SOME PLUME DISPERSION HIGHLIGHTS FROM JU03 AND URBAN 2000

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1. INTRODUCTION

Plume dispersion in an urban environment is affected by many factors that can complicate the reliable prediction of plume behavior and assessment of the potential hazards. This includes the features of the urban canopy itself (e.g., irregularly different heights, widths, geometries, building aspect ratios, street layout) plus complications imposed by complex terrain (e.g., topographic variation, land-sea breezes) and variations in the approach flow related to mesoscale factors. There have been numerous urban dispersion field, laboratory, and numerical modeling studies conducted in recent years that have yielded a wealth of data about the behavior of plumes in the urban environment. Nevertheless, some aspects of urban plume dispersion have received relatively lesser attention and enough uncertainties still exist such that there is still room for the element of surprise. This paper will first highlight some plume concentration fluctuation results from JU03 in Oklahoma City with special emphasis on the potential roles played by time of day, stability, and wind meander. Second, it will show results from URBAN 2000 in Salt Lake City that will make clear the possibility for unexpected plume behavior in an urban environment featuring complex terrain in stable atmospheric conditions. Both sets of results have significance for the assessment of potential hazards in emergency response situations.

Joint Urban 2003 (JU03) was a comprehensive field campaign designed to study the transport and diffusion of pollutants in an urban boundary layer. Its major components were: (1) a major program of meteorological measurements for understanding mean and turbulent flow conditions in the urban boundary layer (Brown et al. 2004a; Hanna et al. 2007; Nelson et al. 2007; Ramamurthy et al. 2007); (2) a major program of tracer concentration measurements for tracking the dispersion of a pollutant in this environment (Clawson et al. 2005); and (3) an extensive modeling effort designed to improve the ability to predict the movement of toxic plumes in urban environments using the meteorological and tracer concentration databases generated (e.g., Burrows et al. 2007; Chan and Leach 2007; Hendricks et al. 2007). JU03 was conducted from June 28 through July 31, 2003 in Oklahoma City, Oklahoma, situated on the southern U.S. high plains, and was focused in the consolidated core of tall buildings that comprise the downtown Central Business District (CBD). The emphasis was on the effects of the urban canopy and of the thermal regime (night and day) on plume dispersion. A complete summary of this study has been provided by Allwine et al. (2004) and Allwine and Flaherty (2006), while the complete JU03 database is available from a website maintained by Dugway Proving Grounds (https://www.ju2003-slc.org).

Health effects associated with the inhalation of chemical, biological, or other toxic agents are related to the length of exposure, the concentration during the time of exposure, and the specific level of toxicity associated with a given agent. Toxicity assessments are often made in the context of Haber's Law, which relates a specified level of physiological response to a toxin, k, to the product of the concentration, c, and exposure time, t (i.e., $ct = k$) (Witschi 1999). While the use of Haber's Law has been widespread, it is now believed that it is just a special case for relating c and t to k and is not universally applicable (Miller et al. 2000). There is a considerable body of evidence that suggests it underestimates the risk associated with short-term exposures to high concentrations (EPA 1999).

A more accurate and broadly applicable means of assessing the danger posed by exposure is through the concept of dosement. Dosement (D) can be expressed as $c^n t$ (Ride 1984; ten Berge et al. 1986; Fairhurst and Turner 1993), where n is a species toxicity factor. For varying concentration, dosement can be expressed as $D = \int [c(t)]^n dt$. It has also been found that toxicity is related to the intensity of the concentration fluctuations. Given the same mean concentration over a specified interval of time, the potential toxic effects associated with a highly fluctuating concentration signal can be greater than for an equivalent uniform signal (Ride 1984). In fact, peak concentrations are considered to be the most important factor in the determination of acute toxic responses in short-term exposures (Kodavanti et al. 1997; EPA 1999; Witschi 1999). The JU03 fast-response tracer measurement database is an excellent resource for providing a means of studying plume concentration fluctuations, a significant factor in evaluating the hazard posed by a plume of toxic material.

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The Vertical Transport and Mixing (VTMX) (Doran et al. 2002) and URBAN 2000 (Allwine et al. 2002) were nocturnal experiments conducted in the Salt Lake Valley in October, 2000. The combined effort was designed to generate tracer and meteorological datasets for developing pollutant dispersion models for use at a range of scales in complex terrain at night. VTMX was a larger scale perfluorocarbon tracer and meteorological study that examined the complex wind field and tracer transport mechanisms across the Salt Lake Valley as a whole. URBAN 2000 was spatially nested within the VTMX experiment and focused on how sulfur hexafluoride (SF_6) tracer released from a site in the downtown area moved through the urban core and out into the neighboring suburbs. As such it featured both urban canopy and topographic effects.

By design the tracer was to be released at a site in the downtown area and transported by southeasterly (typically drainage flow) winds toward samplers mostly arrayed across the central downtown area and in the suburbs to the west and north. A few samplers were also located to the south and east of the release to confirm that the tracer was all dispersing in accordance with prediction. Plume dispersion commonly occurred as expected with drainage flows transporting the plume toward the west and northwest. However, sampling to the south and east of the release site did identify some unexpected dispersion events. It is these events that will be the emphasis of the presentation.

2. EXPERIMENTAL METHODS

During JU03 ten experiments (intensive observational periods – IOPs) were conducted during which the inert tracer gas sulfur hexafluoride (SF_6) was released from several curbside locations in the CBD at a height of 2 m and concentrations measured downwind. There were six daytime IOPs (1-6) and four nighttime IOPs (7-10), with each IOP consisting of three continuous point-source releases lasting 30 min each and up to six instantaneous puff releases.

Two high temporal resolution tracer concentration datasets were collected. One dataset was collected on an array with nine fixed and one mobile, van-mounted, fast-response SF_6 tracer gas analyzers (TGA). Sampling was done through an inlet atop each van at about 2 m above ground level (a.g.l.). The nine fixed TGAs used in the present analysis were deployed downwind of the release site at distances mostly between 175-600 m. The TGA analyzers have an approximately 1 s response time (Benner and Lamb 1985) and data were acquired at a rate of 2 Hz during measurements. The other dataset was based on up to 10 fast-response Miran real-time analyzers deployed at ground level in the immediate vicinity of the SF_6 release site at distances ranging from 25-150 m and mostly within line of sight of the release. The typical data acquisition rate was about 0.9 Hz.

A third tracer dataset was based on time-averaged concentration bag sampling measurements taken with programmable integrating gas samplers (PIGS), usually integrated over 15-min periods. In the CBD, 55 of these samplers were deployed on a high-density, street-level grid on utility poles at 3 m a.g.l., 10 on rooftops, and four in an underground tunnel system. An additional 65 PIGS were deployed on downwind sampling arcs at distances of 1, 2, and 4 km in surrounding residential areas. A detailed summary of the tracer release system and SF_6 tracer gas measurement instrumentation can be found in Clawson et al. (2005).

Six sets of SF_6 tracer gas release experiments (IOPs) were conducted during URBAN 2000. All experiments were conducted between the hours of 2200 and 0700 Mountain Daylight Time (MDT) in October, 2000 in Salt Lake City. Thus almost all of the measurements were made at night and, generally speaking, within a stable boundary layer. Each IOP consisted of three separate one-hour periods during which the inert SF_6 tracer was continuously released. Continuous releases of SF_6 tracer made from a 30-m line source located on the nominally upwind side of the central downtown area will be discussed here. The tracer was measured at half hour intervals during the one-hour release period and then for an additional hour at half hour intervals following the end of each release. At the end of each two hour period the next release would begin. A complete description of these tracer measurements can be found in Clawson et al. (2004).

Two tracer concentration data sets were collected. Concurrent and post-release PIGS measurements of tracer concentrations were made on a gridded array across the downtown area (36 corner with additional mid-block sites), at selected rooftop locations (4), and across a downwind array of (36) samplers deployed along arcs at 2, 4, and 6 km distances from the release site toward the northwest in the nearby suburbs. All PIGS on the arcs and downtown streets were deployed at 3 m a.g.l.

The second concentration data set was measured by 4 mobile and 2 quasi-stationary TGAs. These were deployed at distances of up to 6 km from the release site to identify in real time where the tracer plume was being transported. Data from the TGAs was acquired at a rate of 2 Hz. GPS coordinates of the van-mounted TGAs were continuously recorded.

Most of the wind data acquired for these experiments and reported here was collected at a network of 11 meteorological stations located throughout the Salt Lake Valley. These were operated by the Pacific Northwest National Laboratory (PNNL) as part of the concurrent VTMX experiment. Measurements at these stations were made at a height of 3 m above the local surface (ground or building top) that varied from zero to 121 m (i.e. 3-124 m a.g.l.). Of particular interest are the 4 stations that were in the vicinity of downtown. With the exception of a station at 121 m elevation, all other PNNL stations in the downtown area had measurement heights ranging from 7-23 m a.g.l. Two additional sonic anemometers operated by the Field Research Division of the Air Resources Laboratory (ARLFRD) were collocated in a parking lot 86 m from the release site at 6.9 and 9.81 m a.g.l. (Clawson and Crescenti, 2002). Finally, a set of 6 sonic anemometers were deployed by Los Alamos National Laboratory (LANL) in the vicinity of the release site at heights ranging from 3.5 to 46.3 m a.g.l. (Streit et al. 2001). Five of these were deployed on rooftops near the release site, 39, 48, 69, 103, 471 m away, and the remaining one was deployed at the surface 18 m from the release site.

3. JU03 RESULTS AND DISCUSSION

Daytime and nighttime stability and turbulence conditions in the CBD during JU03 were similar. Nevertheless, significant day-night differences in plume dispersion were observed. Nighttime plumes were more likely to have reduced concentration fluctuation intensities, higher normalized surface concentrations, suppressed vertical mixing, a greater prevalence of data characterized by a normal distribution, and less susceptibility to high toxic loads for a given mean concentration and pollutant toxicity. Daytime plumes were more likely to have higher concentration fluctuations, lower normalized surface concentrations, more uniform vertical mixing, a greater prevalence of data characterized by a lognormal distribution, and greater susceptibility to high toxic loads for a given mean concentration. The concentration fluctuation intensity i (= σ/μ) is the ratio of the standard deviation of concentration σ to the mean concentration μ.

The summary presented here provides highlights of a more comprehensive presentation and discussion of the results found in Finn et al. (2010). Figure 1 illustrates the effects of the species toxicity factor n and concentration fluctuation on toxic dosement. The ratio between the dosement for the actual time series, D_t, and the dosement given by the mean of the time series (represented by the dashed lines), D_m, is keenly sensitive to the level of concentration fluctuations, especially as n increases. A key point here is that Fig. 1a is a typical daytime concentration time series and Fig. 1c is a typical nighttime concentration time series.

Figure 2 provides another illustration of how the level of concentration fluctuations tended to be suppressed within the plume during the nighttime compared to daytime. Values of $i < 0.5$ were common at night while they were very rare during the day. The contour scheme is in common between day and night for the mean normalized concentration and for intensity so that the day and night results can be compared directly. This figure also shows that nighttime was associated with higher normalized surface concentrations (μ/Q where Q is the tracer release rate). High normalized mean concentrations covered relatively larger areas at night and it was common for the highest contour represented (1.1e-05) to be absent during the day.

Figure 4 shows that i tended to increase away from the plume centerline, as expected, but also how i was generally higher during the day than at night.

Figure 5 shows that the mean concentrations measured by vertically collocated PIGS tended to be similar during the daytime but, with the exception of distances less than 200 m at night, exhibited a bias toward higher surface measurements at night. The exception is likely related to the role of tall buildings. The lack of any significant daytime bias is consistent with the normalized mean concentration results of Fig. 2 and suggests that vertical mixing was much more effective during the daytime. Thus nighttime conditions are more favorable to higher normalized concentrations while daytime conditions are more favorable for larger concentration fluctuations that can accentuate D.

Figure 6 is an example of how the normal probability distribution provides a reasonable characterization of most of the nighttime concentration measurements while a lognormal distribution provides a better characterization of the daytime measurements.

Any explanation for these observations requires consideration of (1) wind direction and meander, and (2) stability effects on turbulence and the flow field. A case can be made that wind meander contributed to the observations. In this context, the standard deviation in wind direction, σ_θ, measured atop the Oklahoma Tower ranged from 19-33 degrees for the daytime IOPs and 10.5-12.5 for the nighttime IOPs. Concentrations would abruptly increase/decrease as lateral meander swept contaminated/clean air across an analyzer with corresponding changes in variability and mean concentration. Klein and Clark (2007) and Nelson et al. (2007) documented how flow in crosswind-oriented street canyons was commonly channeled in the along-canyon direction with the direction keenly sensitive to small changes in wind direction during JU03. Flaherty et al. (2007) also found greater variability in wind direction during the day and linked it to the variations observed in tracer concentration profiles 1 km from the release.

There is also a case to be made for the role of stability in explaining the observations. By some measures the evidence for this is weak. There were no large diurnal differences in urban boundary-layer stability during JU03, suggesting that stability effects might not have been significant. Stability conditions varied only from very weakly to weakly unstable within the actual CBD depending upon the stability conditions in the approach flow. Vertical profiles of sensible heat flux in the Park Avenue street canyon were generally small but always positive for all approach flow stability conditions (Ramamurthy et al. 2007). An array of 20 sonic anemometers distributed throughout the CBD with z = 8 m found that the Obukhov length, L, was negative for all IOPs (Hanna et al. 2007), with median values for L yielding z/L of −0.01 and −0.03 for nighttime and daytime IOPs, respectively.

There were also no clear differences in the overall magnitudes of turbulence between day and night during JU03 (Ramamurthy et al. 2007; Nelson et al. 2007; Klein and Clark 2007). Klein and Clark (2007) and Lundquist and Chan (2007) concluded that the in-canyon flows and turbulence in JU03 were driven primarily by the boundary-layer flow at the level of the average roof height and that stability effects were minor. However, there are some points worth noting. Brown et al. (2004b) and Ramamurthy et al. (2004) reported that wind direction relative to street canyon orientation significantly affected the turbulent features present and how that related to the spatial variability of turbulence. Nelson et al. (2007) found that turbulence intensities in the Park Avenue canyon were greater during south and southeast flows compared to southwest flows. Southeast flows were more common during the nighttime IOPs than during the daytime IOPs. Nelson et al. (2007), Ramamurthy et al. (2007), and Klein and Clark (2007) all suggested that tall building effects were important in explaining the turbulence observations in the Park Avenue canyon and that these effects were more pronounced in southeast flows. Klein and Clark (2007) found that cross-canyon vortices developed in the Park Avenue canyon during IOPs 8 and 9 but did not during IOPs 4 and 6. Using CFD modeling of the CBD, Chan and Leach (2007) found that the areal extent of stagnation zones was greater, crosswind flow in canyons was weaker, and zones of strong flow reversal were better developed during IOP8 than IOP3. This is consistent with the observed tracer concentration results but is not consistent with the Nelson et al. (2007) finding of greater turbulence intensities in south-east flows.

There is room for uncertainty in interpreting why there are day-night differences in the concentration data. Nevertheless, the results shown in Figs. 2 and 5 suggest that convective mixing likely played a significant role in creating the observed differences. The much smaller normalized concentration footprints and much better vertical mixing are certainly strong evidence for convective mixing and venting of the tracer from the canopy during the daytime. These observations are difficult to satisfactorily explain without at least some appeal to the influence of stability and convective mixing. It might be conjectured that apparent convective effects on tracer concentrations were being partly expressed through their influence on wind meander.

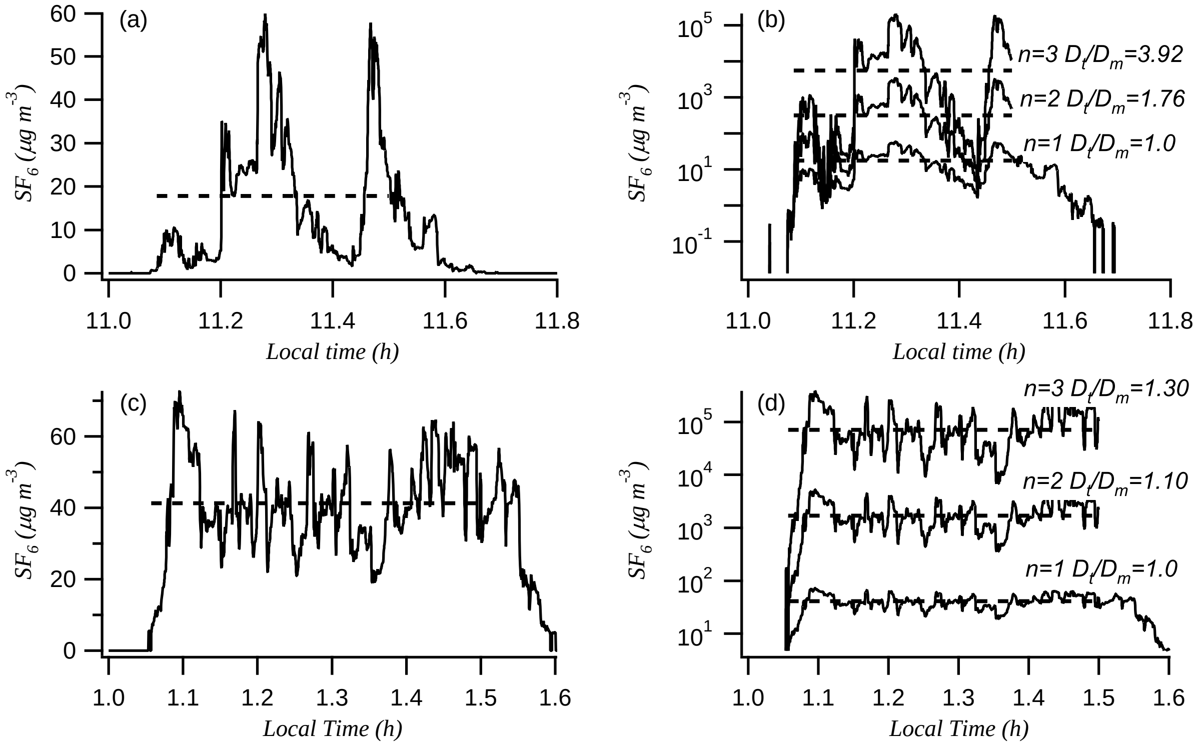

Figure 1. Example tracer concentration time series and corresponding calculation of dosement for varying *n* for actual (solid) and mean (dashed) tracer time series: (a) IOP6, release 2, van0 (location on Fig. 2); (c) IOP8, release 2, van1 (location on Fig. 3); (b and d) corresponding calculations of dosement ratios at varying *n* for actual (D_t) and mean series (D_m) for (a) and (c), respectively.

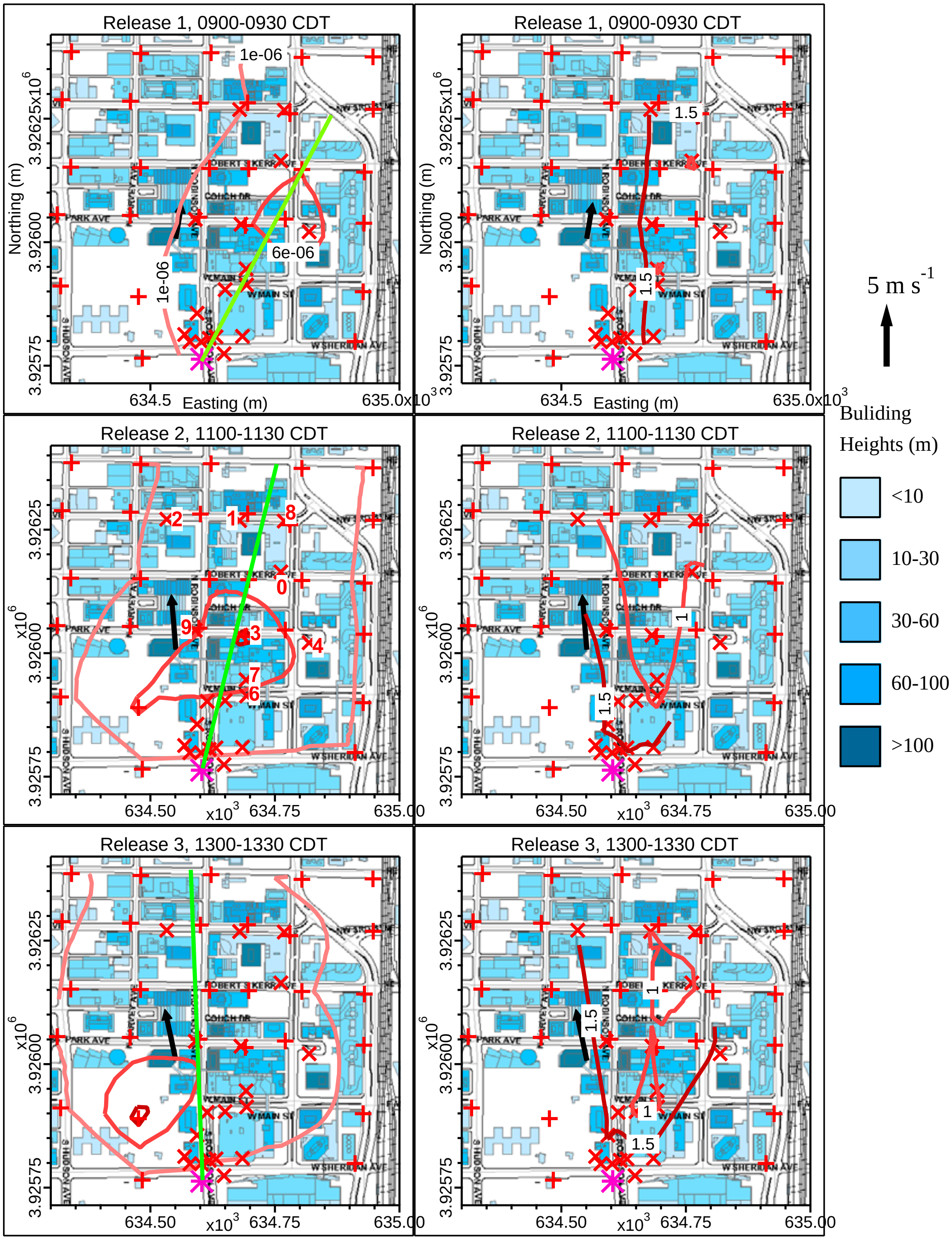

Figure 2. Normalized mean concentration (s m^{-3}) contour maps from street-level PIGS data (left column) and unconditional fluctuation intensity (i_u) contour maps from TGA and Miran data (right column) for the three daytime release periods of IOP6. The '*' is the Botanical Gardens tracer release location, '+' indicate PIGS sampler locations, '×' indicate fast-response analyzer locations, green lines are the estimated plume centerlines, and the wind vectors shown are from atop OKT at 127 m height. Numbers identify TGA van locations for release 2. The cluster of '×' near the source are the Miran analyzers.

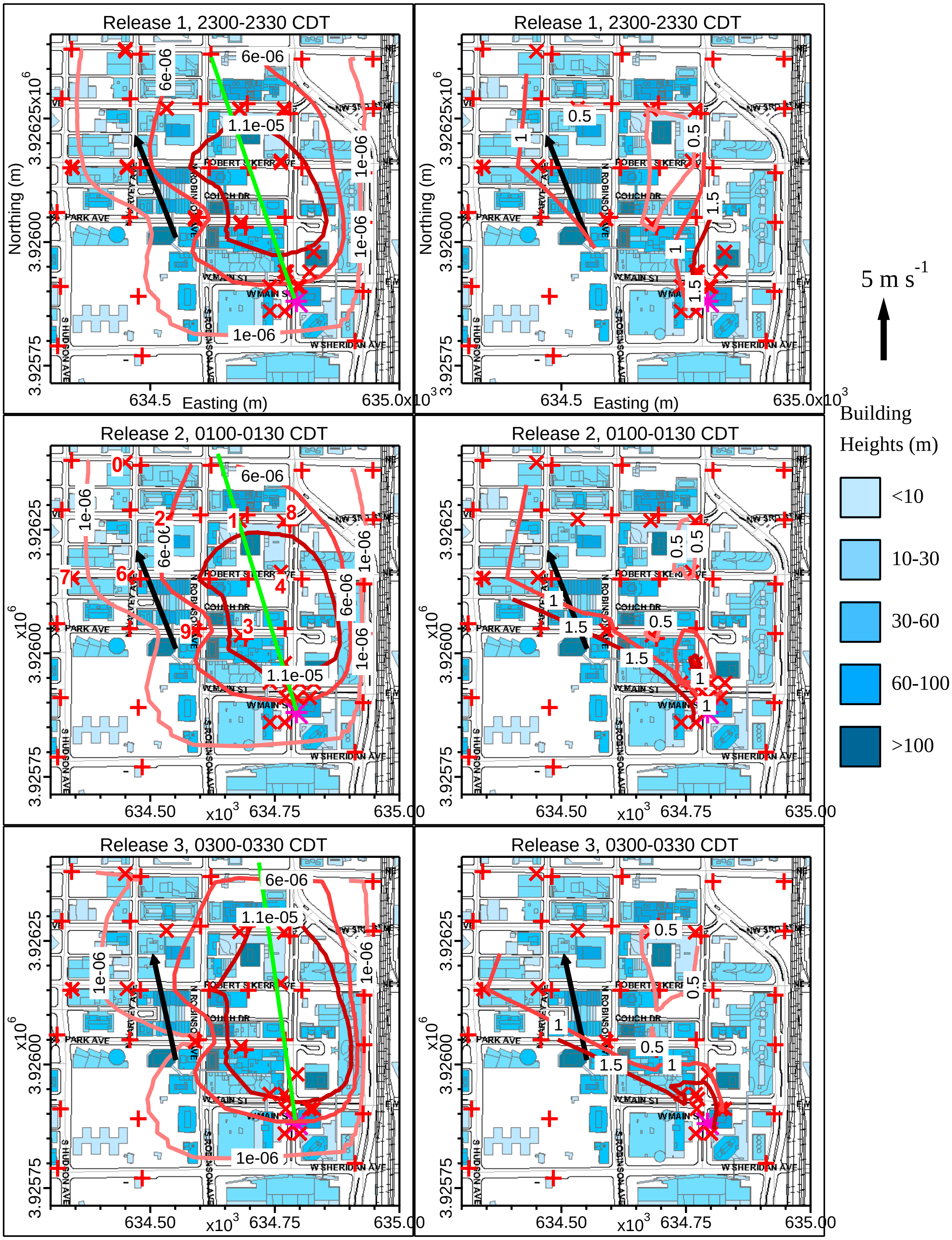

Figure 3. Same as Fig. 2 except for nighttime IOP8 from the Westin release location.

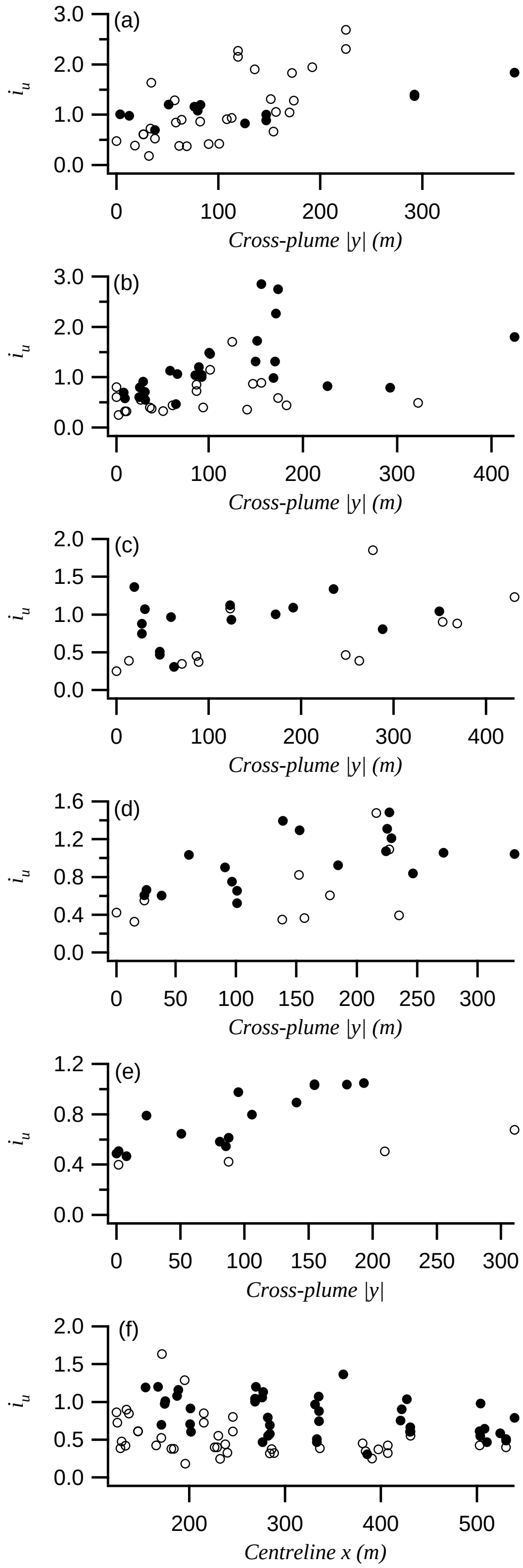

Figure 4. TGA unconditional intensities i_u for day (●) and night (o) as function of the absolute value of distance from the plume centerline and downplume distance: (a) < 200 m; (b) 200-300 m; (c) 300-400 m; (d) 400-500 m; (e) >500 m; (f) as function of distance along plume centerline for cross-plume distances less than 100 m.

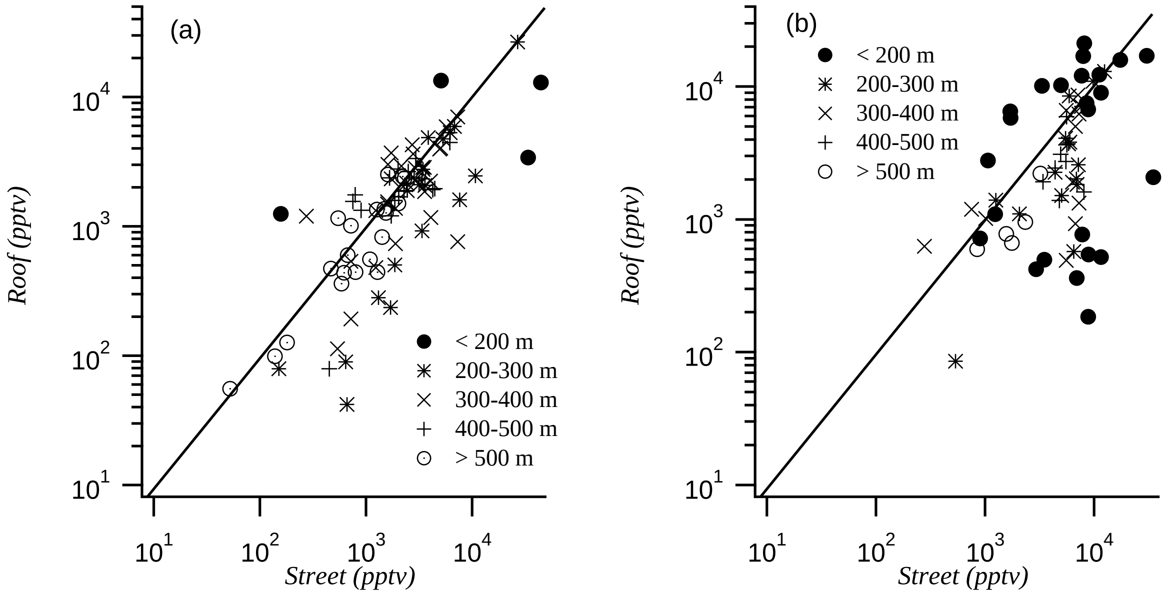

Figure 5. Comparison of vertically collocated (a) daytime and (b) nighttime PIGS tracer concentrations at street and rooftop levels as a function of distance from the release. The lines are 1:1 references.

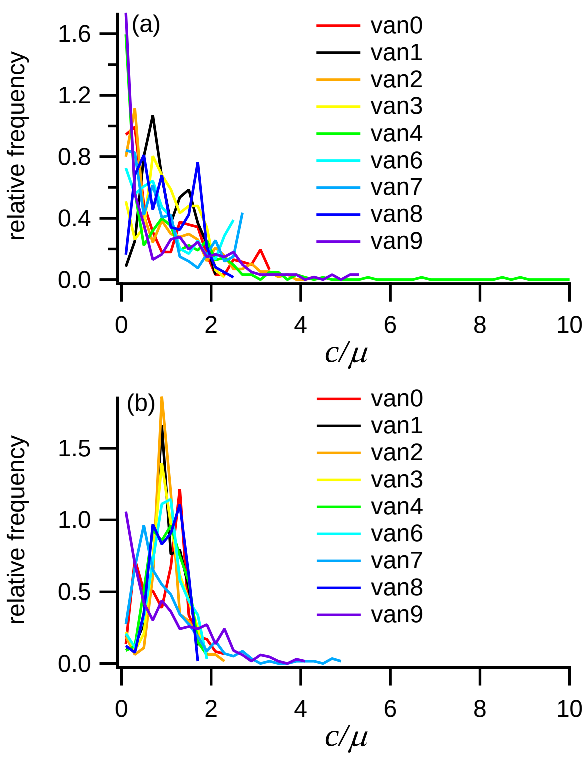

Figure 6. Relative frequency distributions for all TGA time series for release period 2 for (a) IOP6 and (b) IOP8. Locations of the TGA analyzers are indicated on Figs. 2 and 3 for IOPs 6 and 8, respectively.

4. URBAN 2000 RESULTS AND DISCUSSION

While there were several very interesting results from URBAN 2000, one of the experiments (IOP7) stands out as being highly anomalous and provides a strong cautionary tale about the use of some common assumptions in modeling and emergency response. A more comprehensive discussion about this experiment as well as related results from URBAN 2000 can be found in Finn et al. (2008).

During the first half hour of IOP7 (0100-0130 MDT) the winds were light and variable (Fig. 7). Except for the winds measured at the sonic anemometers near the release site, the PNNL wind measurements taken from around the urban area were poorly correlated with the observed westerly, downslope dispersion pattern. Despite the poor correlation, this would be the expected pattern for a drainage flow situation. During the second half hour of release, the tracer plume continued to follow the expected drainage flow pattern. The main tracer plume reached the edge of the downtown sampling grid and turned toward the northwest during the second half hour (Fig. 8). The available TGA data corroborated the plume dispersion pattern given by the PIGS. What is curious is that this northwesterly plume dispersion was in apparent opposition to any of the winds measured at PNNL stations around the downtown area. Winds at the stations to the south and east were typical of drainage conditions and were out of the east or east-northeast. The other two stations showed northeast and southwest winds. In any case, the observed winds were inconsistent with the plume tracking toward the northwest (i.e. no southeast winds).

To further complicate this picture, in the first half hour after the release had ended (Fig. 9), east winds were being measured at all 4 PNNL stations surrounding the downtown area. Nevertheless, high concentrations were still being measured in the vicinity of the release site, even after the bulk of the tracer appeared to have passed through the sampling grid in the first hour, and, significantly, some notably elevated concentrations were detected at 'upwind' samplers. Particularly striking are the high concentrations measured by a mobile TGA over a half km to the east of the release site. Finally, in the next half hour, the concentration field measured at the arc samplers was almost completely homogeneous with some higher concentrations even being reported at some higher elevation samplers in the foothills to the north of downtown (Fig. 10). Again striking is that the highest concentrations in the grid sampler array lay on the eastern, 'upwind' edge of the grid. Mobile TGA traverses between 0230 and 0300 MDT also detected significant tracer concentrations more than a km east of the downtown release site.

The explanation for these apparent anomalies lies in a close examination of the complete wind dataset. Measurements made at the sonic anemometers deployed in the downtown area within 150 m of the release site (ARLFRD, LANL) are consistent with the tracer dispersion patterns (Fig. 11) while all of the surrounding PNNL measurements are generally inconsistent with the observed patterns (Fig. 12). The winds observed at the downtown sites near the release site were mostly easterly throughout IOP7 with the exception of a period extending from 0200 to about 0230 to 0245 MDT, when they were light but westerly. This temporary, localized shift to light westerly winds in the vicinity of the release site was not detected at the stations surrounding the downtown area. Thus it appears as if part of the explanation for the tracer distribution pattern after 0200 MDT was that there was a local, small scale surface wind that was acting to transport tracer to the east and upslope, which was in opposition to all other locally measured winds.

Some conjectures are suggested by this experiment. First, plume movement having little or no correlation with the observed winds implies that dispersion in typical drainage flow conditions is driven mostly by local, small scale flows in a relatively shallow layer, strongly influenced by the local topography (Figs. 7 and 8). Second, there was an obvious persistence of high tracer concentrations in the release area. This suggests that tracer might have been trapped within poorly ventilated areas in the urban canopy, taken up by buildings and later off-gassed, and/or that tracer was transported in some manner off the grid to the east and was later transported back toward the release site. Finally, the post-release results from 0200-0300 MDT (Figs. 9 and 10) reinforces the idea that dispersion in these conditions is driven by local flows on scales that can only be measured by a dense meteorological monitoring grid. Furthermore, these weak local winds can sometimes override the effects of topography even in stable conditions.

The origin of the localized westerly winds measured by the downtown stations near the release from 0200-0230 MDT is a matter of conjecture given the data available. One idea is that these arise from the interaction of near-surface outflow from City Creek Canyon with the urban canopy in the downtown area. City Creek lies in the distinct north-south aligned canyon which emerges from the Ensign Peak area just north of downtown. Flows exiting the canyon would project southward into the downtown area but probably not be detected by the station at 124 m a.g.l. (pink wind vector). It has been found that urban canopies induce channelled flow in street canyons oriented approximately perpendicular to the approach flow with the direction of channelling governed by small changes in wind direction (Klein and Clark 2007; Nelson 2007a; Dobre et al. 2005). If outflow from City Creek Canyon had a slightly westerly component, it could have induced westerly winds in the downtown area as it was redirected by crosswind-oriented (east-west) street canyons. Alternately, the interaction of other flows at canopy height with the heterogeneous Salt Lake City urban canopy could have induced down/updrafts that resulted in zones of convergence and divergence and the generation of local winds (Nelson 2007a; Hosker 1987).

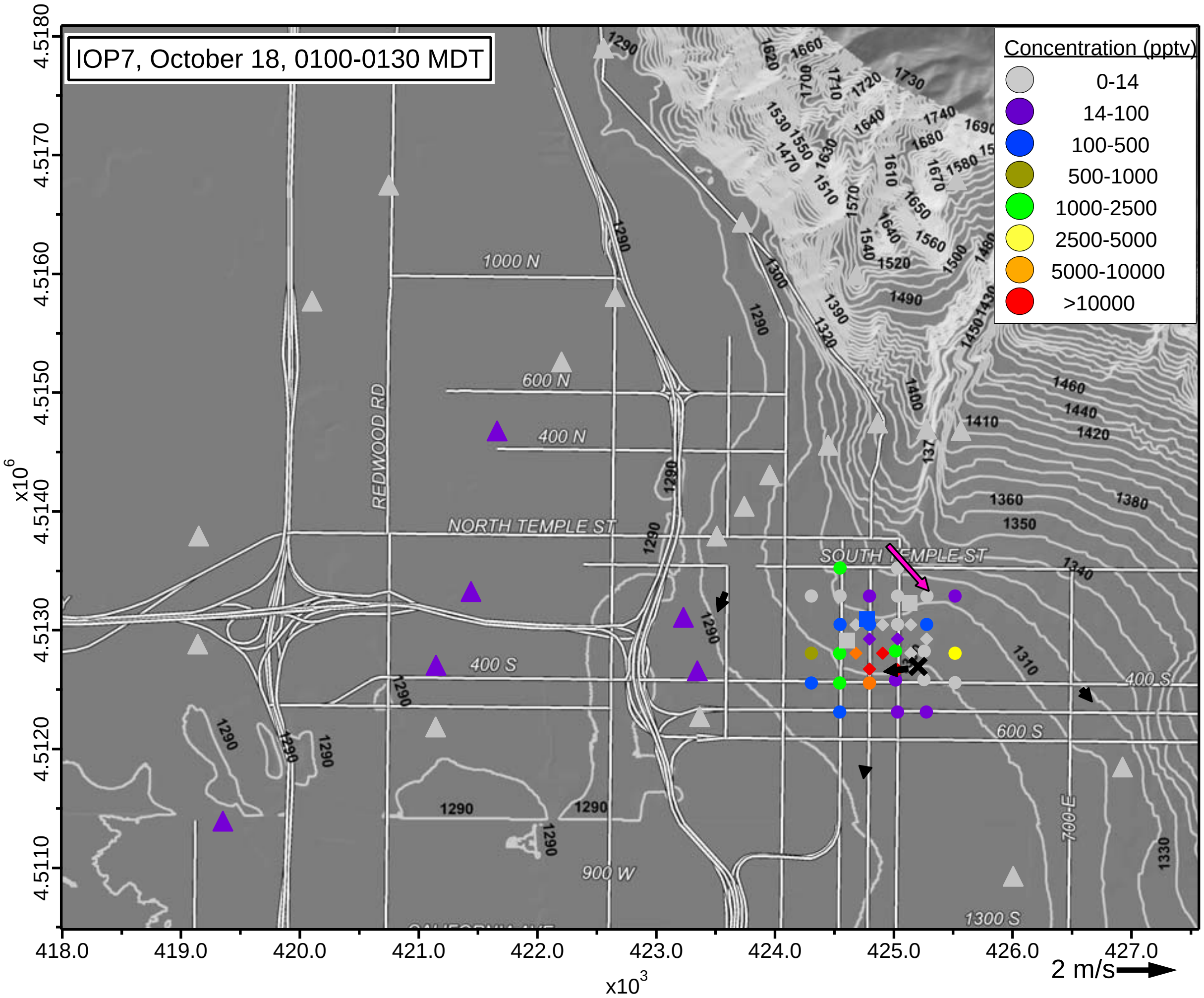

Figure 7. Map of Salt Lake City downtown area for IOP7, release 1, 0100-0130 MDT, 18 October 2000 showing concentration data from sampling grids and wind vector data for a scenario in which plume dispersion is inconsistent with observed winds. PIGS samplers color-coded symbols are circle (street corner), diamond (mid-block), square (rooftop), and triangle (arc). Bold colored lines are mobile analyzer traverses. Bold 'X' indicates the SF_6 release. Scaled wind vectors are black except for LDS station at 124 m AGL (pink). Wind speeds less than 0.4 m s^{-1} are indicated by '+'. The axes are in UTM coordinates (m). The contour lines shown are in meters.

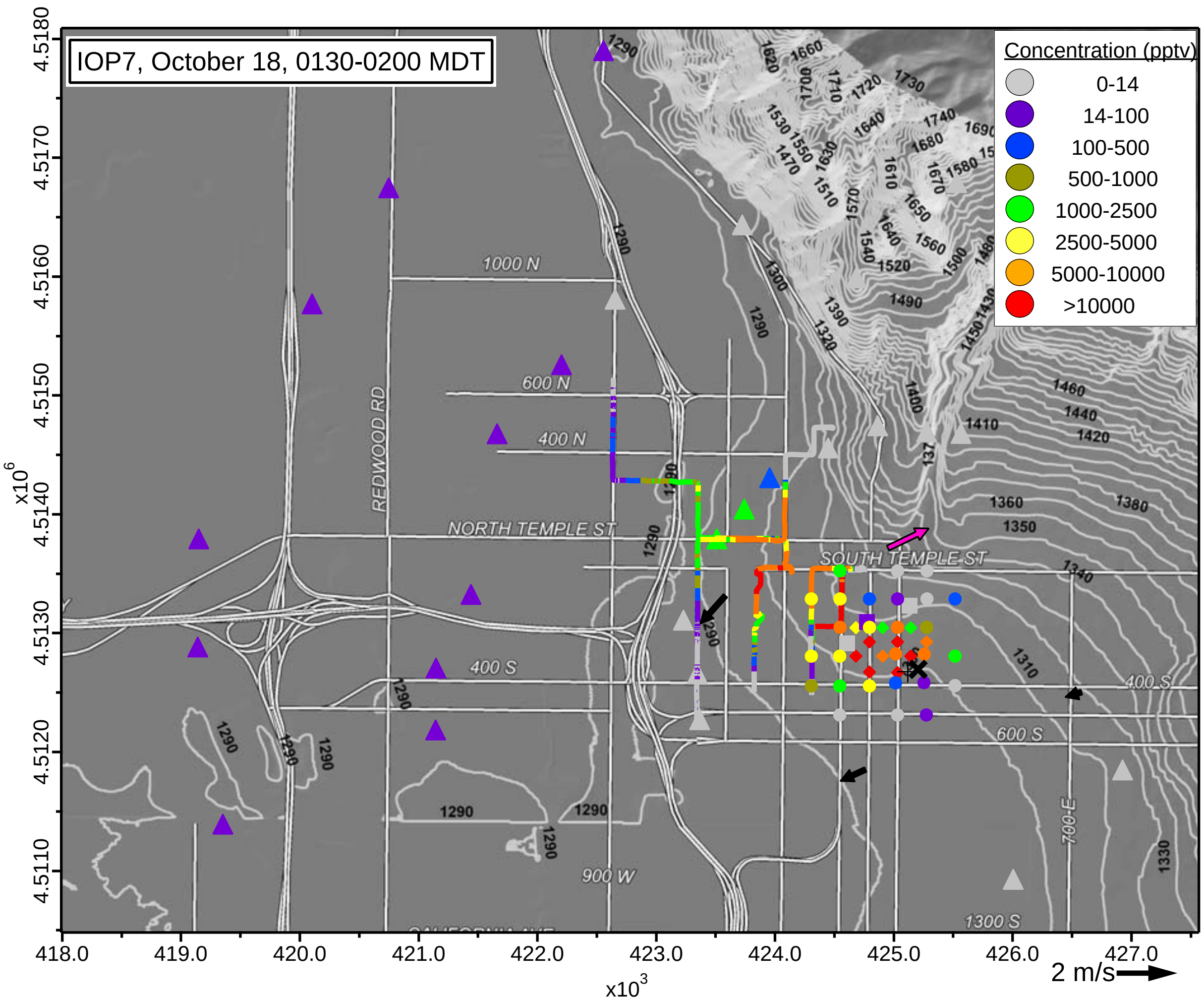

Figure 8. Same as Fig. 7 except 130-0200 MDT, 18 October 2000. Second half hour of the release.

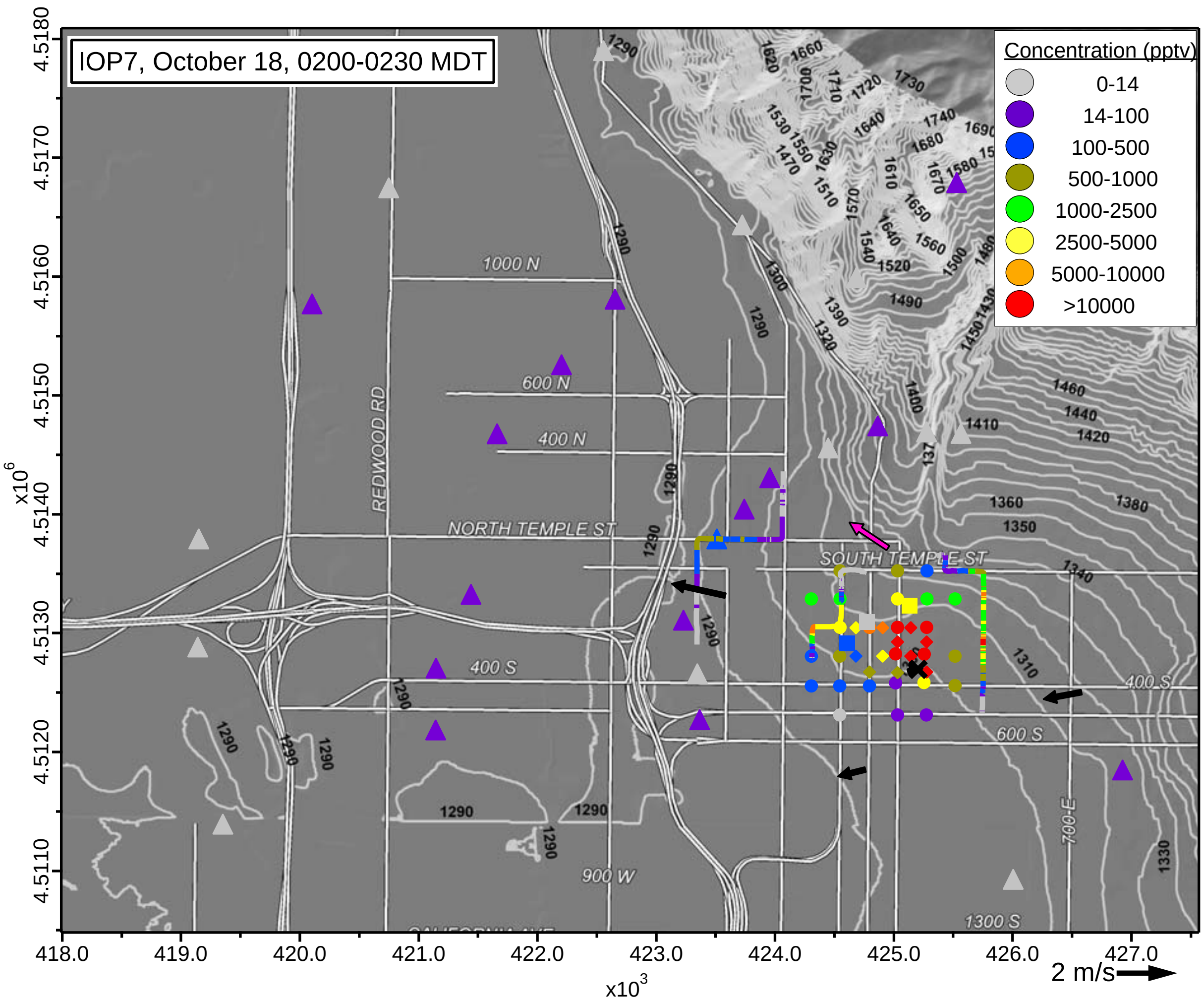

Figure 9. Same as Fig. 7 except for 0200-0230 MDT, 18 October 2000. Release is now off.

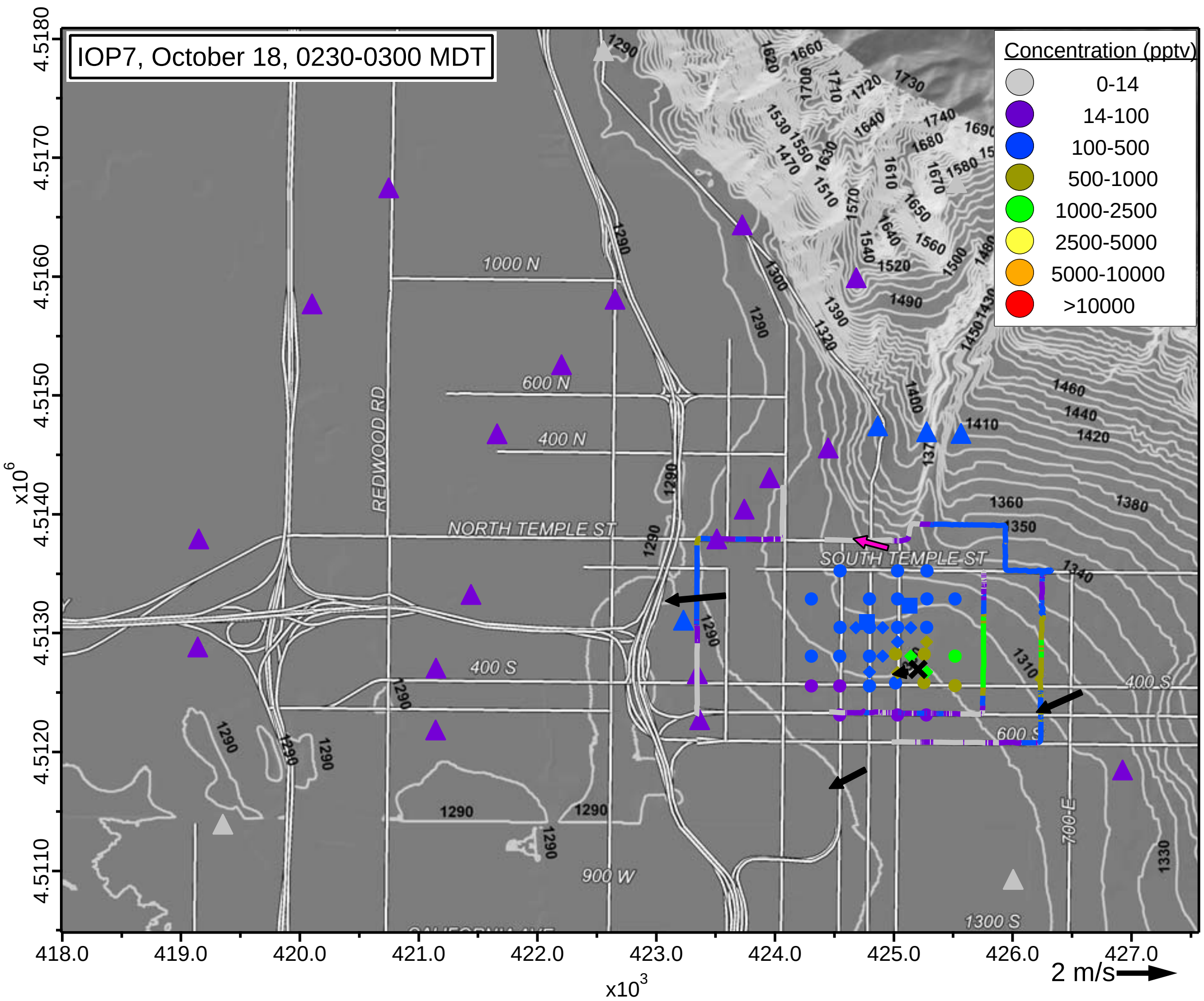

Figure 10. Same as Fig. 7 except for 0230-0300 MDT, 18 October 2000. Release is still off.

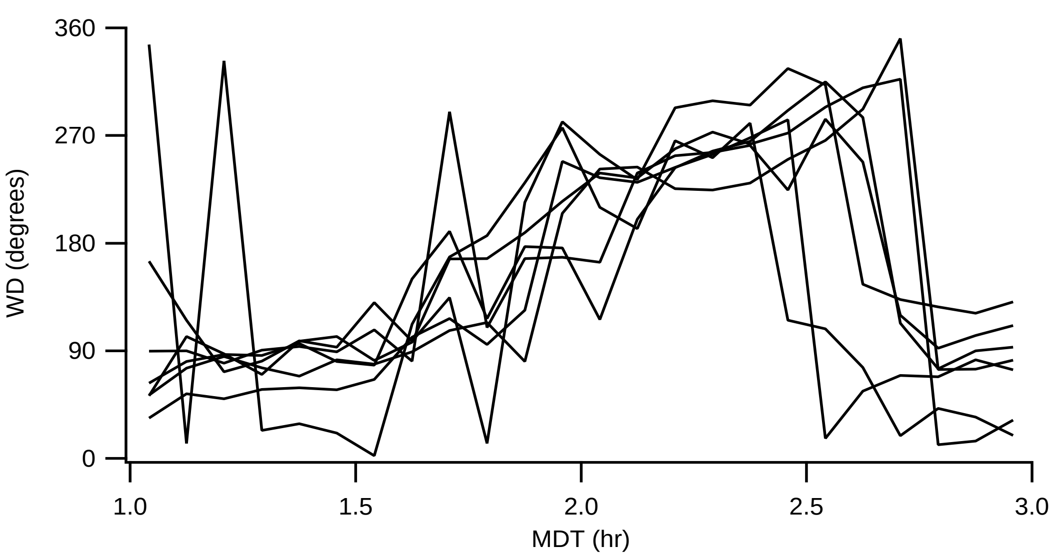

Figure 11. Wind directions measured at anemometers within 150 m of the release site during IOP7.

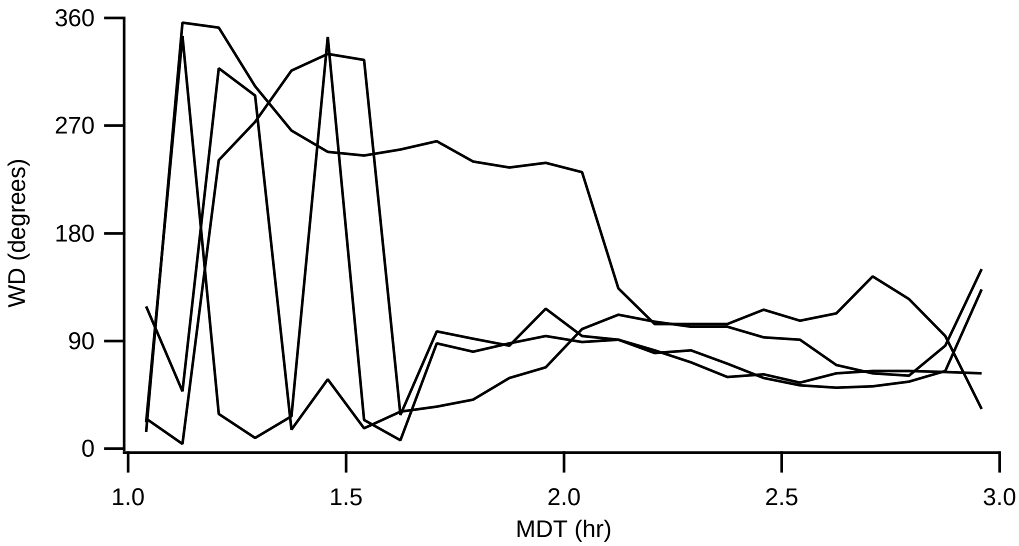

Figure 12. Wind directions measured at PNNL anemometers surrounding downtown area during IOP7.

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