J 9.6 TRANSPORT AND DISPERSION PHENOMENON IN URBAN AREAS: MEASUREMENTS FROM THE JOINT URBAN 2003 FIELD EXPERIMENT

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1. INTRODUCTION

Knowledge of urban dispersion is important for constructing tools that assist in responding to a deliberate or accidental airborne release of toxic materials in cities. The flows that develop in cities are extremely complex and as a result urban transport and dispersion modeling is very challenging. Wind-tunnel and flume experiments and reduced-scale outdoor experiments have been carried out to help obtain a partial understanding of dispersion and flow features in and around buildings. In addition, there have been a number of outdoor experiments in cities measuring concentrations, velocities and/or temperatures, although the measurements obtained have usually been sparse or covered only a small section of the city.

The Joint Urban 2003 tracer experiment was conducted in Oklahoma City to enhance our understanding of transport and dispersion in urban areas (Allwine et al., 2004). This multi-agency experiment included a relatively high density of concentration and velocity measurements in and around downtown Oklahoma City, covering the building scale (~10 m to 100 m), the multi-block neighborhood scale (~100 m to 1 km), and the larger metropolitan scale (~1 km to 10 km). The high density of both velocity and concentration measurements provides a unique opportunity to investigate the phenomena of plume transport and dispersion in cities. In this paper, we show data that reveal transport of the tracer upwind of the source, rapid vertical mixing of the tracer to the tops of tall buildings over very short horizontal distances, enhanced lateral transport of the plume due to channeling of the flow through street canyons, and the effect of upwind stability on the metropolitan-scale plume dispersion for releases within the downtown core.

2. BACKGROUND

Upwind Transport. Laboratory experiments have shown that contaminants can be transported in the opposite direction of the prevailing wind due to flows induced by buildings (e.g., see Hosker, 1987). This can occur around isolated buildings when the contaminant gets caught in sidewall, rooftop, and/or cavity recirculation zones and can be even more pronounced in groups of buildings where contaminants can travel upstream in the cavity of one building to the sidewall eddy of another building and so forth (Brown, 2004). Computational fluid dynamics (CFD) simulations of tracer dispersion in cities have clearly shown upwind transport of the plume over several blocks (e.g., DeCroix, 2002; Coirier and Kim, 2005; Camelli et al., 2006). For a domain with few buildings Hall (2001) found upwind dispersion due mainly to the reversal of flow near ground level at the front face of one of the large buildings.

Enhanced Vertical Mixing. Wind-tunnel experiments have clearly shown that surface releases of contaminants on the downwind side of a tall building can get quickly lofted into the air in the intermittent vortices that develop in the downwind cavity (e.g., Heist et al., 2004). Clear evidence is found in CFD modeling as well (e.g., Patnaik et al., 2003; Hanna et al., 2007). In the former case, releases in downtown Chicago were transported high into the air by groups of tall buildings, while in the latter case; a tall building sticking up above other shorter buildings in Manhattan resulted in the surface release being quickly advected upwards in the cavity of the tall building.

Off-axis Channeling. Laboratory experiments have shown that above roof-level winds oblique to the main streets can be deflected at street level and result in a plume originating at street level being shifted off centerline (e.g., Bächlin and Plate, 1988; Hoydysh and Dabberdt, 1994; MacDonald and Ejim, 2002) When ambient winds are not perpendicular to the axis of the street canyons the street-level flow tends to be unidirectional in the street canyon (Pol et al., 2004). This type of flow feature observed in urban areas is bound to channel the tracer inside street canyons at an oblique angle to the prevailing wind thus enhancing lateral dispersion. Theurer et al. (1996) have developed a plume model that incorporates off-axis channeling depending on the street orientation. In Brown (2004) an example showing simulations performed with and without buildings in Portland with the Urban Dispersion Model illustrate the dramatic effect of channeling, as in the first case the plume travels to the east across the river with the prevailing wind, while in the latter case the plume first gets channeled to the northeast resulting in the high plume concentrations being

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on the opposite side of the river. In addition, wind measurements at street level in Oklahoma City and New York City have shown that channeling can be localized and could be in the opposite direction than expected due to strong downdrafts caused by tall buildings on one side of the canyon (Nelson et al., 2006; Hanna et al., 2007).

Effect of Upwind Stability. Temperature profile measurements in the central core of dense urban areas reveal that the stability is near-neutral from the ground up to heights ranging from 50 m to 500 m (e.g., Bornstein, 1968; Oke and East, 1971; Saitoh et al, 1996). It is generally thought that the mechanical and in some cases thermal mixing result in a well-mixed layer within and just above the city. However, urban tracer experiments held in the 1960's (e.g., McElroy, 1969) clearly show the effect of stability on plume dispersion as epitomized by the Pasquill-Gifford-Turner and Briggs urban plume spread curves (e.g., see Arya, 1999). However, the enhanced urban mixing does result in extremely stable (F stability) or extremely unstable (A stability) conditions to exist in cities. Unlike the majority of these experiments, Joint Urban 2003 had the tracer dissemination point in the downtown hi-rise area of the city.

3. DESCRIPTION OF JOINT URBAN 2003

The Joint Urban 2003 field experiment was performed in July 2003 in Oklahoma City. A large number of meteorological instruments and tracer samplers where deployed in the urban area: meteorological measurements were taken at over 160 different locations (Allwine et. al., 2004) while tracer measurements were made at over 130 locations (Clawson et. al., 2005). The tracer samplers placed at the core downtown area as well as at 1, 2, and 4 km arcs are overlaid on an aerial view map of the city in Fig. 1. Ten intensive operation periods (IOPs) were conducted for both daytime periods and for nighttime periods in which most all meteorological and tracer sampler instrumentation were activated. During the IOPs, continuous point and puff releases of SF6 gas were performed at three different locations in the central business district (CBD) as shown in Fig. 2. Release amounts and locations by IOP are given in Table 1.

During the IOPs, the winds were predominantly from the south. In this paper, tracer and wind data from the IOPs with continuous releases have been analyzed. Each of the releases were of 30 minutes duration. The tracer samplers collected data for 5, 15, and 30 minutes depending on the distance from the source, IOP number, and/or time after the release. The concentrations shown in the figures are in log_{10} of pptv and represent 30 minute averages over the first thirty minutes of the IOP (i.e., during the release period). The portable wind detector at the Post Office (PWID 15), a propeller anemometer, was used to represent the inflow. It was located ~1 km upstream of the release at 50 m above ground on a 35 m rooftop tower free from building effects. Throughout this paper, the prevailing wind direction is represented in the form of wind roses obtained from PWID 15. Further details about the experiment, instrument types and locations, and tracer release information can be found in Allwine et. al. (2004), Clawson et. al. (2005), and Brown et al. (2004).

4. DATA ANALYSIS

Since the Joint Urban 2003 field experiment had a large number of tracer and wind instruments, it was possible to explore the nature of plume dispersion in the vicinity of the source, over many city blocks within the downtown high-rise section of Oklahoma City, and out to several kilometers downwind of the urban core. We looked through the data from the ten Intensive Operating Periods in order to find several of the plume dispersion characteristics outlined in Section 2.

Upwind dispersion. As mentioned earlier, various experimental and modeling studies have indicated the possibility of street-level transport and dispersion of contaminant in the direction opposite to the prevailing wind direction due to entrapment of the contaminant in the recirculation zone(s) of the upwind building(s). We found that considerable upwind dispersion occurred for ~~a~~ certain wind directions, and for other wind directions little or no upwind dispersion was apparent. Figure 3 shows two different 30 minute release periods that were four hours apart during IOP 2. Fig. 3a shows very little upwind dispersion, while Fig 3b shows considerable dispersion upwind of the release point.

This can be explained by observing the wind vectors in the CBD region and the prevailing wind direction. Figure 3(b) shows distinct upwind dispersion most likely due to tracer particles getting intermittently entrained into the downwind cavity formed by building A. The southerly prevailing wind direction for this case creates this flow reversing cavity downwind of building A (which is upwind of the release). The small wind vectors going in different directions just to the north of building A indicate that the street-level winds there are most likely light and variable. The prevailing wind for the case in Fig. 3(a) is from southwest and causes strong west-to-east

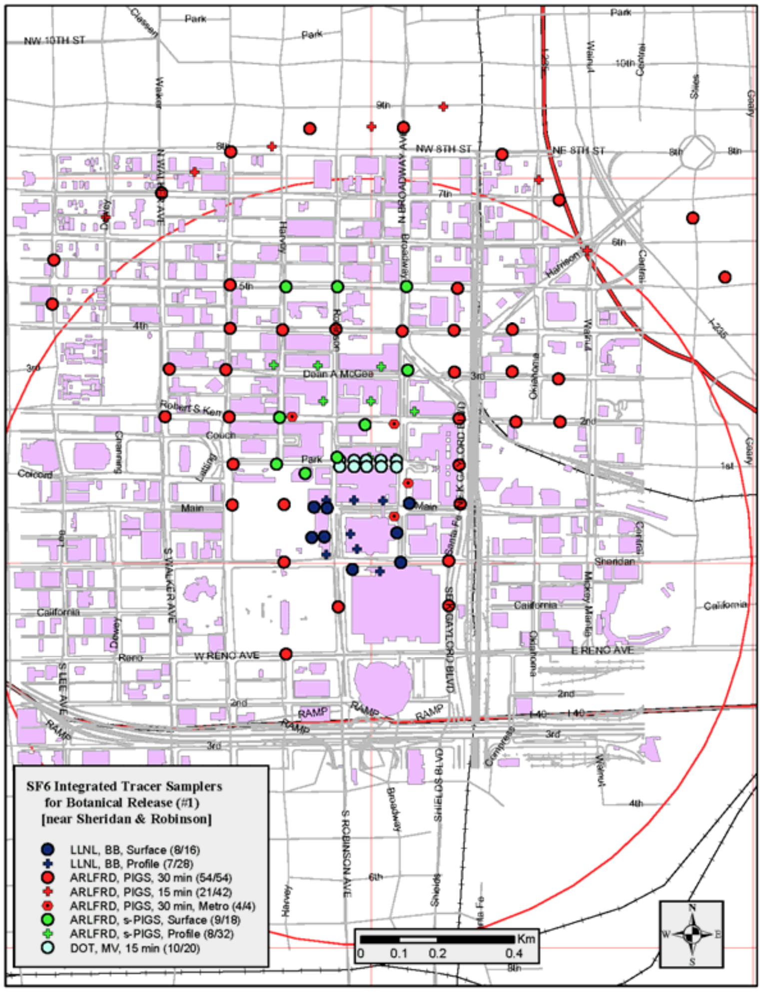


Fig. 1. Tracer samplers covering the Oklahoma city downtown area (from Allwine et al., 2003).

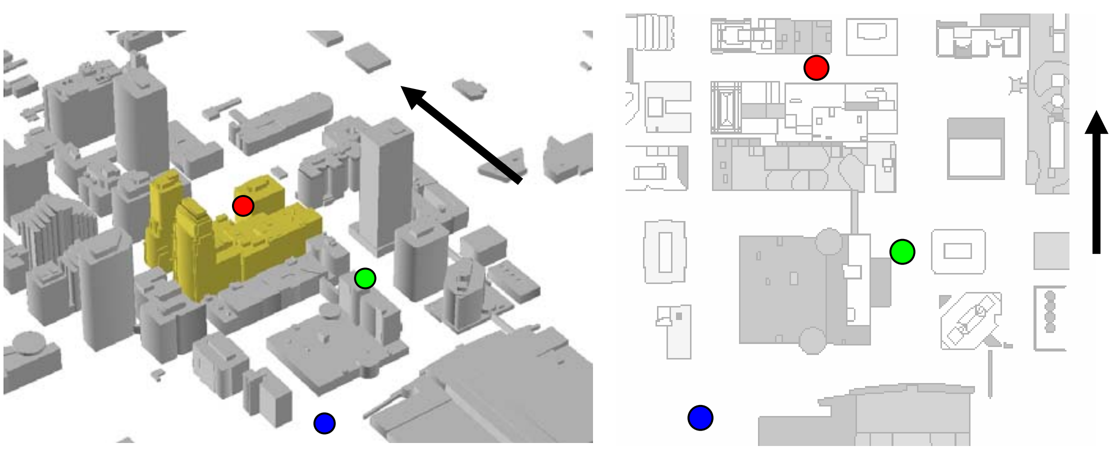


Fig. 2. SF6 release locations in the Oklahoma City CBD during JU 2003 (● Park Avenue, ● Westin and ● Botanical release).

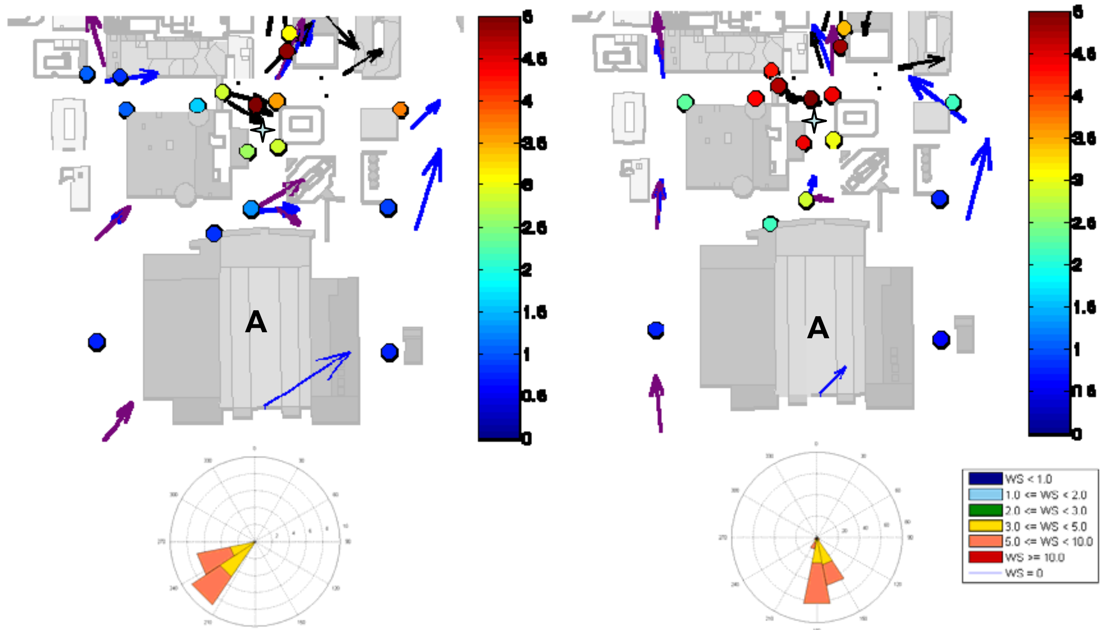
Table 1. Description of the 30-minute SF6 Releases during Joint Urban 2003

IOP	Date	Release Location	Release Type	Release Time UTC/CDT	Mass (g/s)
01	29 June 03 Daytime	Modified Westin	Continuous Continuous	1600-1630/1100-1130 1800-1830/1300-1330	4.8 4.9
02	02 July 03 Daytime	Westin	Continuous Continuous Continuous	1600-1630/1100-1130 1800-1830/1300-1330 2000-2030/1500-1530	5.0 5.0 5.0
03	07 July 03 Daytime	Botanical	Continuous Continuous Continuous	1600-1630/1100-1130 1800-1830/1300-1330 2000-2030/1500-1530	5.0 3.0 3.0
04	09 July 03 Daytime	Botanical	Continuous Continuous Continuous	1600-1630/1100-1130 1800-1830/1300-1330 2000-2030/1500-1530	3.1 3.0 3.0
05	13 July 03 Daytime	Botanical	Continuous Continuous Continuous	1400-1430/0900-0930 1600-1630/1100-1130 1800-1830/1300-1330	2.2 3.0 3.1
06	16 July 03 Daytime	Botanical	Continuous Continuous Continuous	1400-1430/0900-0930 1600-1630/1100-1130 1800-1830/1300-1330	3.0 3.2 3.0
07	19 July 03 Nocturnal	Botanical	Continuous Continuous Continuous	0400-0430/2300-2330 0600-0630/0100-0130 0800-0830/0300-0330	3.0 2.0 2.0
08	25 July 03 Nocturnal	Westin	Continuous Continuous Continuous	0400-0430/2300-2330 0600-0630/0100-0130 0800-0830/0300-0330	3.1 3.0 3.0
09	27 July 03 Nocturnal	Park Avenue	Continuous Continuous Continuous	0400-0430/2300-2330 0600-0630/0100-0130 0800-0830/0300-0330	2.0 2.0 2.1
10	29 July 03 Nocturnal	Park Avenue	Continuous Continuous Continuous	0200-0230/2100-2130 0400-0430/2300-2330 0600-0630/0100-0130	2.2 1.9 2.2

channeling on the north side of building A. In the absence of any entrainment zone, very little upwind dispersion is observed; the upwind dispersion that is apparent can most likely be attributed to turbulent mixing.

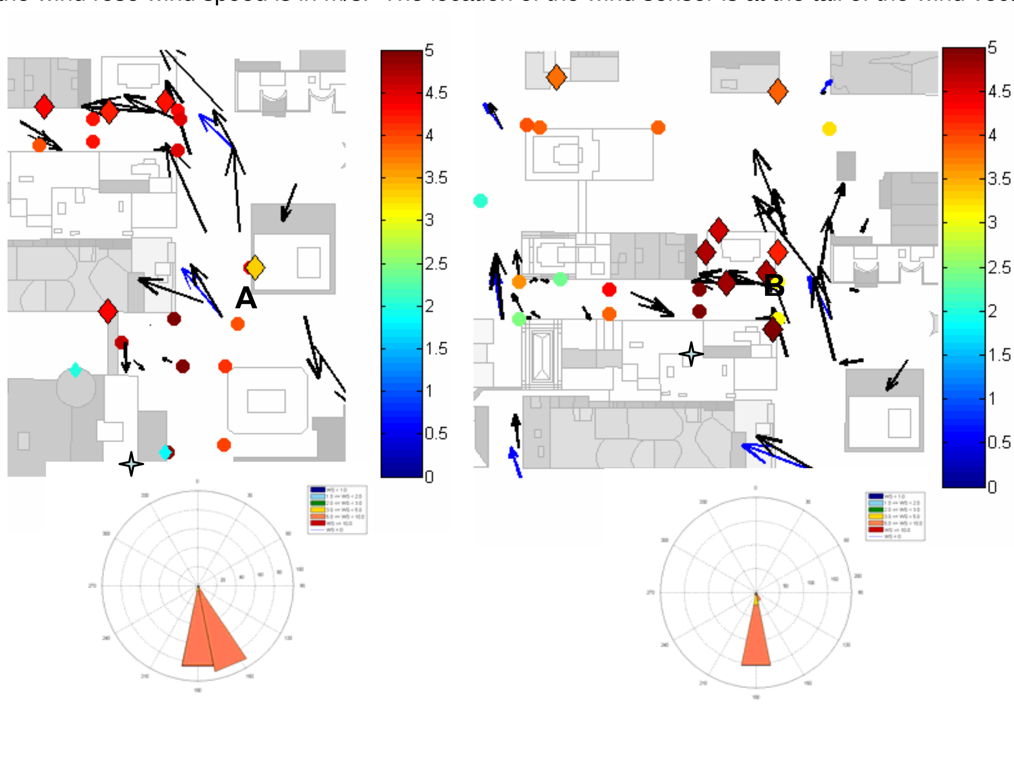
Vertical mixing. An urban area is very likely to consist of buildings having varying heights. These taller buildings often produce vortical structures in their cavity region that can cause vertical lofting of air contaminants. Further, these buildings may form street canyons and for such building clusters, wind-tunnel experiments by Hoydysh and Dabberdt (1988) show intermittent upward spiraling vortices at the corners for such tightly spaced buildings. This phenomenon may cause enhanced vertical mixing close to the release location. Figure 4 shows the tracer samplers and winds in the vicinity of the release location for two different IOPs. The bubbles are the ground level samplers and the diamonds are the rooftop samplers. In Fig. 4a, building A is approximately 50 m from the source and is 150 m tall. The sampler on the roof of building A shows that a considerable amount of material was measured at roof level and indicates significant vertical mixing occurred over a very short distance. Similarly, in Fig 4b, building B is approximately 20 m from the source and is 55 m tall and the samplers on the rooftop show concentrations nearly equal to the maximum concentrations measured near the source at street level. Clearly, these cases provide evidence of enhanced vertical mixing.

Channeling and the effect of prevailing wind direction. Wind-tunnel experiments and modeling have demonstrated that plumes can become trapped in street canyons and travel in an oblique direction to the large-scale prevailing wind. Hoydysh and Dabberdt (1994) include smoke images in their paper that show a fraction of the plume being channeled down side streets and the other fraction being lofted above roof-level and traveling with the prevailing wind. The centerline plume axis is shifted from the direction of the prevailing wind and lateral spread is effectively enhanced.



(a) (b)

Fig. 3. Thirty minute averaged tracer and wind data around the Westin release location during IOP 2 for different prevailing wind directions: (a) 11:00-11:30 (CDT) and (b) 15:00-15:30 (CDT). The southerly inflow resulted in significant upwind transport near street level. Note that the concentration scale is log_{10} pptv, while the wind rose wind speed is in m/s. The location of the wind sensor is at the tail of the wind vector.

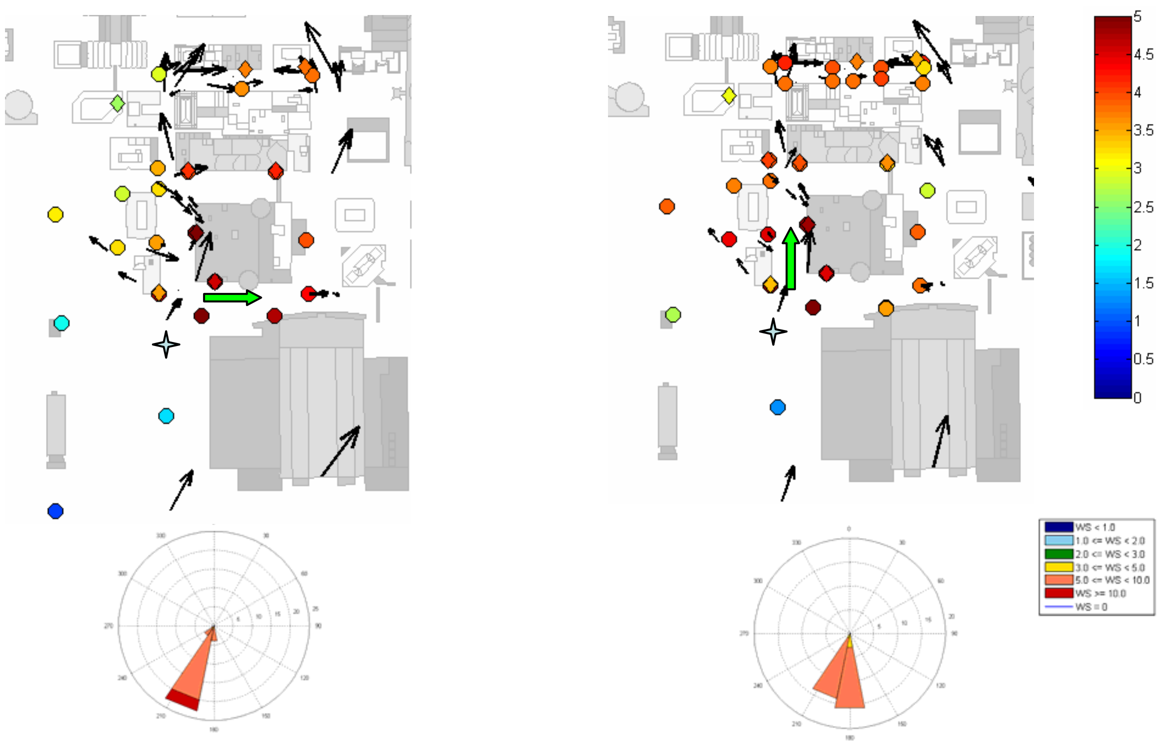


(a) (b)

Fig. 4: Thirty minute averaged tracer and wind data around the release location showing significant vertical dispersion during: (a) IOP 8: 3:00-3:30 (CDT) Westin Release and (b) IOP 9: 1:00-1:30 (CDT) Park Avenue. The diamonds are rooftop samplers, while the circles are street-level samplers. Note that building A is about 150 m tall, and building B is about 50 m tall.

Figure 5 shows the channeling effect observed for two different Botanical Garden releases during IOP 3. The green arrows show the primary flow direction down the streets based on the concentration measurements. A small change in the prevailing wind direction of about 20 degrees has impacted the channeling pattern for the two cases shown. Fig. 5a depicts more south-to-north channeling, while Fig. 5b shows more west-to-east channeling. The plume centerline is shifted somewhat to the east in the latter case.

Due to heterogeneity of urban areas, even a small change in prevailing direction can change the dispersion patterns significantly. Figure 6 shows a zoomed out view of 30 min. averaged tracer data for two different Park Avenue releases during IOP 9. Both cases have similar prevailing wind speeds and wind direction standard deviation σ_{WD}. However, they have slightly different prevailing wind directions of about 15 degrees. It can be observed from Fig. 6a that there is much less lateral dispersion as compared to the case shown in Fig. 6b. The reason for the significantly different lateral spread can be explained by observing the details of the flow structure near the source for the two cases (Fig. 7). Figure 7a indicates that this case has a southerly prevailing wind, but with a slight westerly component. Figure 7b shows the prevailing wind for this case is also from the south, but with a slight easterly component. This slight easterly component results in outflow at the western end of the Park Avenue street canyon which allows the tracer to escape from the western end. This outflow may be caused by the tall building sticking up on the north side of the street at the west end of the canyon. The surface level winds show divergence and this is indicative of a downdraft on the front side of the tall building. For the case shown in Fig. 7a, the slight westerly component in the prevailing wind direction is enough to shut off the outflow at the western end of the canyon and push the plume to the eastern side of the Park Avenue street canyon.



(a) (b)

Fig. 5. Thirty minute averaged tracer and wind data around the Botanical Gardens release location showing channeling: (a) IOP 3: 11:00-11:30 (CDT) and (b) IOP 3: 13:00-13:30 (CDT). The green arrow shows the predominant direction of plume transport for each case. A slight shift in the inflow wind direction has resulted in different near-source plume behavior.

Stability effects on dispersion. Figure 8 shows the 30 min. averaged normalized ground level concentration along the 1 km, 2 km and 4 km arcs for a nighttime and a daytime release. Both cases were chosen such that they had similar prevailing wind speeds and wind direction and the same release location. The higher value of σ_{WD} for the daytime case (Fig. 8a) is indicative of unstable conditions. As seen in Fig. 8a, the plume is much wider and has a lower peak concentration value which is a typical characteristic of a daytime release in unstable conditions. On the contrary, Fig. 8b shows a thinner plume and higher peak concentration values which is a typical characteristic of a nighttime release under stable conditions.

Figure 9 is a scatter plot relating σ_{WD} to the 30 minute averaged normalized C_{max} value on the 4 km arc for all the IOPs (day and night). Although there is a considerable scatter in the data, it can be observed the daytime C_{max} values are higher than the nighttime values. The day-time σ_{WD} values are larger than the nighttime values which suggest that unstable conditions exist upwind of the source. Therefore, it can be concluded that even for releases in an urban area, there are considerable effects of stability on the dispersion pattern as close as 1 km from the source location.

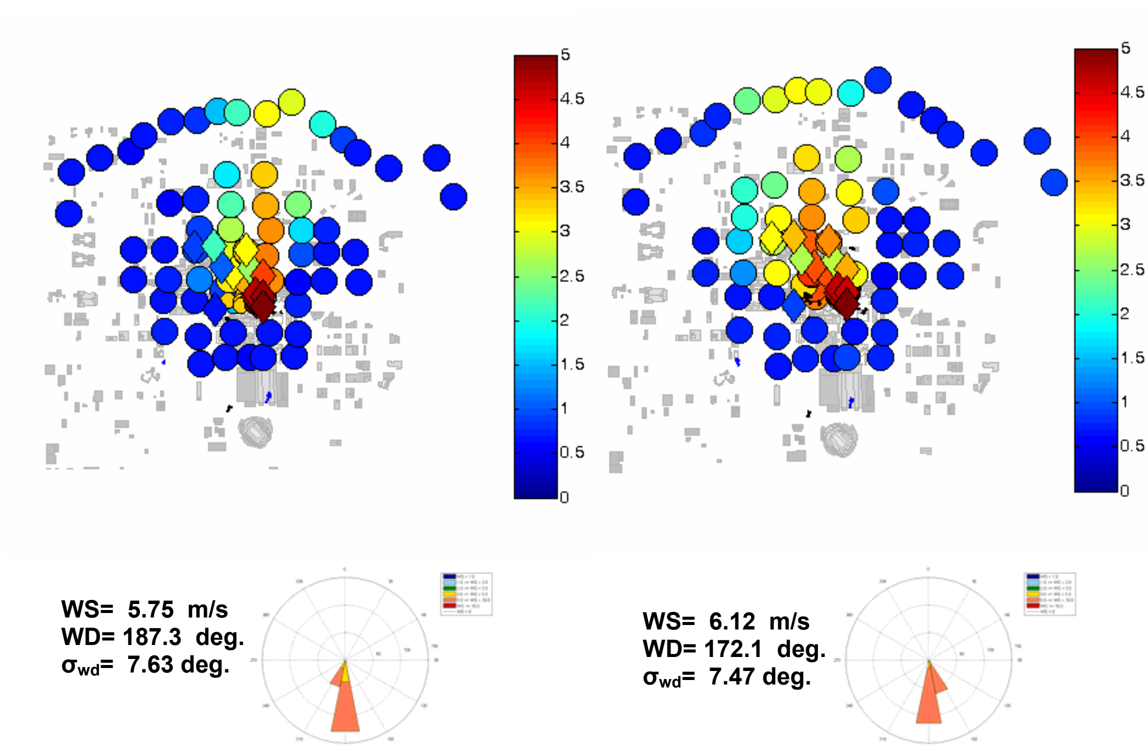


Fig. 6. Thirty minute averaged tracer and wind data in the greater central business district during IOP 9 for the Park Avenue release location: (a) 03:00-03:30 (CDT) and (b) 23:00-23:30 (CDT). A slight change in the prevailing wind direction has resulted in significantly different lateral plume spread.

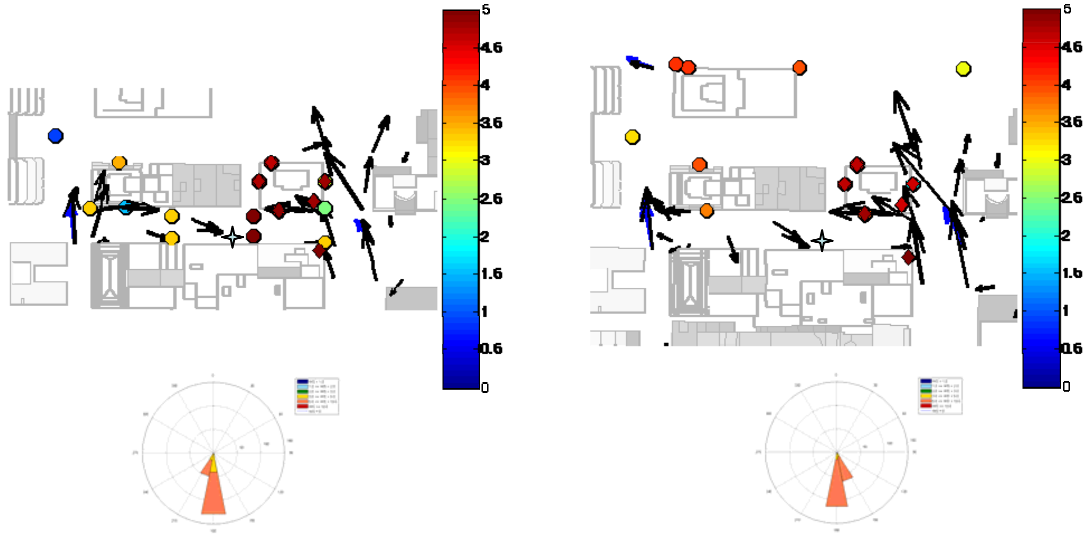


Fig. 7. Thirty minute averaged tracer and wind data around the Park Avenue release location during IOP 9: (a) 3:00-3:30 (CDT) and (b) 23:00-23:30 (CDT). Note that there is outflow at the western end of Park Avenue for case (b).

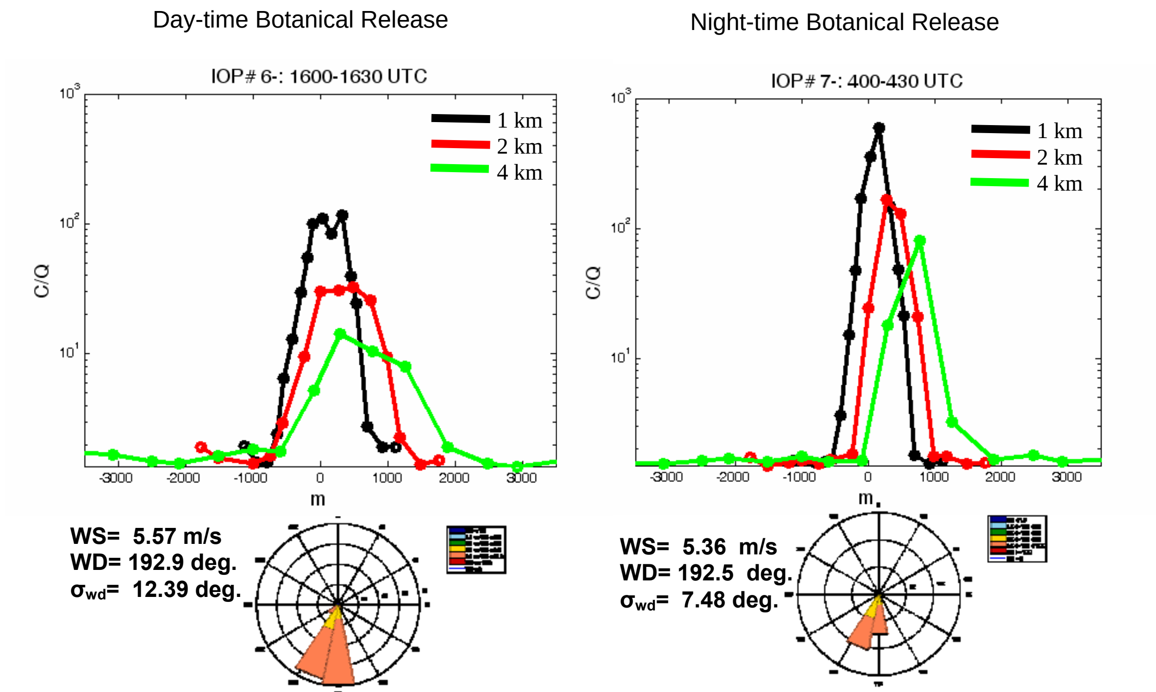


Fig. 8. Thirty minute averaged tracer and wind data on the 1, 2, and 4 km arcs for: (a) IOP 6 daytime release: 11:00-11:30 (CDT) and (b) IOP 7 nighttime release: 23:00-23:30 (CDT).

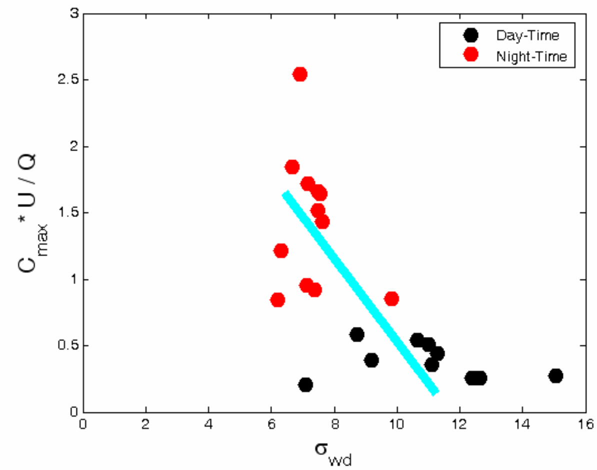


Fig. 9. Scatter plot of 30 minute averaged normalized C_{max} at the 4 km arc and σ_{WD} upwind of the source location.

5. CONCLUSIONS

Analysis of tracer and wind data from the Joint Urban 2003 field experiment has been performed to better our understanding of buildings, the prevailing wind direction, and stability on the flow and dispersion in urban areas. As discussed in earlier studies involving laboratory experiments and CFD modeling, dispersion of tracer upwind of the source has been identified from the observations made in the Joint Urban 2003 field experiment. However, it should be noted that specific upwind conditions are required for the formation of such cavities causing upwind dispersion and therefore upwind dispersion might not always occur in urban areas.

Buildings in urban areas are usually of varying heights and the interaction of the ambient inflow with the taller buildings leads to the formation for vortical structures that vertically lift the tracer up to the height of the tallest buildings. This effect has been observed in earlier wind-tunnel experiments and CFD modeling studies and has been confirmed for a real city through the observations made in this experiment.

Observations from the Joint Urban 2003 field experiment have pointed out the presence of persistent unidirectional flows within street canyons of urban areas that are very sensitive to the prevailing wind direction. The lateral dispersion of the tracer was found to be enhanced if–the ambient winds are such that more cross-flow channeling areas are created, i.e., channeling oblique to the prevailing wind direction. For only slightly different prevailing wind directions, significant differences in the location of the plume were found owing to the effects of off-axis channeling.

Joint Urban 2003 tracer measurements revealed that the plume generally had greater lateral expanse for daytime cases as compared to night time cases signifying higher rates of mixing during the daytime. Likewise, peak tracer concentrations were found to be higher at the 1, 2, and 4 km arcs for the nighttime releases, in agreement with earlier outdoor field studies. It is not clear, however, if ambient stratification plays a role in the transport and dispersion within the urban core at scales less than 1 km.

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