LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-CONF-204906

Gaussian Modeling of Tracer Concentrations during the Joint Urban 2003 Experiment

Frank J. Gouveia

June 2004

Fifth Symposium on the Urban Environment
August 23-26, 2004
Vancouver, BC, Canada

DISCLAIMER

GAUSSIAN MODELING OF TRACER CONCENTRATIONS DURING THE JOINT URBAN 2003 EXPERIMENT

Frank J. Gouveia*
Lawrence Livermore National Laboratory, Livermore, CA

1. INTRODUCTION

The Joint Urban 2003 Experiment (JU2003) was conducted in Oklahoma City, Oklahoma during the summer of 2003. This extensive field experiment included over a hundred scientists measuring airflow, tracer concentration, and other variables pertinent to urban dispersion. A description of JU2003 can be found at this website: http://ju2003.pnl.gov/ .

During JU2003, researchers installed anemometers in and around the urban area for continuous measurement of airflow during the 35-day experiment. Additionally, they fielded instruments to measure the atmospheric concentration of the inert tracer sulfur hexafluoride (SF_6) during ten Intensive Observation Periods (IOPs). Also during the IOPs, additional instruments were fielded to measure airflow using temporary tripod-mounted anemometers (Fig. 1). A 12-hour long IOP featured two or three separate 30-minute tracer releases, and several puff releases. There were a total of 29 thirty-minute releases, and all were evaluated in this study. The location and time of the releases varied for the different IOPs. Releases were made at three locations: Westin Hotel, Botanical Gardens, and Park Avenue. Six of the IOPs were conducted in the daytime, four at night.

In this study, a simple Gaussian model is employed to estimate concentrations at discrete locations. These estimates are compared to concentrations measured by several researchers during the JU2003 field experiment.

Previous studies (e.g., Hanna et al., 2002, 2000, Ramsdell and Fosmire, 1998) have used simple Gaussian models to estimate dispersion in urban environments. These analytical models have used single estimates for plume width based, in part, on the morphology of the buildings. Formulations for plume width based on building morphology were not considered appropriate for the current application since the plume would not be affected by a single building geometry.

* *Corresponding author address*: Frank Gouveia, LLNL L-396, P.O. Box 808, Livermore, CA 94551-0808; *email*: gouveia2@llnl.gov.

2. INSTRUMENTATION

For our measured tracer concentrations, we processed data from LLNL, Volpe, and NOAA. The LLNL and Volpe samplers were all within 350 m of the source, and a few were within 10 m. the arrangement of these samplers was different for each IOP. The NOAA samplers (Programmable Integrating Gas Samplers, PIGS) were placed at street intersections within the urban center (NOAA grid), and in arcs roughly 1-, 2-, and 4-km from the source (NOAA arcs).

There were two types of LLNL samplers: Blue Box (BB), and Miran. The BB samplers are programmable bag samplers. The Miran samplers are infrared spectrometers. Some of the BB samplers were placed on rooftops with the highest placed 54 m above the street surface.

A Gaussian model requires an input of wind

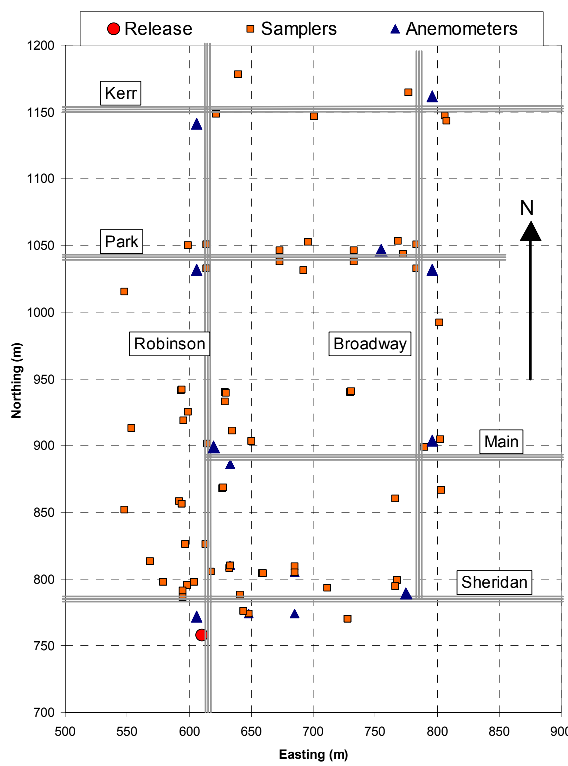

Figure 1. Map of Oklahoma City urban center showing the locations of samplers and anemometers deployed by several researchers during the Botanical Gardens releases (IOPs 3, 4, 5, 6, 7).

speed (u) and direction. Several observations are available for canopy wind. For this study, the driving wind chosen for the model was one that represents the flow between the source and the majority of the samplers. No attempt was made to select an observation that made the best fit to the dispersion pattern. The selection was uncomplicated during the Westin and Botanical releases as the wind observations in general area of the source and samplers were fairly consistent. A nearby PWIDS Portable Weather Information Display System) station, installed by researchers from Dugway Proving Ground, was selected for these releases. For the Park Avenue releases, deep within an urban canyon, the flow divaricated into two along-canyon flows that were at right angles to the ambient flow. An anemometer on the ASU tower (Arizona State University) was used to indicate the general direction of the flow, and the wind was chosen to be either due east (90°) or due west (270°). The only exception to the above is the wind used for the locations of the NOAA arc samplers which was from the lowest level of the LLNL Crane located near the intersection of North Tenth and Harvey (Gouveia et al., 2004).

3. SIMPLE MODEL

The well-known Gaussian model was used to estimate the normalized concentration (χ/Q)

$$\chi / Q = \left(2\pi\sigma_y\sigma_z u\right)^{-1} \exp\left(-y^2/2\sigma_y^2\right) \times \left[\exp\left(-(z-h)^2/2\sigma_z^2\right) + \exp\left(-(z+h)^2/2\sigma_z^2\right)\right],$$

where y is the crosswind distance from the centerline to the sampler, z is the height of the sampler, and h is the height of the source (1 m).

A previous study (Gouveia and Shinn, 2000) unified σ_y and σ_z (plume width and height, respectively) into a single σ. The best fit to the measurements made around a single building was $\sigma = 0.3\ t$. For our application, we separate σ_y and σ_z into two expressions:

$$\begin{aligned} \sigma_y &= 1.0t \\ \sigma_z &= 0.3t \end{aligned}, \qquad (1)$$

where t is the flight time of the center of the plume in seconds. σ_y and σ_z have units of meters. The form of Eq. 1 is based on a review of several field experiments (Gifford, 1977). Hanna et al. (1982) offers coefficients for Eq. 1 that include eddy dissipation rate or friction velocity. Although these turbulence measurements were made during JU2003, the horizontal variability of these quantities among the buildings is very large, much larger than the variability between the 29 tests. Therefore, constant coefficients and exponent of one were used for the current model. The model computations were repeated with a series of coefficients. We found the values presented in Eq. 1 yielded the best results, when compared to the measurements, in the widest range of cases.

4. COMPILE OBSERVATIONS

4.1 Integrated concentration

The raw concentration data was obtained with units of ppb by volume. These data needed to be converted to a normalized concentration with units of μg·sec/m^3 per μg released or sec/m^3. With sufficient accuracy SF_6 concentration can be converted to density,

$$1\text{ppb SF6} = \frac{1779}{T}\frac{\mu\text{g}\cdot\text{K}}{\text{m}^3}.$$

The SF_6 density is multiplied by the duration of that density, and the products are summed over the entire release period. Dividing the sum by the total mass of SF_6 released (Table 1) will yield the normalized concentration, or inverse dilution rate.

4.2 Meteorological data

As described in section 2, the wind observations used in the Gaussian model were obtained from anemometers that represent the flow between the source and the majority of samplers. The station chosen for the Westin releases was PWIDS 08, and PWIDS 11 for the Botanical releases. For the Park Avenue releases (IOPs 9 and 10) the ASU tower that was located in that urban canyon was used to provide the rough direction of flow. The wind vector used for the arc sampler locations was uniformly the lowest level (7.8 m) of the LLNL Crane.

Table 1 includes the actual wind vectors used in the Gaussian model.

4.3 Valid observations and model solutions

The “Total obs” column of Table 2 is a tally of the total number of tracer samples taken during each release. Included are the LLNL Blue Box samplers (~22), LLNL Miran samplers (~10), Volpe samplers (10), NOAA grid samplers (~40), and NOAA arc samplers (~60).

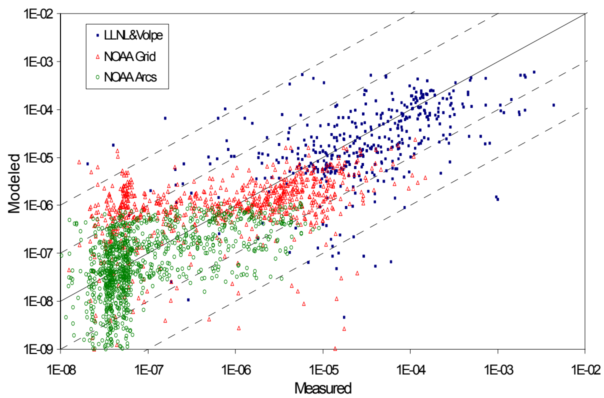

Figure 2. Observed versus modeled normalized concentrations (sec/m^3).

Some of the observations were omitted from further evaluation, and the number of observations remaining appears in the "Total valid obs" column. Observations can be omitted for incomplete coverage of the release period, concentration statistically equal to zero, or a problem with the sampler in the field.

The Gaussian model cannot calculate concentrations upwind of the source. The number of locations downwind of the source appears in Table 2 under the "Total DW" heading. 75% of the valid samples were downwind of the source.

The final column of Table 2 contains the number of locations with a valid observation and model solution.

5. MODEL VERSUS OBSERVATION

Figure 2 shows the observed normalized concentrations plotted against the modeled. This diagram does not include the few locations with very small values of measured or modeled normalized concentration. Most of the modeled concentrations are within an order of magnitude of the measurements.

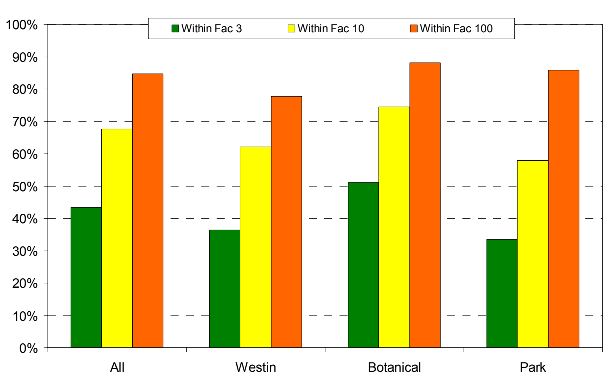

Figure 3. Frequency of modeled X/Q within factors of 3, 10 and 100 of the observed X/Q for all releases combined and the three release locations.

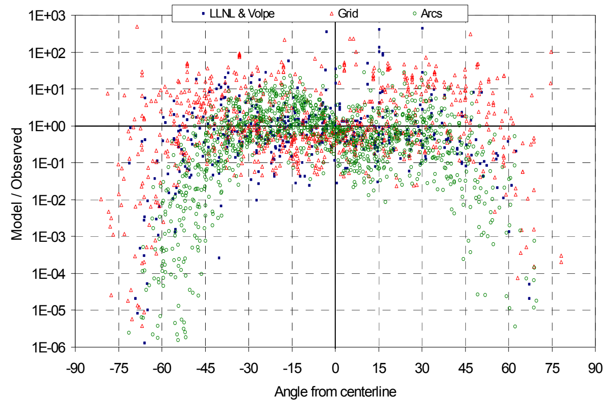

Figure 4. Ratio of modeled-to-observed normalized concentration plotted against the angle (in degrees) of the sampler location to the modeled plume centerline.

There are a large number of NOAA arc samples, and some NOAA grid samples, with concentrations of SF_6 close to the minimum detection limit. These measurements yield normalized concentrations less than 7E-8 sec/m^3.

Figure 3 shows that over 40% of the model solutions are within a factor of three of the observations (N=2568). Additionally, the Botanical releases exhibit the highest frequency (>50%) within a factor three. These releases are situated at the head of an urban canyon that is roughly in line with the wind. It is not surprising that the model is less accurate for the Park Avenue releases, although the frequency within a factor of 100 is comparable to the Botanical releases. Park Avenue is usually at a right angle to the ambient wind.

The ratio of modeled X/Q to observed X/Q is

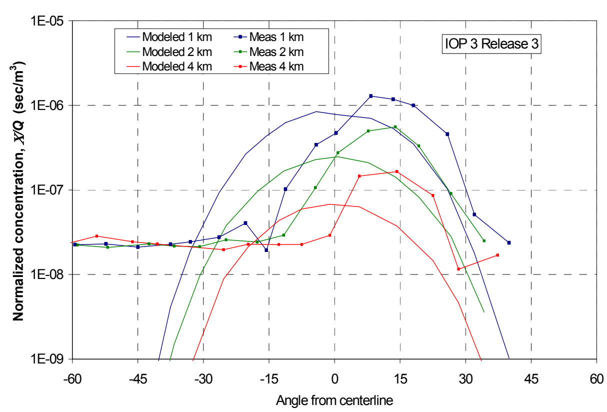

Figure 5. Normalized concentrations (X/Q) from the Gaussian model and NOAA arc measurements plotted by angle (degrees) from centerline.

highly variable when the sampler location is at a great angle to the wind vector used in the model. Figure 4 shows that either the straight line Gaussian model does not perform well at large angles from the centerline, or the samples with extremely low concentrations of SF_6 are not accurately analyzed.

Also noticeable in Figure 4 is a curvature in the cloud of points from the NOAA arc samplers. That is, the modeled-to-observed ratio is often greater than one to the left of the centerline (angle about -15°), and less than one to the right (angle about +15°). Figure 5 illustrates this offset between the modeled and measured plumes. Although this figure shows data from a single release (IOP 3, release 3), similar results can be found in many other releases. The offset may indicate a consistent curvature in the actual plume as it travels from the urban center to the 1-, 2-, and 4-km arcs.

Figure 5 also shows that many samples taken by the NOAA arc samplers were very close to the minimum level of detection. This is a problem that many researchers are faced with. The concentration of SF_6 in these samples is a few parts per trillion, a very low concentration.

6. CONCLUSIONS

A simple analytical model for dispersion was compared against tracer measurements made during the JU2003 field experiment. Discrete locations were compared, not the maximum concentration found on an arc. Further work on this data set may include analysis of centerline concentrations, although this analysis would avoid including wind direction, the most important parameter for dispersion modeling.

The same Gaussian model was used with alternative formulations for plume width and height (Eq. 1). These results are not presented here in favor of brevity. The formulas recommended by Briggs for urban conditions, and published in Hanna et al. (1982), did not perform well with the JU2003 dataset. The values of plume width and height were much smaller that those provided by Eq. 1. It may be that the near-surface releases among the buildings divided the plume much more than predicted.

Figures 4 and 5 suggest that the simple straightline Gaussian model may be improved with a curvature applied to the centerline. The curved centerline may be created with an urban flow model or empirically through tracer studies.

Although a simple Gaussian model is quick, inexpensive, and provides reasonable solutions, there are many limitations to the Gaussian model. First, it is dependent on a single wind vector. Urban wind fields are not as homogenous as open country environments, so the choice of a wind vector strongly affects the results. Second, the Gaussian model as employed here, is not defined upwind of the source. Many researchers found significant amounts of tracer upwind, especially during the Westin and Park Avenue releases. Third, a Gaussian plume model can only calculate steady state averages. It does not include the detail necessary for small time steps.

7. ACKNOWLEDGEMENTS

The author wishes to acknowledge hard work of Marty Leach, Joe Shinn, Bill Ralph, Roald Leif, Ron Pletcher, Garrett Keating, Julie Lundquist, Tom Humphries, and Branko Kosovic from LLNL and Caleb Midgley and Gabriel Rothman from Texas Tech. Invaluable were the measurements made by NOAA's Field Research Division, Dugway Proving Ground, Volpe Center of the U.S. Department of Transportation, and Arizona State University. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48. LLNL document reference number is UCRL-CONF-204906.

8. REFERENCES

Gifford, F.A., 1977: Tropospheric relative diffusion observations. *J. Applied Meteorology*, 16: 311-313.

Gouveia, F.J., and J.H. Shinn, 2002: Dense network of near-field observations of building-canopy winds and tracer concentrations during the URBAN 2000 experiment. *Proceedings of the Fourth Symposium on the Urban Environment*, 20-24 May, 2002, Norfolk, VA, 180-181.

Gouveia, F.J., M. Leach, J.H. Shinn, B. Ralph, 2004: Unique and inexpensive use of a large crane for wind and tracer profiles in an urban setting. *J. Atmos., and Oceanic Technol.*, (in press).

Hanna, S.R., G.A. Briggs, and R.P. Hosker, 1982: *Handbook on atmospheric diffusion*. DOE/TIC-11223, U.S. Department of Energy Atmospheric Turbulence and Diffusion Laboratory, Oakridge, TN.

Hanna, S.R., 2000: Alongwind dispersion–a simple similarity formula compared with observations at 11 field sited and in one wind tunnel. *J. Applied Meteorology*, 39: 1700-1714.

Hanna, S.R., R. Britter, and P. Franzese, 2002: Another simple urban dispersion model. *Proceedings of the Fourth Symposium on the Urban Environment (Joint Session)*, 20-24 May, 2002, Norfolk, VA, J15-16.

Ramsdell, J.V., and C.J. Fosmire, 1998: Estimating concentrations in plumes released in the vicinity of buildings: model development. *Atmospheric Environment*, 32: 1663-1677.

Table 1. Summary information from all the IOPs, including release location, time and amount, wind vectors (WS, speed; and WD, direction) used in the urban area and arcs, and air temperature (T).

			Release	**Release**	**Urban center**			**Arcs**		
IOP	**Release**	**Release location**	**start time (CDT)**	**amount (g)**	**Station**	**WS (m/s)**	**WD**	**WS (m/s)**	**WD**	**T (C)**
1	1	**Westin**	11:00	8820	PWIDS 08	2.4	177	2.9	175	26
1	2	**Westin**	13:00	8640	PWIDS 08	2.3	87	2.0	76	27
2	1	**Westin**	11:00	9000	PWIDS 08	2.6	213	3.7	199	30
2	2	**Westin**	13:00	9000	PWIDS 08	2.4	200	3.0	211	34
2	3	**Westin**	15:00	9000	PWIDS 08	2.0	159	2.7	174	34
3	1	**Botanical**	11:00	9000	PWIDS 11	2.0	208	4.5	194	30
3	2	**Botanical**	13:00	5400	PWIDS 11	2.2	197	3.9	187	31
3	3	**Botanical**	15:00	5400	PWIDS 11	2.3	204	4.0	190	32
4	1	**Botanical**	11:00	5580	PWIDS 11	2.3	200	3.9	201	30
4	2	**Botanical**	13:00	5400	PWIDS 11	2.6	208	4.2	182	32
4	3	**Botanical**	15:00	5400	PWIDS 11	2.5	213	4.5	187	34
5	1	**Botanical**	9:00	3960	PWIDS 11	0.9	236	2.2	205	30
5	2	**Botanical**	11:00	5400	PWIDS 11	1.5	242	3.0	194	32
5	3	**Botanical**	13:00	5580	PWIDS 11	1.5	179	2.2	162	34
6	1	**Botanical**	9:00	5400	PWIDS 11	1.2	223	2.9	201	28
6	2	**Botanical**	11:00	5760	PWIDS 11	1.9	205	3.2	180	31
6	3	**Botanical**	13:00	5400	PWIDS 11	2.0	189	2.7	177	33
7	1	**Botanical**	23:00	5400	PWIDS 11	1.2	203	2.6	183	32
7	2	**Botanical**	1:00	3600	PWIDS 11	0.7	242	2.2	195	30
7	3	**Botanical**	3:00	3600	PWIDS 11	1.3	235	2.4	216	29
8	1	**Westin**	23:00	5580	PWIDS 08	2.0	137	2.3	152	27
8	2	**Westin**	1:00	5400	PWIDS 08	1.8	149	2.0	149	26
8	3	**Westin**	3:00	5400	PWIDS 08	2.6	148	2.8	160	25
9	1	**Park Ave.**	23:00	3600	ASU	1.5	90	3.0	181	31
9	2	**Park Ave.**	1:00	3600	ASU	1.7	90	3.2	184	30
9	3	**Park Ave.**	3:00	3780	ASU	1.0	90	3.2	183	28
10	1	**Park Ave.**	21:00	3960	ASU	1.2	90	2.9	179	34
10	2	**Park Ave.**	23:00	3420	ASU	1.0	90	2.7	184	32
10	3	**Park Ave.**	1:00	3960	ASU	0.5	270	2.5	202	30

Table 2. Total number of observations (obs), number of locations downwind (DW), and number of locations with both observation and model solution.

IOP	Release	Total obs	Total valid obs	Total DW	Obs and DW
1	1	129	122	103	97
1	2	136	90	93	61
2	1	137	120	82	73
2	2	141	130	82	75
2	3	139	128	109	101
3	1	138	135	120	117
3	2	142	136	124	118
3	3	138	134	121	116
4	1	116	113	99	96
4	2	122	117	104	100
4	3	120	119	102	101
5	1	105	102	87	84
5	2	107	83	86	70
5	3	105	104	93	92
6	1	110	103	91	86
6	2	111	110	94	93
6	3	107	106	90	89
7	1	110	109	93	92
7	2	112	97	87	76
7	3	112	90	89	76
8	1	142	141	111	111
8	2	142	137	111	107
8	3	142	138	86	84
9	1	142	136	80	77
9	2	143	131	81	75
9	3	143	126	81	70
10	1	140	132	77	75
10	2	141	123	78	70
10	3	139	111	93	86
	Totals	3711	3422	2747	2568

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551