind profile (see Hanna and Britter, 2002). Although there is some scatter due to variability in the urban area, the theoretical wind profile equations are seen to agree fairly well (i.e., most of the time well within a factor of two) with the observations.

The wind profiles from the D11 sodar in Fig. 2 are seen to exhibit considerable shear in the layer from about 50 to 200 m above the ground in the SLC downtown area. Such a shear layer could be an indication of a stable layer aloft (after all, this is nighttime), but we believe that the shear is more likely due to the fact that the background wind speeds at an elevation of 200 m outside of the urban area (at the upwind N01 site and at the SLC airport site) are relatively high, and it is necessary for the winds above the city to approach the general background flow as heights increase. That is, in order to have 5 m/s wind speeds at a height of 200 m, and 1 m/s wind speeds in the urban canopy, there has to be a strong gradient in the 50–200 m layer.

### 3.2. Concentration observations

The distributions of the observed 30 min averaged concentrations on each of the seven monitoring arcs were plotted and the maximum concentration, $C_{max}$, was identified if there were sufficient data. In some cases, there were problems because the concentrations were all below the threshold of 30 ppt, or there was perhaps only a single high observation, or the plume was obviously on

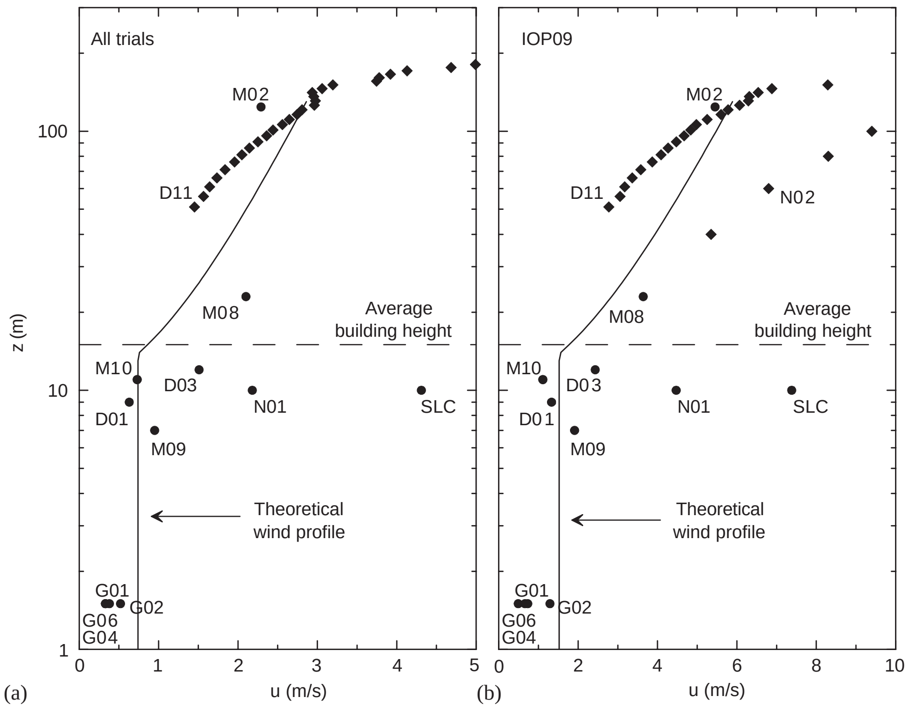


Fig. 2. (Part a) Observed and predicted wind speed profiles averaged over all six IOPs from Salt Lake City Urban 2000. The solid symbols are monitors in the urban area. The open symbols are monitors outside of the urban area. See Fig. 1 for locations and Table 1 for the data. The line is the theoretical formula based on Eqs. (9) and (10), assuming $z_0 = 2.25$ m and $d = 7.5$ m and using the D11 sodar observation at about 120 m to estimate $u^*$. (Part b) Same format but for 00 MST during IOP09.

the edge of the network, and that information was noted in the master file. For those problem trials and arcs, an "n/a" appears in the tables and figures, and those data are not used in the analysis or model evaluations. The data in each IOP were also analyzed for continuity in space and time, and an example of time series of 30-min average $C_{\max}/Q$ is given in Fig. 3 for IOP04 (Trial 4) for each of the seven arc distances. Note that the continuous emission rate, $Q_c$, is shortened to $Q$. The figure shows that the three source releases (from 00 to 01, from 02 to 03 and from 04 to 05) can be distinguished, and that there is a time lag for when the $C_{\max}/Q$ occurs at the distant arcs. The figure suggests that the peak at the 6 km arc (arc 7) occurs after a delay of about $1\frac{1}{2}$ h, which is consistent with the 1 m/s wind speed (it takes $1\frac{1}{2}$ h for the air to travel 5.4 km at a speed of 1 m/s). The figure also shows that the time scale is about 30–60 min for a decrease of concentration by a factor of ten at the closest (156 m) monitoring arc, which can be interpreted as the result of a combination of the along-wind dispersion coefficient $\sigma_t = \sigma_x/u$, the light wind speeds, and some hold-up of the tracer material in the urban building wakes.

The focus of the simple urban baseline model evaluations is on the normalized 1 h averaged maximum $C_{\max}/Q$ anywhere on an arc during the passage of the cloud from each of the three release trials for the six IOPs. It is possible that the observed and predicted maximum concentrations could be slightly displaced in time and in lateral position from each other. Note that the conversion from ppt to g/m$^3$ assumes that 1 ppt = $5.45 \times 10^{-9}$ g/m$^3$. Table 2 contains the observed hourly averaged $C_{\max}/Q$ values, in units of $10^6$ s/m$^3$, for each arc in each trial and IOP (a total of 18 trials and seven arcs). The third column of the table lists the average wind speed for that IOP and Trial. The next to bottom row of the table contain the observed $C_{\max}/Q$ on each arc averaged over the 18 Trials. It is seen that the average wind speed, $u$, is 1.39 m/s. Since the wind speed tends to drop out of the solution for $C_{\max}/Q$ in the Gaussian plume equation when $u <$ about 1.5 m/s, a single predicted solution (referred to in the text below as the "$u$-less" solution) is listed in the bottom row of the table. This solution makes use of the fact that the $u$ in the denominator of Eq. (3) cancels out when it is multiplied by the (0.25 m/s)/$u$ term in the $\sigma_y$ Eq. (15). After these "$u$-less" model comparisons are given, some comparisons will be given for the complete solution, accounting for u, since IOPs 09 and 10 have $u > 1.5$ m/s and the data in Table 2 suggest that $C_{\max}/Q$

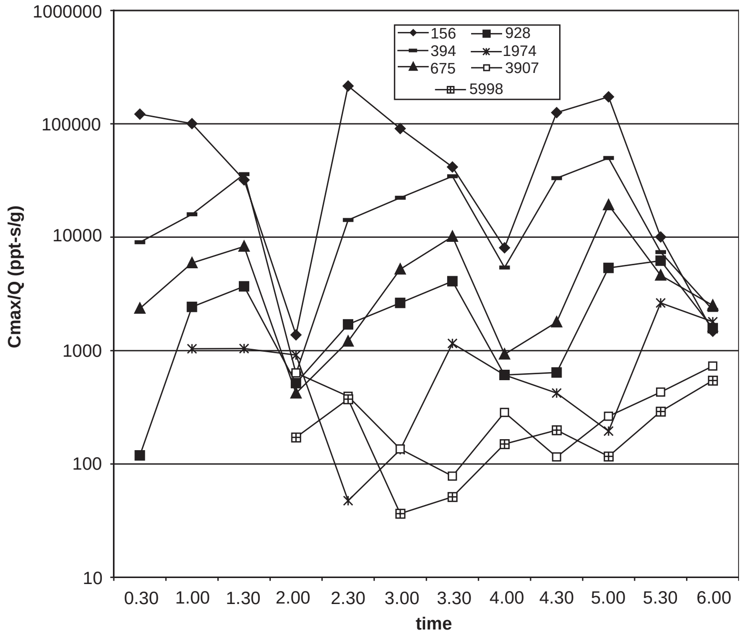


Fig. 3. Time series of observed 30-min average $C_{max}/Q$ for IOP04, for the seven monitoring arcs, at downwind distances in meters given in the legend. $SF_6$ releases occurred between 0:00 and 1:00, 2:00 and 3:00, and 4:00 and 5:00.

Table 2
Observed hourly averaged $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) for the seven monitoring arcs and the 18 trials at Salt Lake City Urban 2000

| IOP | Trial | $u$ (m/s) | Arc, $R$ (m) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Arc 1, 156 | Arc 2, 394 | Arc 3, 675 | Arc 4, 928 | Arc 5, 1974 | Arc 6, 3907 | Arc 7, 5998 |
| 2 | 1 | 0.81 | 317.7 | 79.6 | 14.2 | 3.58 | 3.91 | 1.97 | 0.47 |
| 2 | 2 | 0.61 | 421.2 | 103.7 | 2.85 | n/a | n/a | n/a | n/a |
| 2 | 3 | 0.5 | 366.1 | 86.8 | 7.26 | 1.39 | n/a | n/a | n/a |
| 4 | 1 | 1.13 | 606.3 | 120.1 | 35.4 | 16.2 | 5.67 | 2.81 | 1.48 |
| 4 | 2 | 0.94 | 836.1 | 154.7 | 29.5 | 12.7 | 4.39 | 0.94 | 0.95 |
| 4 | 3 | 0.76 | 573.1 | 186.7 | 60.6 | 21.1 | 11.3 | 2.53 | 2.28 |
| 5 | 1 | 0.64 | 149.6 | 77.3 | 22.2 | 13.8 | 3.87 | 1.19 | 2.98 |
| 5 | 2 | 0.91 | 249.4 | 80.5 | 19.3 | 13.6 | 4.09 | 1.35 | 1.32 |
| 5 | 3 | 1.06 | 402.2 | 118.3 | 20.1 | 12.8 | 8.09 | 1.5 | 1.25 |
| 7 | 1 | 1.01 | 520 | 187.7 | 32.4 | 17.9 | 6.08 | 1.98 | n/a |
| 7 | 2 | 1.04 | 200.6 | 25.8 | 28.9 | 9.16 | 10.3 | 2.47 | 2.59 |
| 7 | 3 | 1.21 | 207.6 | 75.8 | 41.8 | 36.4 | 10.5 | 3.13 | 1.85 |
| 9 | 1 | 2.69 | 129.3 | 49.6 | 44.9 | 4.77 | n/a | 0.63 | 0.49 |
| 9 | 2 | 2.47 | 243.7 | 56.8 | 32.5 | n/a | n/a | 1.06 | 1.01 |
| 9 | 3 | 3.23 | 115.3 | 37.3 | 11 | 7.56 | 2.63 | 1.5 | n/a |
| 10 | 1 | 1.51 | 158 | 33 | 10.6 | 4.05 | 2.03 | 1.19 | n/a |
| 10 | 2 | 2.16 | 153.4 | 31.9 | 9.84 | 8.1 | 3.45 | 1.87 | n/a |
| 10 | 3 | 2.31 | 72.9 | 22.7 | 4.22 | 1.78 | 1.48 | 0.58 | n/a |
| Avg. Obs. | | | 317.9 | 84.9 | 23.8 | 11.6 | 5.56 | 1.67 | 1.52 |
| Avg. Pred. | | | 229.1 | 52.4 | 21.2 | 12.5 | 3.71 | 1.36 | 0.76 |

The symbol "n/a" means that the data did not meet acceptance criteria. The bottom two rows of the table contain the averaged observed $C_{max}/Q$ for each monitoring arc, followed by the predicted $C_{max}/Q$ by the "$u$-less" baseline urban model

observations for IOPs 09 and 10 are an average factor of about two less than the $C_{max}/Q$ observations for the low-wind IOPs (02, 04, 05, and 07).

Fig. 4 presents the comparisons of maximum 1-h average predicted ("$u$-less") and observed $C_{max}/Q$, as a function of downwind distance, $x$. The plotted points are

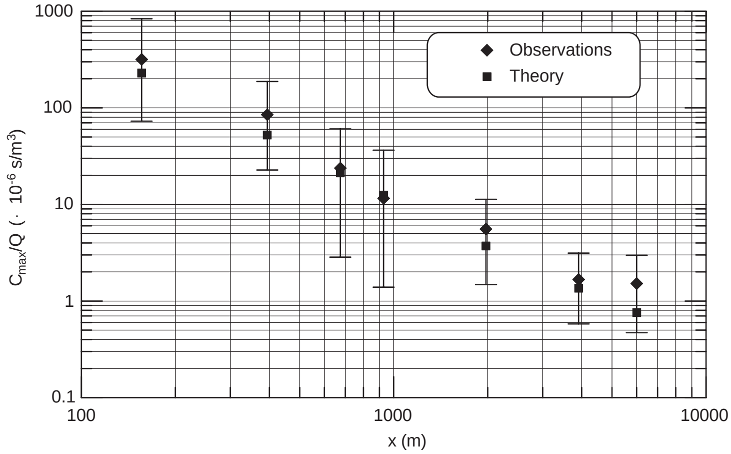


Fig. 4. Salt Lake City Urban 2000 observed and predicted hourly averaged $C_{max}/Q$ for all 18 trials for the seven monitoring arcs. The solid symbols represent the averages over all the trials, and the range of the 18 observations is shown as the vertical bar. The predictions represent the simplest "$u$-less" model assumptions.

taken from the bottom two rows of Table 2. The mean $C_{max}/Q$ values of both the observations and predictions follow an approximate $x^{-1.5}$ power law in Fig. 4, in agreement with observations at other field studies (Hanna et al., 1982). The mean and the range of the 18 observations (six IOPs times three trials per IOP) at each downwind arc are shown, where the range is determined from the 18 $C_{max}/Q$ observations listed in Table 2 for each $x$. It is seen in Fig. 4 that the predicted points are within the uncertainty range of the observed points at all distances, implying that there is no significant difference, at the 95% confidence level, between the predictions and the observations. On average, the "$u$-less" baseline urban dispersion model underpredicts by about 25–30%, with little trend with distance. However, it is seen in Table 2 that the "$u$-less" model overpredicts the $C_{max}/Q$ for the higher-wind IOPs 09 and 10 by about a factor of two.

Because of the factor of two overpredictions mentioned above for the "$u$-less" baseline model in IOPs 09 and 10, comparisons were also made with the simple urban baseline model using the full Eq. (15) for $\sigma_y$, for which $\sigma_y$ is independent of $u$ at $u >$ about 1.5 m/s. Fig. 5 contains a scatter plot of the observed versus predicted $C_{max}/Q$ using Eq. (15) to calculate $\sigma_y$. The low wind IOPs (02, 04, 05, and 07) are distinguished by triangles and the moderate wind IOPs (09 and 10) are distinguished by circles. It is seen that there is little bias in the moderate wind IOP predictions, which are less than those in Fig. 4 and Table 2 by a factor of about two. The low wind IOP predictions are little changed from the "$u$-less" predictions in Fig. 4 and Table 2, and still show fairly good agreement, with a mean overprediction bias of about 25–30% at all $x$. "Factor of two" agreement lines are drawn on the figure, and it is found that about $\frac{3}{4}$ of the predictions of $C_{max}/Q$ are within a factor of two of observations.

## 4. Comparisons with LA data

It is fortunate that there is an independent set of urban tracer dispersion data available from LA, which can be used to confirm the analysis carried out in the above section with the SLC Urban 2000 data. The US Marine Corps sponsored the LA tracer experiments in August and September of 2001 (Rappolt, 2001). Table 3 contains a summary of the major conditions, inputs, and observed concentrations for the 11 trials that yielded satisfactory data. The experiments covered day and night, as well as the morning transition period. $SF_6$ releases were of duration 5 min from point sources near street level in the downtown area, as seen in Fig. 6, which also shows locations of $SF_6$ monitors and of meteorological instruments. The releases were from different locations, depending on the expected wind direction. The 50 monitors were all located within about 1 km of the source. $SF_6$ concentrations were reported in a data file for 2.5 min averages over a 30 min sampling period during each trial.

Table 3 shows that the release rate, $Q$, ranged from about 0.75 to 5 g/s. The downtown buildings in the domain of the field experiment are taller in LA than in SLC ($H_b$ is about 30 m in LA, versus 15 m in SLC) although the morphological parameter $\lambda_f$ remains at about 0.3. $z_0$ is estimated to be about $0.15H_b = 4.5$ m. As in SLC, observed wind speeds in the urban canopy were light (averaging about 1 m/s) at the single wind monitor located 8 m above street level, in a small park.

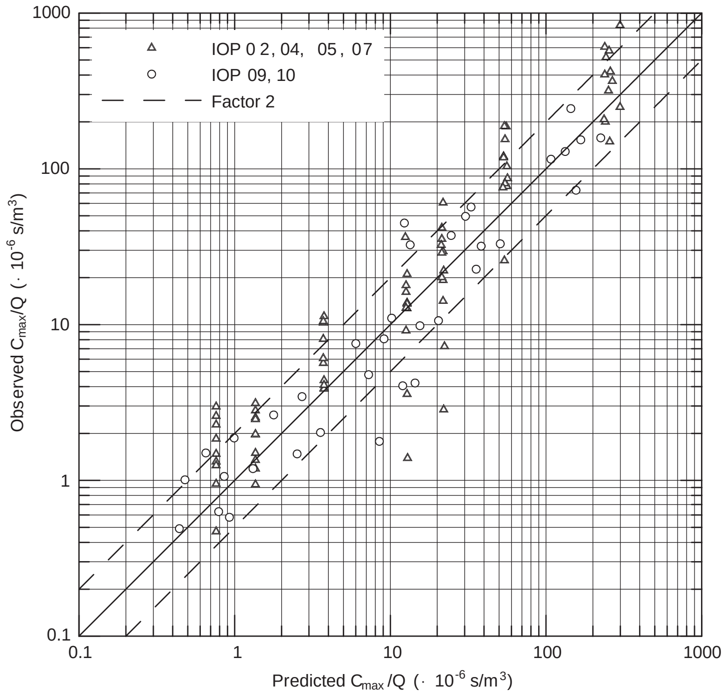


Fig. 5. Salt Lake City Urban 2000 observed and predicted hourly averaged $C_{max}/Q$ for all 18 trials for the seven monitoring arcs. The predictions incorporate the $u$-dependency in Eq. (12) for $\sigma_y$. The triangles represent the "low wind" IOPs 02, 04, 05, and 07. The circles represent the "moderate wind" IOPs 09 and 10. The dashed lines correspond to a factor of plus and minus two agreement.

Because the $SF_6$ monitors were set out on a roughly rectangular grid pattern (see Fig. 6) and the release location varied in LA, it was not possible to define sets of monitoring arcs for comparisons of concentrations, as was done in SLC. Instead, the LA evaluation exercise makes use of the "Overall $C_{max}/Q$" for each Trial and the "Distant $C_{max}/Q$" for each Trial, which are listed in Table 3, along with the monitor number at which the $C_{max}/Q$ was observed. The 2.5 min time period number during which the observed $C_{max}/Q$ occurred is also listed. Note that, with 12 2.5 min time periods in the 30-min sampling duration, the first two time periods (0–5 min) mark when the release occurred. Thus the 6th time period number would be the 12.5–15 min time period and the 10th time period number would be the 22.5–25 min time period after the release was initiated.

The "Overall $C_{max}/Q$" is the highest $C_{max}/Q$ observed during the Trial, and the "Distant $C_{max}/Q$" is the maximum $C_{max}/Q$ observed near the downwind edge of the monitoring network. The $C_{max}/Q$ values predicted by the simple baseline urban dispersion model are also listed in the table. The averaging time, $T_a$, is only 2.5 min in the LA C data, which is a factor of 24 less than the 60 min averaging time used for the SLC C data. For this simple baseline model exercise, we are not correcting for averaging time as long as $T_a$ is in the range from a few minutes to 1 h.

For the "Distant $C_{max}/Q$" group, where $x > 0.5uT_d$, the $T_d$ correction in Eq. (7) is applied to the predicted continuous plume concentration, and is seen to produce good agreement with data. The bottom row of the table contains the mean of that variable for the 11 trials.

There are a few fundamental findings that can be gleaned from the results in Table 3:

- The average $C_{max}/Q$ decreases from about $103 \times 10^{-6}\,s/m^3$ for the "Overall Maximum" to about $3 \times 10^{-6}\,s/m^3$ for the "Distant Maximum", and these occur at mean downwind distances of about 110 and 650 m, respectively. This implies that $C_{max}/Q$ varies approximately with $x^{-2}$. The relation at SLC was closer to $x^{-1.5}$, as seen in Fig. 4. A faster decrease in $C$ with $x$ is expected as the cloud becomes more "puff-like" and dispersion occurs in three dimensions rather than just two dimensions.
- The time period number when the "Overall Maximum" is observed averages about 3.5 (or about 4 min after the release ended) and for the "Distant Maximum" averages about 8 (or about 15 min after the release ended). Since the "Distant Maximum" is located about 650 m from the source, this 11 min = 660 s transport time is consistent with the observed mean wind speed of about 1.2 m/s.

Table 3
Summary of Los Angeles observations from 11 $SF_6$ tracer release trials, as determined from the report by Rappolt (2001)

| Trial | Release time PDT | $u$ (m/s) | WD (deg) | $Q$ (g/s) | Overall monitor with $C_{max}$ | Overall period with $C_{max}$ | Overall monitor distance (m) | Overall observed $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) | Overall predicted $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) | Distant monitor with $C_{max}$ | Distant period with $C_{max}$ | Distant monitor distance (m) | Distant observed $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) | Distant predicted $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 1.12 | 253 | 0.75 | 34 | 5 | 150 | 29.3 | 168.4 | 43 | 12 | 950 | 4.28 | 1.9 |
| 3 | 4 | 0.98 | 276 | 2.13 | 15 | 3 | 150 | 233 | 175.3 | 17 | 9 | 800 | 8.08 | 2.7 |
| 4 | 10 | 1.07 | var | 2.87 | 32 | 3 | 70 | 67.6 | 247.8 | 16 | 6 | 400 | 2.2 | 6.9 |
| 5 | 4 | 0.9 | 205 | 3.05 | 32 | 3 | 300 | 38 | 68.4 | 10 | 9 | 800 | 4.16 | 2.5 |
| 6 | 10 | 1.61 | 214 | 3 | 32 | 3 | 50 | 80.7 | 235 | 3 | 4 | 420 | 0.69 | 6 |
| 7 | 4 | 0.9 | 213 | 3.07 | 23 | 2 | 100 | 153 | 291 | 35 | 9 | 700 | 2.93 | 3.5 |
| 8 | 8 | 0.98 | 198 | 3.05 | 34 | 4 | 120 | 29 | 229.7 | 3 | 7 | 750 | 1.79 | 3.2 |
| 9 | 4 | 0.67 | 188 | 1.52 | 31 | 5 | 70 | 58.9 | 472.2 | 29 | 10 | 270 | 2.54 | 31.1 |
| 10 | 8 | 1.3 | 232 | 2.78 | 13 | 3 | 50 | 142 | 455.2 | 35 | 8 | 650 | 3.85 | 5.9 |
| 11 | 16 | 2.24 | 256 | 4.59 | 5 | 4 | 70 | 65.3 | 118.4 | 18 | 6 | 630 | 0.5 | 1.9 |
| 12 | 4 | 1.16 | 262 | 1.52 | 5 | 3 | 70 | 236 | 372.1 | 35 | 7 | 800 | 5.45 | 3.1 |
| Average | | 1.18 | | 2.58 | | | 110 | 103 | 258 | | | 652 | 3 | 6 |

The release duration was always 5 min, starting at the time indicated, and the location varied as seen in Fig. 6. Winds are averaged over ten minutes beginning when the release started. Averaging period for the $SF_6$ observations is 2.5 min. There were 12 sequential "periods" of $SF_6$ observations for each Trial for each monitor. Trial 3 is not included because concentrations were too low. Focus is on the "Overall $C_{max}/Q$" and "Distant $C_{max}/Q$", where the former is the highest $C_{max}/Q$ at any of the 50 monitors (but usually at a monitor within 100 m of the source), and the latter is the $C_{max}/Q$ at the set of monitors on the downwind edge of the network (usually at a distance of about 800 m, as expected from inspection of Fig. 6).

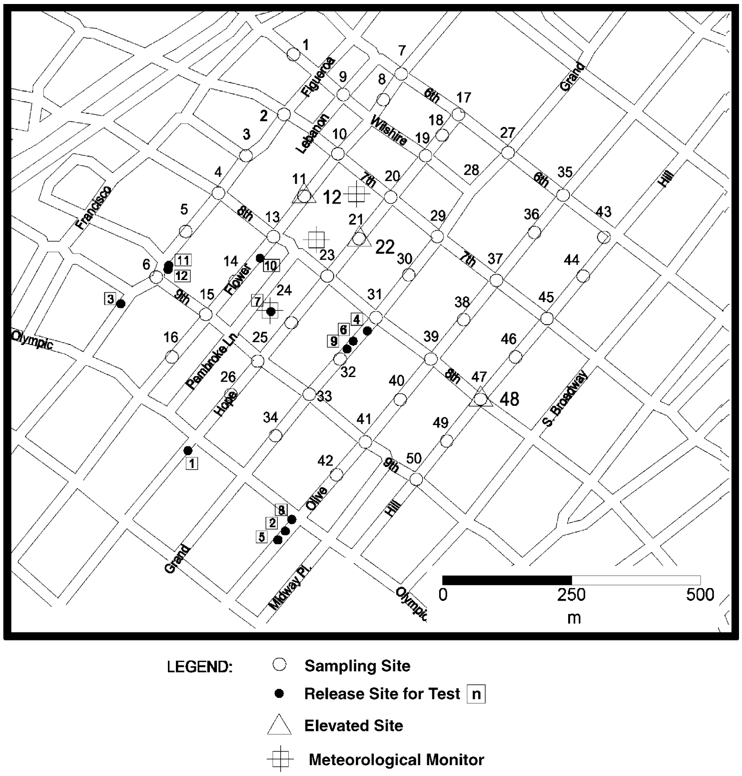


Fig. 6. Map of Los Angeles $SF_6$ tracer experiment site, from Rappolt (2001). The N-S dimensions of the map are 1100 m. All samplers (marked with open circles) are near street level at height about 1.5 m, except for samplers 12, 22, and 48, which are marked with triangles and are at height 36 m. The primary meteorological site, where the wind observations were taken at a height of 8 m, is at the location marked by a black dot where test release 7 is shown. Building locations are not indicated on this map; however, the average building height is about 30 m, the area coverage, $\lambda_p$, is about 0.3, and the maximum building height is about 200 m.

- On average, the predicted "Overall $C_{max}/Q$" is about three times larger than the observed value.
- On average, the predicted "Distant $C_{max}/Q$" is about a factor of two larger than the observed value.
- The "Overall Maximum" results seem to separate somewhat by time of day and by release location. For example, the four largest $C_{max}/Q$ occur during nighttime with release locations all in the western part of the domain (see Fig. 6). These are Trials 3, 7, 10, and 12.

As mentioned in the last bullet above, the four largest $C_{max}/Q$ appear to form a group with similar characteristics, and these data are summarized separately in Table 4, which has the same format as Table 3, but lists only Trials 3, 7, 10, and 12. On average for the four trials listed in Table 4, the performance is better than that seen in Table 3, and the simple baseline urban model overpredicts the "Overall $C_{max}/Q$" by about 70% and underpredicts the "Distant $C_{max}/Q$" by about 20% in Table 4. This agreement is fairly good, considering the variability in the observations at LA.

## 5. Further comments and recommendations

The analysis has shown that the simple baseline urban dispersion model is able to explain much of the variability in the tracer observations at SLC and LA. However, the model is expected to be less useful near buildings in the vicinity of the source. In that situation, more complex models that directly account for the details of the flows, such as recirculation zones around individual buildings, may be more helpful.

As a further limitation, because the baseline model assumes a relatively homogeneous underlying urban surface, it is expected to be less useful at large mesoscale distances, after the cloud passes out of the urban area and is being advected over downwind rural areas. The effective wind speed and the dispersion rates would be modified over the new surface. Furthermore, the wind field may show variations in wind direction in space and time over such distances and time periods. The effects of these variations can be seen in some of the observed $SF_6$ tracer plume patterns in SLC, when sometimes the $SF_6$ cloud would change direction and blow off the edge of the monitoring network.

Table 4
Stable Trials 3, 7, 10, and 12 from Los Angeles $SF_6$ tracer releases, as determined from the report by Rappolt (2001)

| Trial | Release time PDT | $u$ (m/s) | WD (deg) | Q (g/s) | Overall monitor with $C_{max}$ | Overall period with $C_{max}$ | Overall monitor distance (m) | Overall observed $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) | Overall predicted $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) | Distant monitor with $C_{max}$ | Distant period with $C_{max}$ | Distant monitor distance (m) | Distant observed $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) | Distant predicted $C_{max}/Q$ ($\times 10^{-6}$ s/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 4 | 0.98 | 276 | 2.13 | 15 | 3 | 150 | 233 | 175.3 | 17 | 9 | 800 | 8.08 | 2.7 |
| 7 | 4 | 0.9 | 213 | 3.07 | 23 | 2 | 100 | 153 | 291 | 35 | 9 | 700 | 2.93 | 3.5 |
| 10 | 8 | 1.3 | 232 | 2.78 | 13 | 3 | 50 | 142 | 455.2 | 35 | 8 | 650 | 3.85 | 5.9 |
| 12 | 4 | 1.16 | 262 | 1.52 | 5 | 3 | 70 | 236 | 372.1 | 35 | 7 | 800 | 5.45 | 3.1 |
| Average | | 1.09 | | 2.38 | | | 93 | 191 | 323 | | | 738 | 5 | 4 |

Averaging period for the observations is 2.5 min. Focus is on the "Overall $C_{max}/Q$" and "Distant $C_{max}/Q$", where the former is the highest $C_{max}/Q$ at any of the 50 monitors (but usually at a monitor within 100 m of the source), and the latter is the $C_{max}/Q$ at the set of monitors on the downwind edge of the network (usually at a distance of about 800 m, as expected from inspection of Fig. 6).

Despite the limitations to the baseline model listed above, it is clear from the results in this paper that the model is able to provide a reasonable agreement with observations. Apparently the effects of the wind shift, the variations in underlying surface, and the effects of local buildings tend to produce variability, but the variability averages out in the final assessments over many trials.

Questions remain about the most appropriate assumptions for stability in urban areas. We assume that nearly neutral conditions dominate in built-up downtown areas, where generation of mechanical turbulence by the buildings is optimized, but more study is needed.

The focus of this paper has been on the continuous plume model, with simple analytical corrections for finite duration releases. In the case of highly time-variable releases, and variable meteorological conditions and/or underlying terrain, a more detailed model such as a Lagrangian puff model may be more appropriate.

It is suggested that the simple baseline urban dispersion model be used as a measure against which the performance of more complex models can be compared. Any more complex model should be able to show a significant improvement in accuracy over the baseline model.

The main aspects of the SLC and LA data bases have been listed in this paper and should allow other modelers to quickly develop inputs for their models and compare the predictions against the listed observations.

## Acknowledgements

This research was sponsored by the Defense Threat Reduction Agency, by the Department of Energy, and by the American Institute of Chemical Engineers. The authors acknowledge the assistance of Jerry Allwine of Pacific Northwest National Laboratory, who provided the Urban 2000 data, and Dennis Metz, of Simulation Technologies Inc., who provided the Los Angeles data. We also appreciate the assistance of Joseph Chang of George Mason University, who helped prepare many of the data tables and figures.

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