5.1 USE OF URBAN FIELD STUDY DATA

Steven R. Hanna*, Harvard School of Public Health, Boston, Massachusetts
Joseph C. Chang, George Mason University, Fairfax, Virginia

1. INTRODUCTION

The potential for the atmospheric release of chemical, biological, radiological, and nuclear (CBRN) or other hazardous materials is of increasing concern. Hazardous releases can occur due to accidents, such as the release of toxic industrial chemicals in Bhopal, India in 1984 or the Chernobyl nuclear power plant disaster in the Ukraine in 1986 or as the unintentional result of military actions, such as the U.S. destruction of rockets with chemical warheads at Khamisiyah, Iraq in 1991. More recently, military conflicts and terrorist incidents, such as the events of 11 September 2001 in New York City and Washington D.C., are occurring in urban settings with increasing regularity. The exposure of large urban populations to accidents and military or terrorist activities involving the atmospheric release of hazardous materials presents the possibility of mass casualties.

In addition to the concerns about emergency responses to terrorist releases of CBNR materials in urban areas, there is an increasing concern in environmental effects of toxics released routinely from industrial and mobile sources in urban areas.

Reliable transport and dispersion models are needed for making emergency response decisions and for planning controls for releases from routine sources at street level in a built-up downtown urban area. The wind flows as well as the characteristics of turbulent dispersion must be known. Several recent field experiments have been carried out in order to improve urban modeling capabilities and demonstrate the accuracy of their predictions. Section 2 of this paper describes the objectives of the studies and the observations made during some of these experiments, including Urban 2000 (Salt Lake City, Allwine et al., 2002), Los Angeles 2001 (Rappolt, 2001), Barrio Logan 2001 (San Diego, Venkatram et al., 2002), Birmingham 1999/2000 (Cooke et al., 2001), Basel 2002 (Batchvarova, 2003) and Joint Urban 2003 (Oklahoma City, Allwine et al., 2003). In all cases, detailed meteorological and SF_6 tracer gas observations have been made. The current paper surveys these field experiments and describes some procedures used for analysis of the data and for modification and evaluation of models.

At heights less than the building tops, the urban area is characterized by relatively low wind speeds, high turbulence intensities, and a tendency towards neutral stability (Hanna and Britter, 2002). These effects are due to the large drag on the atmosphere, the anthropogenic heat sources, and the relatively high rates of generation of mechanical turbulence by the building obstacles. In Section 3, some methods of estimating wind and turbulence profiles in urban areas are compared with the field data. Some basic characteristics of the SF_6 tracer gas releases and the monitoring data are also summarized for the field experiments and general relations presented.

As an example of the use of the field data to evaluate transport and dispersion models, Section 4 includes an overview of the evaluation of the Urban HPAC suite of models using the tracer data from the Urban 2000 experiment. The experiment consisted of six nights during which three one-hour releases of SF_6 tracer were made at ground level in the downtown area. 30-minute averaged concentrations were observed at about 70 monitors located on arcs at distances from about 150 m to 6000 m downwind. Meteorological variables were observed at over 20 sites throughout the domain, including several vertical soundings. Five alternate assumptions for wind inputs were tested. For the various Urban HPAC model combinations, the relative mean bias and relative scatter in predicted concentrations was calculated. Several individual algorithms in the model were also evaluated, such as the modules for lateral and vertical dispersion and for effective cloud transport speed.

2. DESCRIPTIONS OF URBAN FIELD EXPERIMENTS INVOLVING TRACER RELEASES

The focus of the current paper is on field studies. There have also been extensive fluid modeling studies of flow and dispersion around obstacles, but these studies are not included in the current review. In general, the fluid model and full-scale field results are consistent.

There were two fundamental tracer studies carried out in urban areas in the 1960s. The St. Louis experiments (McElroy and Pooler, 1968), sponsored by the predecessor to the EPA, became the basis for the widely-used McElroy-Pooler urban dispersion curves, as still used in the EPA's ISC model. The releases were from a point source near the ground. In general the dispersion (as measured by σ_y and σ_z) was observed to be about two or three times its magnitude in rural areas, due to the enhanced turbulence in urban areas. The Fort Wayne experiments (Hilst and Bowne, 1966), sponsored by the U.S. Army, focused on dispersion of aerosols released at a height of about 100 m from a line source upwind of the urban area. The data from these two studies are available only in hard copy reports.

Since the 1970s, there have been extensive field studies of ozone in urban areas, but these have not

*Corresponding author: 7 Crescent Ave., Kennebunkport, ME 04046; phone: 207 967 4478; fax: 207 967 5696; e-mail: hannaconsult@adelphia.net

focused on tracer releases and usually emphasize the regional nature of the problem and the importance of chemical reactions.

The Indianapolis tracer experiments, sponsored by EPRI in 1985, focused on an elevated plume from a power plant stack adjacent to the city. There was an extensive monitoring network (about 200 monitors) and many data trials (about 200 hours) during a variety of types of meteorological conditions (Hanna and Chang, 1992). These data exist in electronic format and have been widely distributed and used for model development and evaluation.

The current paper primarily concerns the new urban tracer data sets generated over the past five years, as a result of concerns about toxic pollutants in downtown urban areas. The following subsections briefly describe the Urban 2000, Joint Urban 2003, Los Angeles 2001, Barrio Logan 2002, Birmingham 1999/2000, and Basel 2002 tracer data. In later sections, further scientific and statistical analyses of the Urban 2000 and Los Angeles 2001 data sets are described.

2.1 Urban 2000 (Salt Lake City)

The Urban 2000 field experiment was conducted in downtown Salt Lake City, Utah (Allwine et al., 2002). SF_6 tracer gas was released during the night for six intensive operating periods (IOPs), where there were three SF_6 release trials in each IOP, for a total of 18 release trials. All SF_6 releases were of duration one hour from a point source or a "short" 30 m line source near street level in the downtown SLC area. Figure 1 shows the SLC metropolitan area or the "urban domain," where the release point is marked by a star near the middle of the domain, and the SF_6 monitors are marked as black dots. The 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 square area known as the Urban 2000 "downtown domain," shown in Figure 2, there were grids of samplers located on block intersections and midway along the blocks. These samplers were used by Hanna et al. (2003) to define four additional arcs at distances from about 0.15 km to 0.9 km. Therefore, a total of seven sampling arcs can be defined for Urban 2000. Some of the meteorological monitors are also shown in Figure 1. The Salt Lake City (SLC) National Weather Service (NWS) anemometer is at the airport in the northwest corner of the figure. The N01 surface anemometer, N02 sodar, and N03 profiler 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, for the SLC downtown area is about 15 m and the surface roughness, z_o, is estimated by Hanna *et al.* (2003) to be about $0.15H_b = 2.25$ m.

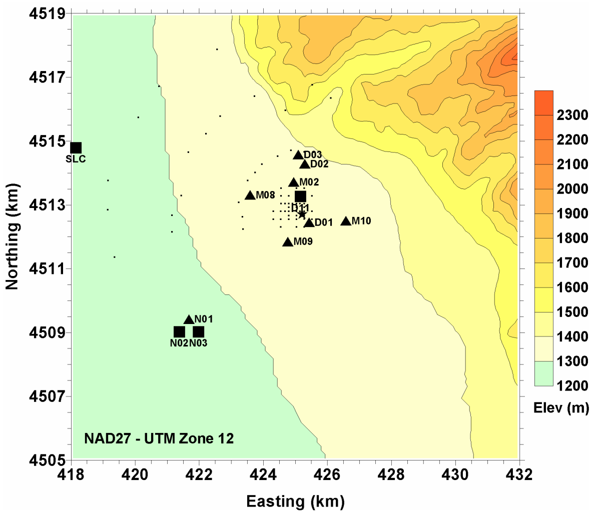

Figure 1. Map of Salt Lake City Urban 2000 domain, showing terrain elevations (m) and locations of tracer samplers (small dots) and meteorological measurement sites (triangles indicate surface sites; and squares indicate vertical profile sites, where D11 and N02 are sodar sites, N03 is a profiler site, and SLC is a radiosonde site). Also, four sonic anemometers surround (within ~ 50 m) the release point.

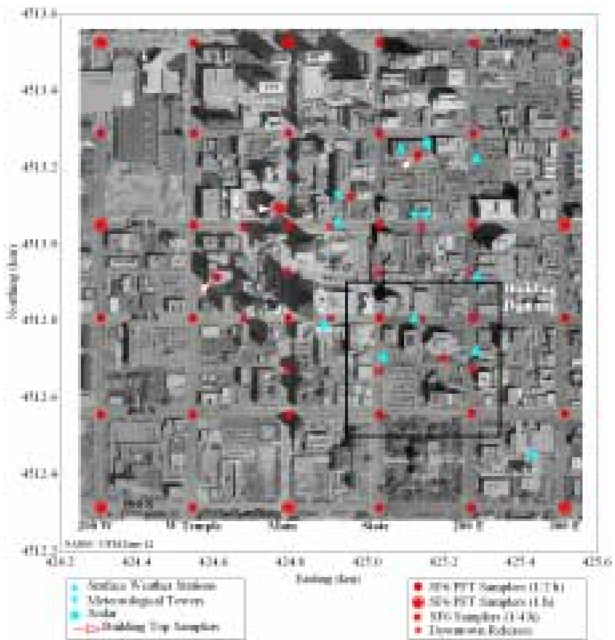

Figure 2. Map of downtown Salt Lake domain studied in Urban 2000, with locations of tracer samplers (solid dots), meteorological instruments (triangles and squares), and source (star). The odd-shaped building just north of the source is the Heber-Wells building. Figure courtesy of Allwine *et al.* (2002).

All SF_6 releases were maintained at a constant rate for one hour during each trial. For all IOPs except IOP09, the release rate was about 1 g s^{-1}, beginning at 0, 2, and 4 MST (Mountain Standard Time). For IOP09, the release rate was 2 g s^{-1} beginning at 21, 23, and 1 MST. Most SF_6 concentrations were reported as 30-minute averages over a six-hour period during each night. Additional information regarding the analysis of the Urban 2000 field data can be found in Hanna *et al.* (2003) and Chang *et al.* (2003b).

2.2 Joint Urban 2003 (Oklahoma City)

The Joint Urban 2003 (JUT) experiment took place in July 2003 in Oklahoma City, and was a follow-on to the Urban 2000 field experiment (Allwine et al., 2003). As in Urban 2000, there was an extensive network of meteorological instruments, ranging from sonic anemometers to sodars, lidars, and radar profilers. Surface energy balances were observed at several locations both inside and outside the city. In addition to the Urban 2000-like SF_6 releases in the downtown area with focus on downwind arrays of monitors, there were several intensive special studies, including a street canyon study and indoor experiments.

The data are still being QA'd and are not yet available. However, the principal investigators report that the weather cooperated and the experiment was very successful. The data should be able to be used to develop new theories and to independently evaluate existing models

2.3 Los Angeles 2001

The Los Angeles field trials were similar to the Urban 2000 field trials except that monitoring arcs could not be easily defined. Figure 3 (from Rappolt, 2001) contains a layout of the locations of the meteorological station, the 50 SF_6 monitors, and the 12 release locations. The release location was near the ground and shifted around depending on the meteorological conditions, and the 50 SF_6 monitors were permanently set up on an approximate rectangular grid. The release duration was five minutes and the SF_6 concentrations were averaged over 2.5 min for a total period of 30 min. The releases and the SF_6 monitors were close to ground level. Unlike Urban 2000, where all the releases were at night, the releases were equally split between day and night in Los Angeles.

There was only one good wind monitor, on an 8 m tower in a small downtown park.

Hanna et al. (2003) identified the monitor close to the release position that recorded the highest 2.5 min C/Q for each trial, and the monitor near the edge of the network (the 'distant' monitor) where the center of the cloud was passing out of the network. They showed that their baseline urban dispersion model was consistent with the data, as long as the model accounted for the finite duration of the release, which was less than the travel time to the farthest monitors.

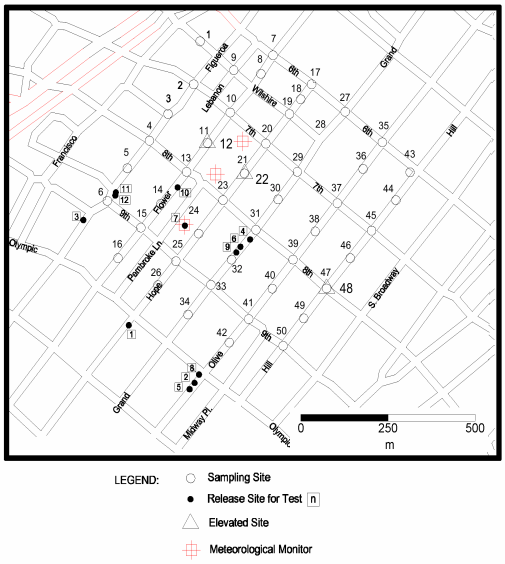

Figure 3 – Map of Los Angeles SF_6 tracer experiment site, from Rappolt et al. (2001). All samplers (marked with open circles) are near street level at height about 1.5 m, except for samplers 12, 22, and 48, which are marked with triangles and are at height 36 m. The primary wind observation site (z = 8 m) is marked by a black dot where test release 7 is shown.

2.4 Barrio Logan 2001

Venkatram et al. (2002) describe the Barrio Logan (San Diego, CA) tracer experiments, which took place during the period 21-31 August 2001. The experiment was intended to address environmental problems that occur in disadvantaged neighborhoods. Barrio Logan consists primarily of closely-packed small residences, with nearby industrial facilities. The SF_6 was released from a point, 5 m above ground, in a shipyard adjacent to the residential area, and concentrations were measured by 50 monitors on arcs at distances of 100, 500, 1000, and 2000 m. Many sonic anemometers were used to observe mean winds and turbulence.

A simple urban dispersion model was verified by Venkatram et al. (2002) with the Barrio Logan data. The basis of the model is that turbulence intensities are relatively large in urban areas and it is important to observe turbulence for input to the model.

2.5 Birmingham 1999/2000

Cooke et al. (2000) discuss the releases of two PFT tracers in Birmingham, UK. The experiment, which consisted of three days of trials in 1999 and 2000, was part of the UK Urban Regeneration and the

Environment research program, sponsored by the National Environmental Research Council. The experiments had two goals: 1) tests of the PFT release and sampling system, and 2) collection of data for model development and evaluation. There were limited numbers of samplers (5 to 10), and they were generally arranged on a single arc, about 3-4 km downwind on 1 July 1999, and about 1 km downwind on 1 Feb 2000 and 2 August 2000. The ADMS dispersion model was evaluated with the data, which are available as an electronic file.

2.6 Basel

An SF_6 tracer study took place as part of the BUBBLE urban meteorological study in 2002 in Basel ,Switzerland. Batchvarova (2003) presented preliminary results of the experiment, where the SF_6 was released continuously at rooftop-level and the monitors were also at rooftop level. Extensive boundary layer observations (e.g., many sonic anemometers and vertical profilers) were available.

3. EXPLORATORY ANALYSIS OF FIELD DATA

In most cases, the urban field experiments are intended for use in developing and evaluating transport and dispersion models. Section 4 will give an example of the evaluation of the Urban HPAC model with the Urban 2000 field data. However, it is important to first analyze the field data (i.e., exploratory analysis) to determine how well they conform to basic scientific understanding, such as whether the observed wind profiles follow expected formulations and whether the concentration distributions agree from one urban area to another. Now that we have a number of urban field and laboratory experiments in hand, it is possible to identify some fundamental scientific relations. The following subsections investigate some scientific issues in the Urban 2000 and Los Angeles 2001 field data.

3.1 Analysis of Urban 2000 Data

Section 2.1 gave an overview of the Urban 2000 field study in Salt Lake City. Some analyses of winds and concentrations are given below. Hanna et al. (2003) provide more details.

a. Wind observations

Observed wind speeds were very light (about 0.2 to 0.5 m s^{-1}) at street level (1.5 m height) and were about 1 to 2 m s^{-1} at a height of 50 m for most IOPs. Wind speeds were higher (about 1 m s^{-1} at street level and 4 to 5 m s^{-1} at 50 m) for IOPs 09 and 10. A summary of the average wind observations below and above the urban canopy layer during each IOP was made using 12 of the anemometers shown on Figure 1. There were four sonic anemometers mounted at a height of 1.5 m in the area around a large building (the Heber-Wells building in Figure 2) just downwind of the source location. All speeds and directions are vector averages. An average wind speed, based on the two "D" anemometers and the four "M" anemometers, was defined and used in subsequent analysis.

There are a few major conclusions that can be drawn from the wind data:

- IOPs 02, 04, 05, and 07 have similar low wind speeds, averaging from 0.70 to 1.07 m s^{-1}.
- IOPs 09 and 10 have moderate wind speeds, with IOP 09 averaging 2.64 m s^{-1} and IOP 10 averaging 1.72 m s^{-1}.
- The sonic anemometers at a height of 1.5 m consistently yield low wind speeds - about 0.1 to 0.5 m s^{-1} for IOPs 02, 04, 05, and 07, and about 0.4 to 1.3 m s^{-1} 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 National Weather Service (NWS) anemometer at Salt Lake City 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, σ_θ, was also calculated for each of the anemometers discussed above. As expected, for the turbulent light-wind urban canopy region, σ_θ is relatively large, with a median over all trials of about 40 degrees. σ_θ decreases to about 20 degrees for the moderate-wind period, IOP09, consistent with the known behavior of σ_θ being inversely proportional to wind speed.

Figure 4 contains observed and theoretical wind profiles (from Hanna *et al.* 2003) in part (a) for "all six IOP averages", and in part (b) for a one-hour average at time ending 00 MST in IOP09. IOP09 is the field trial 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 of about 120 m above the surface is used to define the friction velocity (u_*) for both parts of the figure. A roughness length, z_o, 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 2) with the observations.

Figure 5 shows time series of 15-minute average wind vectors for low-wind IOP07. Relatively large variability is seen, with an apparent periodicity or

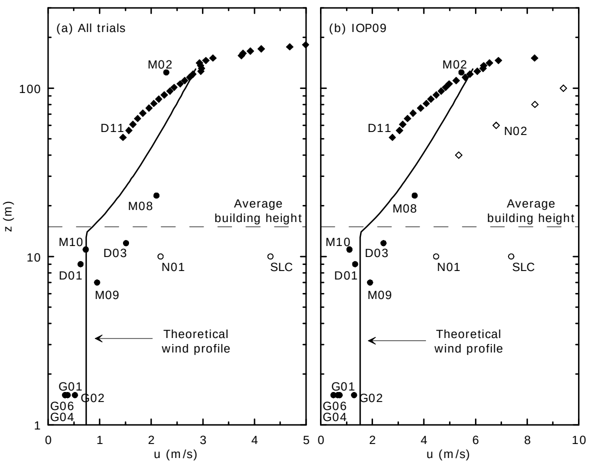

Figure 4. (a) Observed and predicted wind speed profiles averaged over all six IOPs from Salt Lake City Urban 2000. The solid symbols are monitors in the urban area. The open symbols are monitors outside of the urban area. See Figure 1 for locations. The line is a theoretical formula, assuming z_o = 2.25 m and d = 7.5 m and using the D11 sodar observation at about 120 m to estimate u_*. (b) Same format but for 00 MST during IOP09.

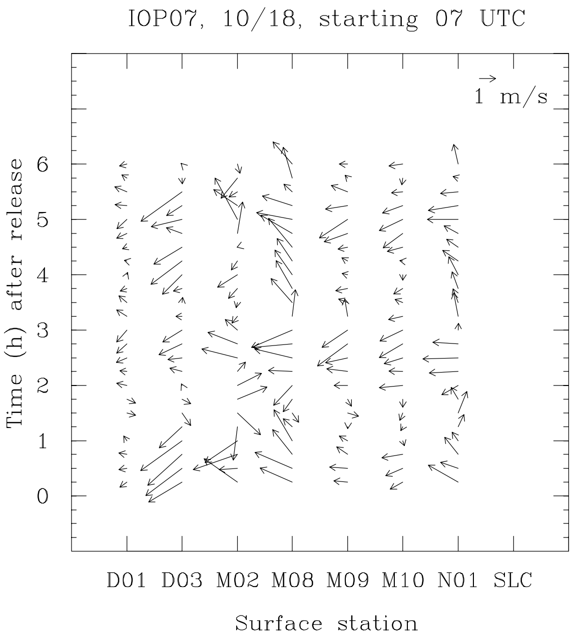

Figure 5. 15-min vector-average surface wind fields for anemometers D01, D03, M02, M08, M09, M10, and N01 for IOP07 during Urban 2000. No 15-min data are shown for SLC, because the data were only available every hour. Time refers to period ending.

"pumping" of the winds during this nighttime period. Similar variations were seen on other nights. Possible reasons for the two-hour period are the drainage flow fluctuations and "sloshing" of the stable air mass in the valley. It is suggested in Section 4 later that there was not an improvement in dispersion model predictions when all the meteorological stations are input, and this may be due to the variability seen in Figure 5.

b. Concentration observations

The distributions of the observed 30-minute average concentrations on each of the seven sampling 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 quite low (say, < 45 ppt), or there was perhaps only a single high observation, or the plume was obviously on the edge of the network. The C_{max} values for those problem trials and arcs were not used in the analysis or model evaluations based on C_{max}. The data in each IOP were also analyzed for continuity in space and time, and an example of time series of 30-minute average arc-maximum concentration normalized by the emission rate (C_{max}/Q) is given in Figure 6 for IOP04 for each of the seven arc distances. The figure shows that the three source releases (from 00 to 01, from 02 to 03 and from 04 to 05 LST) 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 ½ hours, which is consistent with the 1 m s^{-1} wind speed (it takes 1 ½ hours for the air to travel 5.4 km at a speed of 1 m s^{-1}.

Table 1 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). Note that 1 ppt = 5.45 10^{-9} g m^{-3}. The third column of the table lists the average wind speed within the urban canopy for that IOP and trial. The bottom row of the table contains the observed C_{max}/Q on each arc averaged over the 18 trials. Figure 7 presents the maximum one-hour average observed C_{max}/Q, as a function of downwind distance, x, using the numbers in the bottom row of Table 1. The mean C_{max}/Q values follow an approximate $x^{-1.5}$ power law, in agreement with observations at other field studies. The range of the 18 observations (six IOPs times three trials per IOP) at each downwind arc are also shown, where the range is determined from the 18 C_{max}/Q observations listed in Table 1 for each arc distance.

3.2 Tracer Cloud Transport in Urban 2000 and Los Angeles

For releases near the surface in built-up urban areas, much of the initial transport of the cloud occurs within the so-called urban canopy. The purpose of the

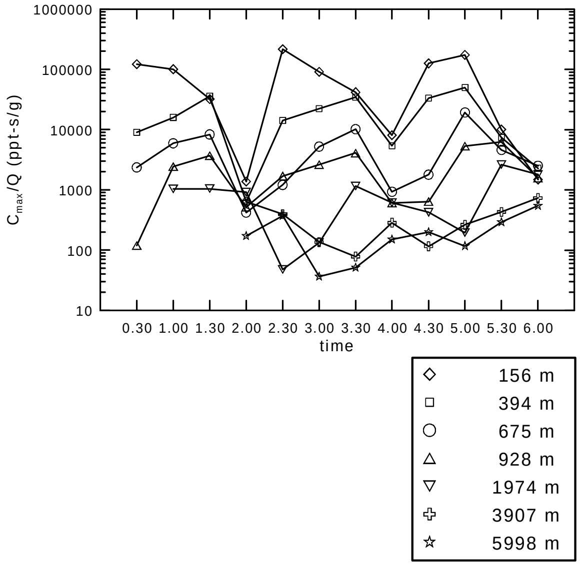

Figure 6. Time series of observed 30-minute average arc-maximum concentration normalized by the emission rate (C_{max}/Q) for IOP04 during Urban 2000, for the seven monitoring arcs, at downwind distances in meters given in the legend. SF_6 releases occurred between 0:00 and 1:00, 2:00 and 3:00, and 4:00 and 5:00 LST.

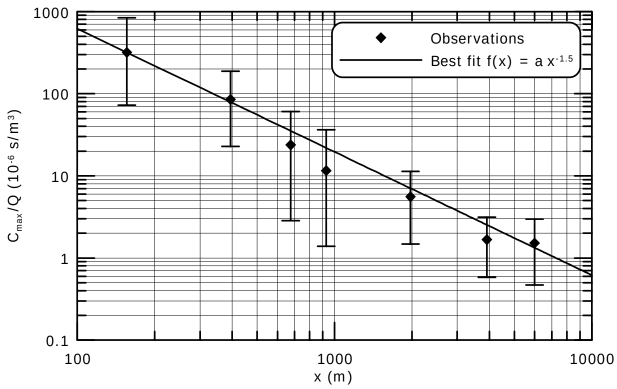

Figure 7. Urban 2000 observed hourly-average arc-maximum concentration normalized by the emission rate (C_{max}/Q) for all 18 trials for the seven monitoring arcs. Solid diamonds represent the averages over all the trials, and the range of the 18 observations is shown as the vertical bar. The solid line represents the best fit function proportional to $x^{-1.5}$. Data are in Table 1.

current subsection is to use the Urban 2000 and Los Angeles SF_6 observations to compare the SF_6 cloud speed with the observed wind speeds in the downtown urban areas. If there is good agreement, there is justification for using urban canopy wind observations in dispersion models

The Urban 2000 field trials were described above. Tracer gas releases and concentration observations were made near the ground. Figure 6 contained the time series of C_{max}/Q (in ppt-s/g) for Intensive Operating Period (IOP) 04. The cloud speeds were calculated as the distance between the 156 m arc and the arc of interest, divided by the time delay in the arrival of the peak.

Table 1. Observed hourly-average C_{max}/Q (in 10^{-6} s m^{-3}) for the seven monitoring arcs and the 18 trials at Urban 2000. The third column also lists the average wind speed within the urban canopy (*i.e.*, the average over anemometers D01, D03, M02, M08, M09, and M10). The bottom row of the table contains the observed C_{max}/Q for each monitoring arc averaged over all IOPs and trials.

			Sampling Arc and Distance (m) From Source						
IOP	Trial	u	Arc 1	Arc 2	Arc 3	Arc 4	Arc 5	Arc 6	Arc 7
		(m s^{-1})	150	400	700	900	2000	4000	6000
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 over all IOPs and trials		1.39	317.9	84.9	23.8	11.6	5.56	1.67	1.52

For each of the 18 release trials in Urban 2000, an average wind speed was calculated based on the observations at six locations on building tops (heights ranging from 7 to 122 m with a median of about 12 m) in the downtown area. Observed wind speeds at SLC were very light (about 1 m/s) for most IOPs and slightly higher (about 2 m/s for IOPs 09 and 10. With a 1 m/s wind speed, the cloud would take 6000 sec or 100 minutes to travel to the 6000 m arc, in rough agreement with the delay seen in Figure 6. Cloud speed estimates could be confidently made for about 30 % of the trials and arcs. The average observed wind speed and the average observed cloud speed are very close (1.39 m/s vs 1.35 m/s). The observed cloud speeds are largest for trials 9 and 10, when the observed wind speeds were also largest.

The Los Angeles field trials were similar to the Urban 2000 field trials except that monitoring arcs could not be easily defined. Hanna et al. (2003) identified the monitor close to the release position that recorded the highest 2.5 min C/Q for each trial, and the monitor near the edge of the network (the 'distant' monitor) where the center of the cloud was passing out of the network. The cloud speeds were calculated as the distance between the close and distant monitors, divided by the time delay in the arrival of the peak C/Q. Since most observed wind speeds (from the anemometer at z = 8 m) were about 1 m/s, the cloud would take about 600 sec (10 min) to travel the distance from about 50 m to about 650 m. The observed cloud speeds and wind speed are listed in Table 2, showing that the average observed wind speed and average observed cloud speed are very close (1.18 m/s vs 1.1 m/s). The ranges in speeds are also similar, and the three trials (6, 11, and 12) with the largest wind speeds are also the trials with the largest cloud speeds.

Table 2. Observed wind speeds and cloud speeds in Los Angeles for 11 SF_6 tracer release trials. The release duration was always 5 minutes, starting at the time indicated, and the location varied as seen in Figure 3. Winds are averaged over ten minutes beginning when the release started. Averaging period for the SF_6 observations is 2.5 minutes. Cloud speeds are estimated from the arrival times of the peak C_{max}/Q at the close and distant monitors.

Trial	Rel. Time PDT	Obs u m/s	Close Mon. with C_{max}	Close Arr. Time min	Close Mon. Dist. m	Distant Mon. With C_{max}	Distant Arr. Time min	Distant Mon. Dist. m	Cloud Speed m/s
1	4	1.12	34	12.5	150	43	30	950	0.76
3	4	0.98	15	7.5	150	17	22.5	800	0.72
4	10	1.07	32	7.5	70	16	15	400	0.73
5	4	0.9	32	7.5	300	10	22.5	800	0.56
6	10	1.61	32	7.5	50	3	10	420	2.47
7	4	0.9	23	5	100	35	22.5	700	0.57
8	8	0.98	34	10	120	3	17.5	750	1.4
9	4	0.67	31	12.5	70	29	25	270	0.27
10	8	1.3	13	7.5	50	35	20	650	0.81
11	16	2.24	5	10	70	18	15	630	1.87
12	4	1.16	5	7.5	70	35	17.5	800	1.22
Average		1.18			110			650	1.1

It is concluded that, based on the Urban 2000 and Los Angeles observations, the tracer cloud travels with approximately the same speed as the observed wind speed in the urban canopy. These conclusions can be used in the development of transport and dispersion models, since they provide justification and confidence in the use of observed urban canopy winds in the models.

4. EVALUATION OF URBAN HPAC WITH URBAN 2000 DATA

The HPAC dispersion model (DTRA, 2001) is widely used for assessments of possible impacts of chemical and biological agent releases by terrorists. HPAC is based on the Second-Order Closure Integrated Puff (SCIPUFF; Sykes *et al.* 2000) dispersion model. HPAC has been recently been upgraded to apply to urban areas, referred to as Urban HPAC, and now includes the Urban Wind Field Model (UWM; Lim *et al.* 2002) and the Urban Dispersion Model (UDM; Hall *et al.* 2002). UWM is used as a low-resolution computational fluid dynamics (CFD) model. UDM uses empirical parameterizations to account for the effects of individual buildings on the transport and dispersion of atmospheric releases within or upwind of urban domains. UDM is used at short range (downwind distances less than 1 km), where the effects of individual buildings must be considered, and SCIPUFF is used at longer range (downwind distances greater than 1 km), where the vertical scale of the disseminated clouds is much higher than the urban roughness elements and it is necessary only to parameterize the effects of urban roughness on wind and turbulence profiles.

Urban HPAC has two alternate diagnostic wind models, SWIFT (Stationary Wind Fit and Turbulence) and MC-SCIPUFF (Mass-Consistent algorithm in SCIPUFF). SWIFT is the default choice for Urban HPAC. Neither SWIFT nor MC-SCIPUFF accounts for wind speed profiles in urban canopies.

In addition to the UWM and UDM algorithms in urban HPAC, a simplified version of Urban HPAC exists where SCIPUFF was extended for urban applications by accounting for urban canopy wind profiles (Cionco 1972).

Urban HPAC model has been evaluated using the Urban 2000 field data and details of the study are described in a comprehensive project report (Chang *et al*. 2003). The current paper provides a summary of the procedures and the results.

4.1 Model Configuration and Meteorological Input Data Options

As described above, a number of enhancements, such as the urban canopy parameterization in SCIPUFF, the UDM module, and the UWM module, have been implemented in order to provide HPAC with urban modeling capabilities. In order to evaluate the performance and adequacy of these enhancements in a comprehensive way, four optional

Urban HPAC configurations were explored. Option UC refers to the "baseline" case, *i.e.*, SCIPUFF with its urban canopy parameterization. For option DM, the UDM module was invoked for the dispersion calculations over the 2 × 2 km urban sub-domain, where the UWM module was not invoked. For option WM, the UWM module was invoked for the flow calculations over the 2 × 2 km urban sub-domain, where the UDM module was not invoked. For option DW, both the UDM and UWM modules were invoked for the dispersion and flow calculations, respectively, over the 2 × 2 km urban sub-domain.

In addition to the above four model configuration options, five realistic meteorological input options (ranging from data sparse to data rich scenarios) were also considered. For Option SLC, airport data were used. As seen in Figure 1, the SLC airport is located about 10 km from the downtown area. Option LDS used the wind data from the top of the tall (122 m) LDS building. Option RGW used a single upwind profile (from the Raging Waters site) for urban modeling, therefore testing the ability of Urban HPAC to adjust the upwind flow pattern when approaching an urban area. Option ALL used all downtown wind monitors seen in Figure 1. Finally, Option OMG used the outputs of the OMEGA mesoscale meteorological model.

A total of 20 combinations of the model configuration options and the meteorological input options were considered. Consequently, 20 sets of Urban HPAC predictions were generated for the 18 SF_6 tracer release trials during the Urban 2000 field campaign. Table 3 summarizes the keywords used throughout this paper to indicate various model and weather options, and their combinations. Because there was no *a priori* guidance on which model option or meteorological input option should be considered to be the optimum combination, this evaluation exercise is therefore also a sensitivity exercise. Most of the results are given as a range over the 20 model combinations.

Table 3. Keywords for the four Urban HPAC model configuration options and the five meteorological input options, and the resulting 20 combinations, used in the evaluations with Urban 2000 data.

	Urban HPAC Configuration Options			
Met Input Opt.	UC	DM	WM	DW
SLC	UC_SLC	DM_SLC	WM_SLC	DW_SLC
LDS	UC_LDS	DM_LDS	WM_LDS	DW_LDS
RGW	UC_RGW	DM_RGW	WM_RGW	DW_RGW
ALL	UC_ALL	DM_ALL	WM_ALL	DW_ALL
OMG	UC_OMG	DM_OMG	WM_OMG	DW_OMG

4.2 Model Performance Evaluation Methodology

Standard statistical measures have been used in this study to appraise model performance. The evaluations of Urban HPAC followed procedures developed and published by the authors over the past ten years (*e.g.*, Hanna *et al.* 1993, Chang and Hanna 2003).

In order to evaluate the predictions of a model with observations, Hanna *et al.* (1993) recommend the use of the following statistical performance measures, which include the fractional bias (FB), the geometric mean bias (MG), the normalized mean square error (NMSE), the geometric variance (VG), the correlation coefficient (R), and the fraction of predictions within a factor of 2 of observations (FAC2):

$$FB = \frac{\left(\overline{C_o} - \overline{C_p}\right)}{0.5\ \left(\overline{C_o} + \overline{C_p}\right)} \tag{1}$$

$$MG = \exp\ \left(\overline{\ln C_o} - \overline{\ln C_p}\right) \tag{2}$$

$$NMSE = \frac{\overline{\left(C_o - C_p\right)^2}}{\overline{C_o}\ \overline{C_p}} \tag{3}$$

$$VG = \exp\ \left[\overline{\left(\ln C_o - \ln C_p\right)^2}\right] \tag{4}$$

$$R = \frac{\overline{\left(C_o - \overline{C_o}\right)\left(C_p - \overline{C_p}\right)}}{\sigma_{C_p}\sigma_{C_o}} \tag{5}$$

$$FAC2 = \text{fraction of data with } 0.5 \le \frac{C_p}{C_o} \le 2.0 \tag{6}$$

where C_p is model predictions, C_o is observations, overbar ($\overline{C}$) is the average over the dataset, and σ_C is the standard deviation over the dataset.

A key question of the study is whether the Urban HPAC performance meets criteria for model acceptance. Chang and Hanna (2003) have estimated the criteria for an "acceptable" model, based on the evaluations by them and by others of many models with many field data bases. For example, a "good" or "acceptable" model would have a relative mean bias (FB) with magnitude ranging from –0.7 to +0.7 (plus and minus a factor of 2), a relative mean square scatter (NMSE) of less than about 4 (corresponding to scatter equal to two times the mean), and the fraction of predictions within a factor of 2 (FAC2) more than about 0.5. These suggestions are for maximum concentrations at given arc distances, and the criteria should be relaxed somewhat if the data are paired in time and space.

4.3. Results of Statistical Evaluation of Urban HPAC

Because 20 possible ways of running Urban HPAC were considered (see Table 3), *i.e.*, combinations of four model configuration options and five meteorological input data options, it is of interest to determine the range of model performance measures over the 20 runs, and whether there are large differences in the performance measures for various combinations of options. Furthermore, it is also possible to determine which model combinations yield more satisfactory results for Urban 2000.

With any statistical methodology for evaluating model performance, there are many ways to define the model outputs to be used. For example, one can perform paired-in-space-and-time comparisons, or unpaired-in-space-and-time comparisons. The current paper uses two options for data pairing: single overall maximum anywhere in the domain and over all the IOPs, and the maximum concentration along each arc (defined below) and for each IOP. The longer report (Chang et al., 2003) also considers the paired-in-space-and-time comparisons based on the data from all the sampler locations and time periods. The current paper uses averaging times of 30-min, and the longer report also considers 2-hr dosages.

The SF_6 concentrations from 66 whole-air samplers were included in the evaluation. These 66 samplers were further grouped according to seven arc distances ~150, 400, 700, 900, 2000, 4000, and 6000 m from the source. The first four arcs are considered to be in the downtown domain (Figure 2) and the last three arcs are in the general urban domain defined in Figure 1.

The simplest comparison is of the single, unpaired in time and space, maximum observed 30-min averaged concentration anywhere on the monitoring arcs over all the IOPs. In other words, the single maximum value is selected from observations and predictions from each of the 20 model combinations. This maximum concentration is of importance because it defines the maximum expected health impact to an individual. These maximum values always occur on the closest (x ~150 m) monitoring arc. The observed maximum concentration is 173430 ppt. For each model configuration option, there are five weather input options. Table 4 lists the median and the range of the five predictions (due to different weather inputs) for each model option. It is seen that the DM and DW model configuration options produce predictions of the overall maximum that are always within a factor of 2 of the observed maximum. The UC and WM model configuration options tend to overpredict by a factor of 2 to 3, because these options do not account for the enhanced dispersion due to buildings and obstacles. This trend will be seen to continue with the evaluations based on other options of data pairing.

Consider the predicted and observed arc-maximum for each IOP, paired only by arc distance and by IOP (date). In this case, the maximum 30-min concentration along each of the seven arcs is selected for each of the six IOPs for observations and predictions. Therefore, the total number of data points involved is 42 (= 7 arcs $\times$ 6 IOPs).

Table 4. Median and range (over the five weather options) of the overall maximum predicted 30-min SF_6 concentrations anywhere in the domain and over all the IOPs during Urban 2000 for each Urban HPAC model configuration option.

Urban HPAC Model Configuration Option	Median (ppt)	Range (ppt)
Urban Canopy (UC)	450350	60270 to 969170
Urban Dispersion Model (DM)	142800	93600 to 230730
Urban Wind Model (WM)	412420	136370 to 505910
Urban Dispersion and Wind Field Models (DW)	216750	146800 to 287030

Figure 8 provides a concise summary of the FB, NMSE, MG, and VG, together with their confidence intervals, for the for 20 Urban HPAC combinations based on the arc-maximum concentrations for each IOP. When all 20 model combinations are considered, the fractional bias, FB, has a median of –0.37 (*i.e.*, ~50% mean overprediction) and, ignoring the outlier, a range from –0.02 to –1.17 (*i.e.*, between a 2% and a factor of 4 overprediction). The FB = +0.73 on the figure for the UC_OMG combination (the urban canopy algorithm coupled with the OMEGA profiles) is an outlier, and indicates a mean underprediction of roughly a factor of 2. The median MG is 0.49, also suggesting a median overprediction bias of about a factor of 2. The range in MG is 0.24 to 0.75, corresponding to between a 33% and a factor of 4 mean overprediction. Note that although both FB and MG are meant to indicate a degree of mean bias, the former is based on a linear scale, whereas the latter is based on a logarithmic scale.

Except for the outlier (the UC_LDS combination), the median NMSE is 1.7 with a range from 0.8 to 6.8, implying a median random scatter of roughly a factor of 3. The range in NMSE is 0.8 to 6.8, implying a random scatter of about a factor of 2 to 9. For all the 20 model combinations, the values of VG are between 1.9 and 16.5, *i.e.*, between a factor of 2 and 5 random, with a median scatter of a factor of 3. Again, note that NMSE is based on a linear scale, whereas VG is based on a logarithmic scale These results are fairly consistent across all model options. Note that these median biases and scatters are within the model acceptance criteria suggested by Chang and Hanna (2003) and listed earlier.

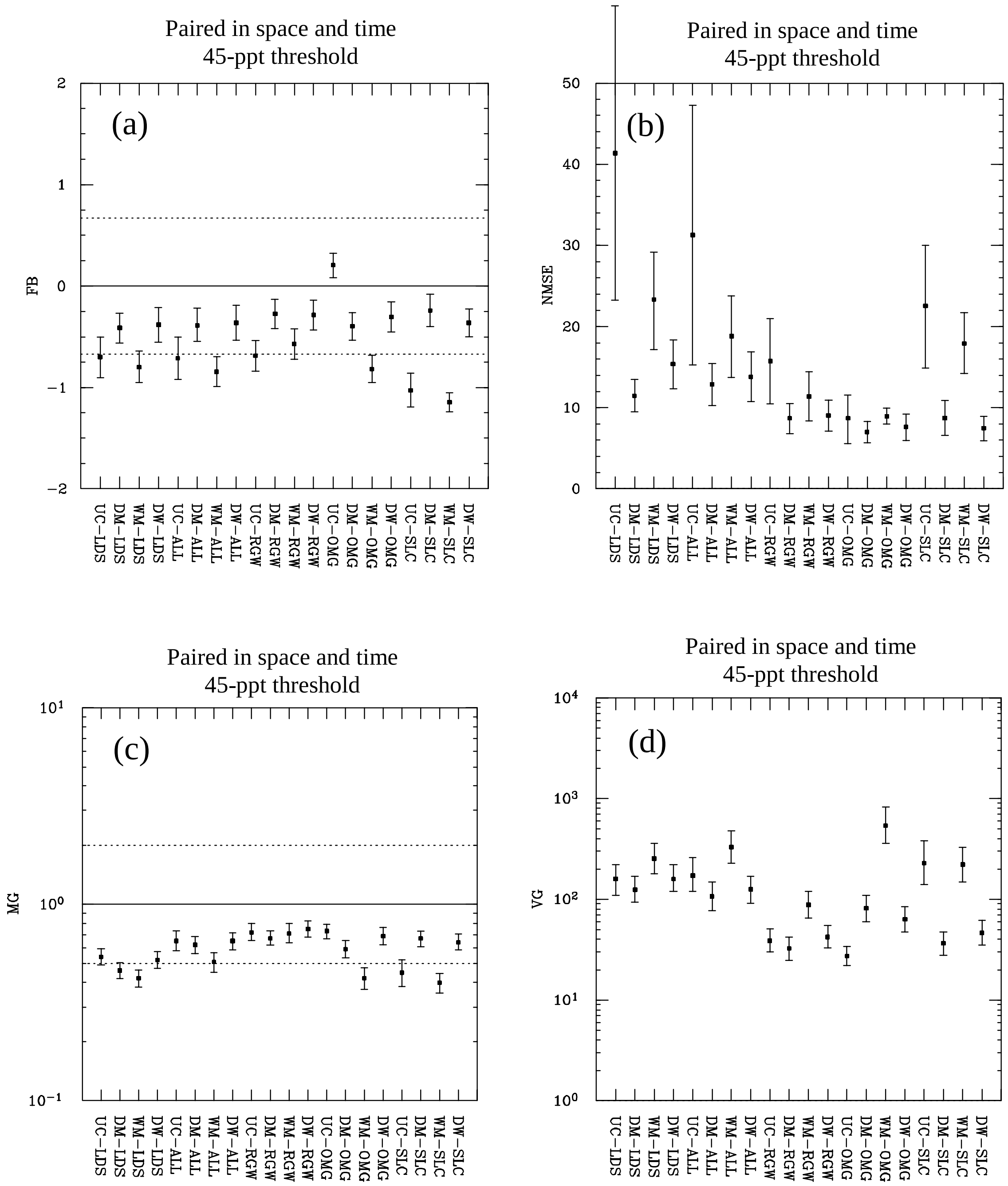

Figure 8. (a) FB, (b) NMSE, (c) MG, and (d) VG for Urban HPAC options evaluated with Urban 2000 data, together with their confidence intervals based on 30-min SF_6 concentration paired in space and time with a lower data acceptance threshold of 45 ppt, for each combination of model and meteorological input data options (20 combinations in total).

Figure 8 does not contain the FAC2 (fraction of predictions within a factor of 2 of observations) information. The median FAC2 for the 20 model combinations is ~40% with a range between 5% and 58%. The median FAC2 is also comparable to the range of acceptable model performance.

It is concluded that, for all the 20 model combinations considered in this study, the DM_RGW model combination (*i.e.*, UDM coupled with the upwind Raging Waters wind input) has slightly better performance, followed closely by the DM_SLC model combination (*i.e.*, UDM coupled with the Salt Lake City airport observations), and the DW_RGW model combination (*i.e.*, UDM and UWM coupled with the upwind Raging Waters wind input). On the other hand, the UC_SLC model combination tends to show larger, factor of 2 to 4 mean overpredictions. Note that, without the "urban" upgrades (*i.e.*, the Urban Dispersion Model and/or the Urban Wind Field Model) and onsite, research-grade meteorology, the operational mode of HPAC is equivalent to the UC_SLC model combination (*i.e.*, basic urban canopy algorithm coupled with the airport weather data).

In can also be seen from Figure 8 that overall, the DM model configuration option yields slightly better performance (*i.e.*, less overprediction) than the WM and UC model options. The RGW weather option generally leads to better model performance, whereas the OMG weather option also leads to better agreement, except for the UC_OMG outlier. The LDS weather option with data from downtown Salt Lake City and the ALL weather option with data from many stations, including downtown, did not improve the model performance, which was an unexpected result. A possible reason is that the downtown observations exhibited relatively large fluctuations in wind direction and speed, which caused the predicted plume to be spread out too much. Actually the σ_y evaluations reported above confirmed the tendency to overpredict σ_y when the LDS or ALL weather inputs are used. As just mentioned, the use of the OMEGA mesoscale meteorological model outputs with average 2-3km horizontal grid resolution (the OMG weather option) led to mixed results.

4.4 Scientific Evaluation of Urban HPAC Algorithms

The scientific evaluation of Urban HPAC in this study consisted of assessments of model components such as cloud speed, vertical and lateral cloud spread, and wake retention time. These variables are sometimes called "intermediate variables" since they are not directly output by the model but have to be inferred from concentration predictions.

The lateral plume width, σ_y, was estimated from the concentration predictions on the six to ten samplers on a given arc distance. The maximum concentration, C_{max}, was identified and then the distance to the estimated point of $C_{max}/10$ on either side of the plume was estimated. σ_y was then estimated based on the known distance to $C_{max}/10$ in a Gaussian distribution. The vertical plume depth, σ_z, could not be estimated in such a way because of insufficient data coverage in the vertical direction. The analysis of vertical depth was based on the ratio of concentration at the building top to concentration at ground level for predictions and observations. The cloud speed was estimated by studying time series of 30-minute average C_{max} on each monitoring arc, and estimating the delay between the time of observed cloud peak at distant arcs and that at close arcs. The wake retention time was estimated by determining the rate of decrease of concentration in the above-mentioned time series at the closest (x ~150 m) arc.

The inspection of derived quantities or intermediate model outputs to better understand model behavior shows that for the lateral distance scale of the concentration distribution (σ_y), the values of FAC2 for all 20 Urban HPAC model combinations are 0.5 and higher, except for the UC_SLC option (*i.e.*, the urban canopy parameterization coupled with the meteorological data from the SLC airport) whose FAC2 is 0.333. In the UC_SLC runs, σ_y is overpredicted on average by a factor of 2.

A limited evaluation of the vertical dispersion was carried out. There were only three sites where concentrations were measured on building tops (heights of 36, 56, and 64 m) and concentrations were also measured at ground level not too far from the buildings. However, there was a ~100-m horizontal displacement between the building-top samplers and the nearby ground-level samplers. The median ratio of the observed concentration at the building top to that at ground level is about 0.5. This implies that σ_z is about 30 to 50 m at a distance of about 200 m downwind of the source. Most model combinations provide rough agreement with the observations. For example, the DM_RGW option (*i.e.*, UDM coupled with the meteorological model at the Raging Waters site) predicts a ratio of 0.6. The value of σ_z is consistent with standard McElroy-Pooler urban σ_z curves derived from tracer observations in St. Louis in the 1960's (McElroy and Pooler 1968).

Comparisons were made of observed tracer cloud speeds with Urban HPAC predicted cloud speeds for each of the IOPs. The cloud speeds were estimated by determining the delay in arrival time of the cloud at various downwind monitoring arcs. It was found that there was good agreement (*i.e.*, within a factor of 2 most of the time and with little mean bias).

In addition, the time series of observed concentrations on the closest monitoring arc (x ~150 m) were studied to determine the typical time scale associated with the decrease in concentration after the release ceased in each trial. Typically the e-folding time scale is about 30 to 60 minutes. This is a factor of 30 or more larger than the building wake retention time scale in UDM. However, the difference is probably due to the relatively low wind speeds in Urban 2000, which upwind dispersion to be important and contribute to the slow decrease in concentration after the release ceases.

5. CONCLUSIONS

Thanks to the availability of many recent urban field experiments with tracer gas releases in downtown built-up areas, including observations of concentrations by extensive monitoring networks, and detailed supporting meteorological observations, it is possible to identify fundamental physical relations governing flow and dispersion in urban areas. The field data can also be used to evaluate and improve a variety of urban dispersion models. This has allowed development and demonstration of the performance of new models used for estimating the health effects of terrorist releases of chemical and biological agents in urban downtown scenarios, and used for estimating the environmental impacts of toxic pollutants routinely released by mobile sources and commercial/industrial sources in downtown areas.

This paper provides summaries of the tracer experiments and the supporting meteorological information from several urban field experiments carried out in the past five years, including Urban 2000 (Salt Lake City), Los Angeles 2001, JUT (Oklahoma City, 2003), Barrio Logan (San Diego, 2002), Birmingham 2000, and Basel 2002. Examples are given of ways of analyzing and plotting the tracer and meteorological data to derive fundamental physical relations. For example, it is demonstrated that observed concentrations from near-ground releases vary with downwind distance raised to a power between –1.5 and –2, that observed cloud speeds agree with averaged wind speeds in the urban canopy, that observed winds in and above the urban canopy layer conform to standard theoretical wind profile relations, and that enhanced turbulence in urban areas causes relatively large plume lateral and vertical spread.

As an example of the use of the new urban field data, the Urban HPAC dispersion model is evaluated using data from Urban 2000. Several urban options and meteorological input options are tested. This paper focuses on the maximum 30-minute averaged SF_6 concentration on each of seven monitoring arcs during an Intensive Operating Period. The evaluations include both statistical and scientific components, and comparisons with model acceptance criteria determined from previous evaluations with other models and field data sets. The statistical evaluations show that the predictions of the model options were within the range of acceptance, with relative mean bias showing about a 50 % overprediction, and with about 40 % of the predictions within a factor of two of the observations. Unexpectedly, the use of the many downtown wind observations does not improve the performance, possibly because of the stochastic variability of the winds at the individual sites. The scientific evaluations show that the model's estimates of lateral and vertical dispersion and cloud speed are also within acceptance bounds. However, given that concentrations are often observed to only slowly decrease near the source with time after the source release is turned off, it is unclear whether the dominant cause is upwind dispersion or entrainment in building wakes.

Clearly there is a wealth of new urban data available from many locations, and the analyses performed so far have only scratched the surface of the large data sets. Significant advances in knowledge are anticipated over the next few years as these urban data are more thoroughly analyzed. Furthermore, additional urban field experiments are now underway or are planned in cities such as London and New York City, and we look forward to adding these data from "very large" cities to the growing urban data base.

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