5.1 **URBAN DISPERSION – CHALLENGES FOR FAST RESPONSE MODELING**

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1. Introduction

There is renewed interest in urban dispersion modeling due to the need for tools that can be used for responding to, planning for, and assessing the consequences of an airborne release of toxic materials. Although not an everyday phenomenon, releases of hazardous gases and aerosols have occurred in populated urban environments and are potentially threatening to human life. These releases may stem from on-site accidents as in the case of industrial chemical releases, may result during transport of hazardous chemicals as in tanker truck or railroad spills, or may be premeditated as in a chemical, biological, or radiological (CBR) agent terrorist attack.

Transport and dispersion in urban environments is extremely complicated. Buildings alter the flow fields and deflect the wind, causing updrafts and downdrafts, channeling between buildings, areas of calm winds adjacent to strong winds, and horizontally and vertically rotating-eddies between buildings, at street corners, and other places within the urban canopy (see review by Hosker, 1984). Trees, moving vehicles, and exhaust vents among other things further complicate matters. The distance over which chemical, biological, or radiological releases can be harmful varies from tens of meters to many kilometers depending on the amount released, the toxicity of the agent, and the atmospheric conditions. As we will show later, accounting for the impacts of buildings on the transport and dispersion is crucial in estimating the travel direction, the areal extent, and the toxicity levels of the contaminant plume, and ultimately for calculating exposures to the population.

i) Why fast urban dispersion modeling?

Fast running models are essential for vulnerability studies where many cases must be simulated in a limited amount of time or for emergency response scenarios when an answer is needed quickly.

Most emergency response dispersion models currently in use have little or no building "awareness" and could be misused for urban applications in a way that could lead to fatal consequences. Fast response models will actually get more use day in and day out performing vulnerability studies or in training applications. Fast response models are needed for planning and assessment, where many CB agent attack scenarios must be run. They could be used in next-generation training with unscripted table-top exercises and provide immediate feedback. Fast response models could be run around the clock at a military base or high-profile target (e.g., the DC Mall) ingesting local wind measurements in real-time. Fast response urban dispersion codes have also be used for determining the optimal placement of CBR agent sensors around building complexes (e.g., Streit et al., 2004). A fast model is needed because thousands of cases need to be run in order to determine where to place sensors around a building complex to maximize the probability of detecting a CB agent attack.

There is a great need - and opportunity - to develop fast running urban dispersion models that explicitly account for the effects of buildings on transport and dispersion. These models would fill a significant void between fast, but low fidelity conventional plume dispersion models and high fidelity, but slow, computational fluid dynamics models. However, due to the complexities of flow in urban areas, there are also significant challenges in developing a simplified fast running model that can adequately account for the impacts of buildings. In this paper, we present an overview of challenges for fast response urban dispersion modeling based on our team's experience in this field. This review is not comprehensive, but is meant to inform the reader of some of the key issues with respect to successful implementation of dispersion models in urban areas.

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2. Urban Dispersion Modeling Background

In the 70's and 80's, there was a strong push to develop street canyon models for carbon monoxide hotspot calculations at intersections and in street canyons. The APRAC model allowed for concentrations to be higher on one side of the canyon as opposed to the other due to the in-canyon vortex (Dabberdt et al., 1973). Likewise, Yamartino et al. (1989) developed the Canyon-Plume-Box model for computing vehicle emission concentrations in street canyons and utilized a unique segmented Gaussian plume model adapted to the in-canyon vortex. In the 80's and 90's, models that accounted for enhanced mixing due to a single building for accidental releases at nuclear energy facilities were being described in the literature (e.g., Ramsdell and Fosmire, 1995). Other canyon models (e.g., the CAR model (Eereens et al., 1993), the OSPM model (Berkowicz, 2000)), isolated building models (e.g., EPA Prime (Schulman et al., 2000)), and combined models (e.g., ADMS (Robins and McHugh, 2000)) have been developed as well to compute localized concentrations. Although generally successful for their applications, these models were not really intended for problems beyond a single street canyon or building and, in general, do not compute wind fields around building complexes.

A range of fast-running urban dispersion models have been developed to look at transport over greater distances. Theurer et al. (1996) modified the Gaussian plume model to account for the plume centerline shift due to channeling. Hall et al. (2000) developed a Gaussian puff model called the Urban Dispersion Model (UDM) for use on neighborhood to city scales. The puffs interact with buildings and the model can account for building wake mixing and some channeling. Röckle (1990) derived a unique model that computes flow around buildings using empirical equations and mass conservation. It has since been incorporated into the ABC and ASMUS models and has been used for dispersion applications at industrial sites (Röckle, 1990). Kaplan and Dinar (1996) report on results using a Lagrangian dispersion model linked with their own version of the Röckle model. Our team as well has utilized the Röckle concept and made enhancements to the flow algorithms (e.g., Pardyjak and Brown, 2001; Bagal et al., 2004) as well as linked it to an urbanized Lagrangian dispersion model (see Williams et al., 2004 this conference). This

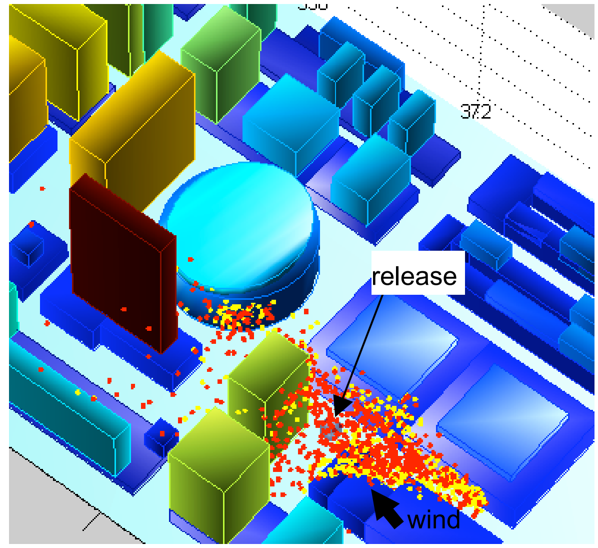

Figure 1. Plume dispersal calculations by the QUIC modeling system in the vicinity of Madison Square Garden, New York City. Red dots represent contaminant in the air, while yellow dots represent deposition on street and building surfaces.

package, called the Quick Urban & Industrial Complex (QUIC) dispersion modeling system, contains a graphical user interface and has been applied to neighborhood-scale problems in such places as NYC, Washington DC, Chicago and Salt Lake City (e.g., see Fig. 1).

There are also a handful of groups investigating the use of computational fluid dynamics (CFD) models for fast response applications. Ideas range from coarse resolution simulations using drag (e.g., Lim et al., 2001; Chan et al., 2004) to library approaches were a large number of cases are precomputed and results for specific cases are interpolated from the library (e.g., Smith and Brown, 2002; Young et al., 2004).

3. Challenges and difficulties

There are both challenges and difficulties introduced by the setting (urban areas) and the application (dispersal of a toxic contaminant cloud for exposure assessment). The problem is made more difficult by the constraint of using fast running dispersion models, i.e., how does one account for the complexity of urban transport and diffusion in a simplified model.

This paper is intended to highlight several challenges and difficulties and focuses on the impact of groups of buildings in urban areas.

Excellent reviews on flow around isolated buildings and building clusters can be found in Cermak (1976), Meroney (1982), and Hosker (1984).

a) Enhanced mixing.

Numerous urban tracer field experiments have found that near-source dispersion is enhanced in urban areas (McElroy, 1997). For neutral conditions, urban plume spread parameters are about a factor of two greater than rural parameters in the lateral direction and a factor of 2-5 in the vertical between 1 and 5 km down-wind of the source (Draxler, 1984). However, there is considerable scatter in the data by city and release location as shown by McElroy (1997) which one could argue is due to local building geometry, relative source location, and meteorological conditions. Wind-tunnel experiments have shown that buildings significantly impact both lateral and vertical dispersion close to the source and immediately downwind (Fig. 2). These experiments indicate that the arrangement of buildings (e.g., aligned vs. staggered) impact the dispersion rate (e.g., Davidson et al., 1996; Macdonald et al., 2000). Experiments around nuclear facilities showed extreme sensitivity in the amount of mixing (plume spread) based on wind direction changes and subtle differences in the release location (Start et al., 1977). Accounting for the macroscopic effects of enhanced mixing in urban areas is quite straightforward through the use of urban plume spread parameters. However, the nature of increased mixing near the source depends strongly on the geometry of the buildings and their layout, which is more difficult to parameterize through plume spread curves.

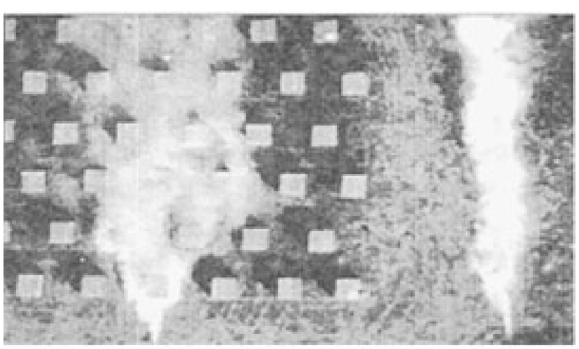

Figure 2. Plan view of smoke dispersal through an array of staggered cubes (left) and unobstructed fetch (right). From Davidson et al. (1995).

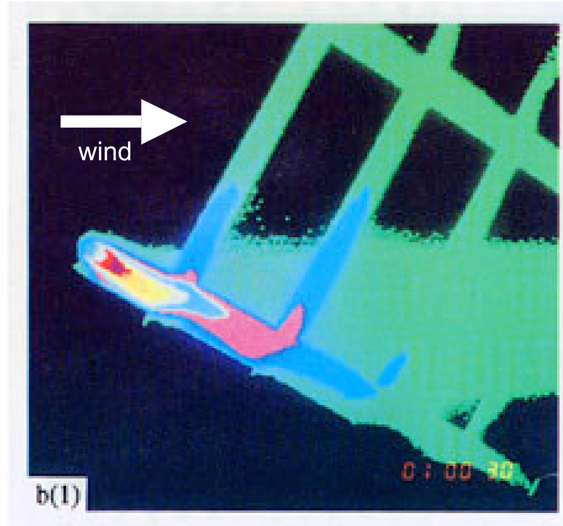

Figure 3. Top view of wind-tunnel experiment showing tracer being channeled in streets at oblique angles relative to the above roof-level wind. From Hoydysh and Dabberdt (1994).

b) Importance of plume location & coverage

For applications involving hazardous contaminant dispersal, we are not only interested in providing reasonable estimates of the magnitude of concentration, but also the location of the contaminant plume. This is because ultimately the plume calculation will be used to assess exposures to the population, or to determine what areas need to be evacuated, have been contaminated, and/or need to be cleaned up. Furthermore, in contrast to most air quality applications where the maximum concentration is one of the most important metrics, low values of concentration need to be accurately calculated as well because they may significantly impact population exposure assessments. For example, the lethality of low concentrations may not be as great, but because the area of the dilute plume covers more area, it can impact just as many people. Plume location and coverage need to be considered when developing and evaluating urban dispersion models and pose a very difficult challenge.

c) Displacement of plume by street channeling.

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)). As shown in Fig. 3, near the

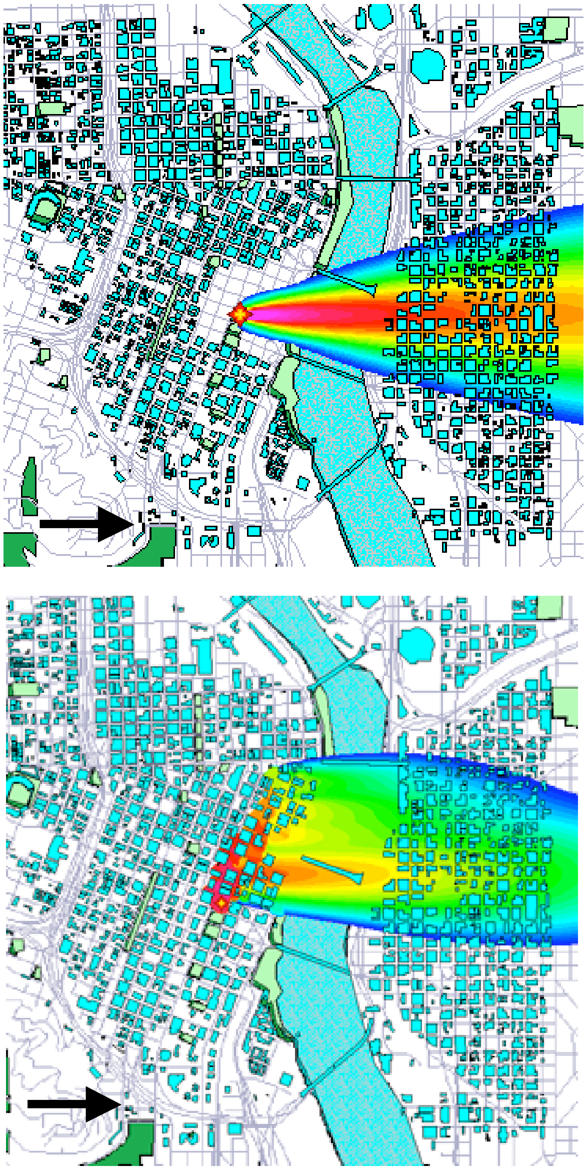

Figure 4. Simulations of plume dispersion in downtown Portland using the Urban Dispersion Model without (top) and with (bottom) buildings near the release location. With prevailing westerly winds, the plume is displaced to the northeast due to channeling when the influence of buildings are considered.

surface the plume can travel up side streets at oblique angles to the above-roof wind and only follows the upper-level wind when it is mixed above the building tops.

Figure 4 illustrates the importance that channeling can have on longer range plume transport. As shown in the two simulations using the Urban Dispersion Model, one without building effects and the other with building effects, the ground-

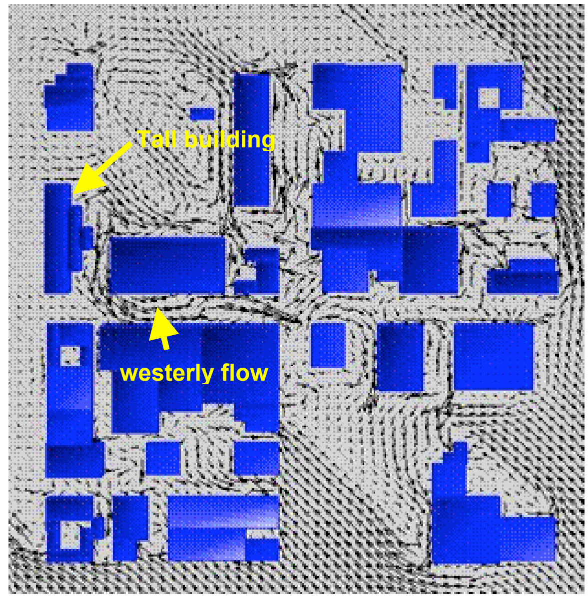

Figure 5. Simulation of winds in downtown Salt Lake City using the QUIC model. For southeasterly inflow, the tall building deflects some of the flow downwards into the street canyon resulting in westerly flow near street level, opposite to what is normally expected.

level concentrations are significantly displaced from one another. With the prevailing wind from the west, the case without buildings shows the plume traveling eastward leading to dangerous zones (denoted by the red areas) across the river to the east. With buildings, the plume first gets channeled to the northeast and then once the material gets above rooftop it travels eastward with the prevailing wind. However, the dangerous zones are now in a completely different place, to the west of the river and to the northeast of the release point.

d) The direction of winds in street channel.

As the wind shifts from being perpendicular to the street canyon axis to oblique angles, the flow pattern in the canyon is thought to switch from an in-canyon vortex to channeling. For idealized street canyons, the direction and strength of the channelized wind is often assumed to be proportional to the component of the wind aloft parallel to the street canyon (e.g., Yamartino et al., 1989). But for more complicated building arrangements (i.e., more realistic) these assumptions may not hold. Tall buildings can deflect the flow and result in ground-level winds in the opposite direction to that expected. For example, Fig. 5 shows a simulation with a prevailing wind from the southeast. In the east-west running canyons, the flow at street level is expected to be from the east. The results show winds in the opposite direction in one of the east-west running streets. This occurs because of flow blockage due to a tall building on the downstream side of the canyon which deflects the flow downwards into the street canyon resulting in westerly flow. This example illustrates that simple rules for channeling may not work in areas where building heights vary significantly. Models may need to keep some physics, e.g., mass conservation, in order to account for flow distortion and deflection by realistic building layouts.

e) Channeling – an intermittent phenomenon?

Channeling of winds at street level by buildings may be an intermittent phenomenon. That is, channeling may turn on and off and switch directions on short time scales resulting from subtle changes in the prevailing winds. Figure 6 shows measurements from a street canyon in downtown Oklahoma City where the winds periodically switch directions. This same phenomenon has been found in wind time series measured in a New York City street canyon (Reynolds, 1994). If this proves to be a common feature of street canyon winds, this will be difficult to account for in fast response models due to the intermittent nature of the process and the difficulty of specifying above-roof winds.

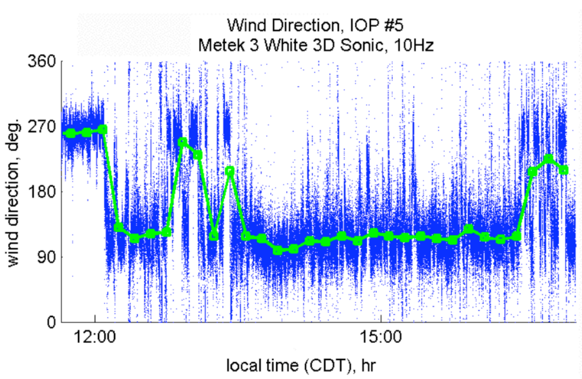

Figure 6. Time series of wind direction measured in a street canyon illustrating periods of rapid variation in flow direction.

f) Conditions of in-canyon vortex formation.

Many studies have confirmed the existence of a mean flow in-canyon vortex when the ambient wind is close to perpendicular to the street canyon axis (Fig. 7). The in-canyon vortex rotates vertically with an axis parallel to the street canyon and has been found to influence within street canyon concentrations and ventilation out of the street canyon (e.g., Georgi et al., 1967; Hoydysh et al., 1974). The literature suggests that the in-canyon vortex may disappear (or at least be secondary in importance to channeling) when the above-roof wind is within 30 degrees of parallel to the street canyon axis (Ludwig and Dabberdt, 1972; Yamartino et al, 1989). It is likely that this angle is dependent on street canyon length, the width of the street canyon and side streets, and the height (and relative heights) of buildings, among other things. For a street canyon in Chicago with a height-to-width ratio of about 1.4, Depaul and Sheih (1986) also found that the in-canyon vortex does not exist below a roof-level wind speed of 1.5-2.0 m/s. The conditions under which the in-canyon vortex forms and does not form needs to be accounted for in fast response dispersion models in order to accurately compute concentration distributions within street canyons.

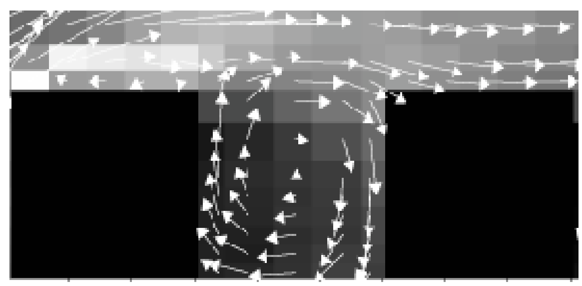

Figure 7. Wind-tunnel measurements showing In-canyon vortex in an array of wide buildings. Flow perpendicular to building face and building height-to-street width ratio of one. From Brown et al. (2000).

g) Deep-canyon mixing.

Computational fluid dynamics modeling (e.g., Mestayer et al., 1995; Baik and Kim, 2000) and laboratory experiments (e.g., Baik et al., 2000) suggest that there may be counter-rotating vertically-stacked vortices in deep street canyons. The stacked vortices alter the nature of vertical transport and dispersion. However, to date, there has been no confirmatory evidence of this in real street canyons. Several presentations at this meeting may address this issue (e.g., Eliasson et al., 2004).

h) Real cities vs. idealized building geometries.

Most of our understanding of flow and dispersion in and around building complexes comes from wind-tunnel experiments where the inflow wind is constant and building arrangements are generally idealized. For example, the ideas we have regarding the in-canyon vortex for skimming flow (H/W < 1) and counter-rotating vortices for wake interference flow (H/W ~ 2/3) originate from wind-tunnel experiments of wide buildings that are of equal height and the mean flow is more-or-less two-dimensional. For a real city, with buildings of different heights and shapes, and spacing between buildings varying in space (see Fig. 8, for example), it may be hard to find regions where simple straight-forward in-canyon vortex flow exists. That is, the flow field will most likely be a complex combination of 2D and 3D vortices (both horizontally and vertically rotating) and channelized flow.

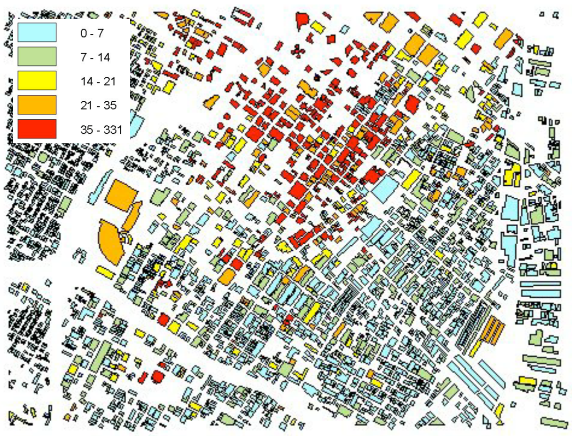

Figure 8. Building footprints for downtown Los Angeles. Color scale represents building height in meters.

i) Rapid vertical mixing.

It is well documented that a building that sticks up above surrounding buildings can result in enhanced vertical mixing (e.g., Wedding et al., 1977). It is hypothesized that intermittent spiral vortices develop on the downwind side of tall buildings exposed to the ambient flow. As shown in the snapshot in Fig. 9, these spiral vortices can transport material from near the ground rapidly to building top. This will reduce street-level concentrations locally near the release and change the downwind timing of the passage of the plume. Intermittent phenomenon that are non-local in nature are difficult to account for in fast response models. For a Gaussian puff type model, one common approach would be too force the puff to be equal to the building height when it interacts with the

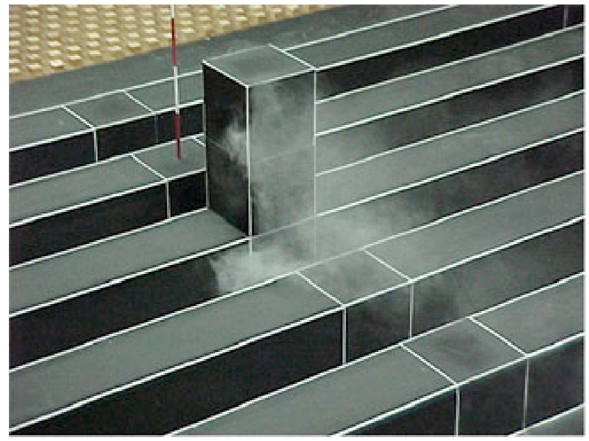

Figure 9. Snapshot of smoke mixing upwards on the backside of the building. The smoke release is at street-level in the canyon and the prevailing wind is coming out of the picture perpendicular to the building face. This intermittent mixing phenomenon is thought to occur due to intermittent spiral vortices that develop on the downwind-side of the building. Photo from the USEPA Meteorological Wind Tunnel courtesy of Bob Lawson.

building. However, because it is an intermittent phenomenon this would most likely result in an overestimation of vertical mixing.

j). Upstream transport.

Few fast response dispersion models account for upstream transport induced by building recirculation zones. Many experiments have shown that contaminants can be transported in the opposite direction of the prevailing wind due to the eddies and mean 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. As shown in the HIGRAD Large Eddy Simulation in Fig. 10, material from the release point is transported upstream in relation to the ambient wind due to the cavity flow, sidewall recirculation and channeling induced by the upwind buildings. This figure illustrates how initial lateral plume spread is greatly enhanced. In some cases, contaminated areas and potentially exposed population can be dramatically changed by upstream transport. Dispersion models that do not account for these near-source effects could provide misleading information if applied in cities.

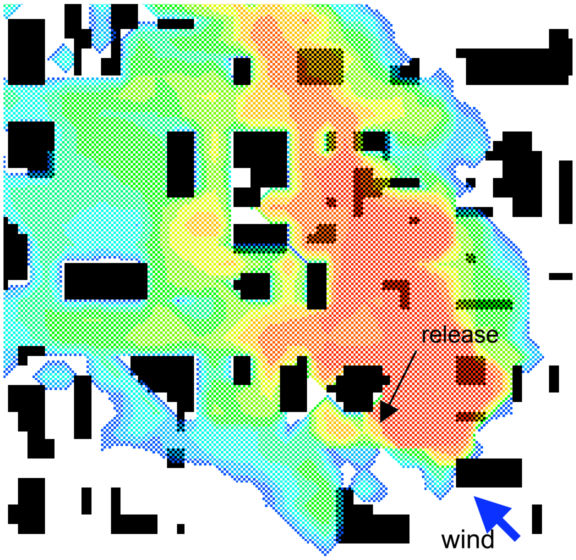

Figure 10. Concentration contours produced by HIGRAD LES illustrating upstream transport at point of release. Dispersion is dramatically enhanced laterally due to this upwind transport. From DeCroix and Brown (2002).

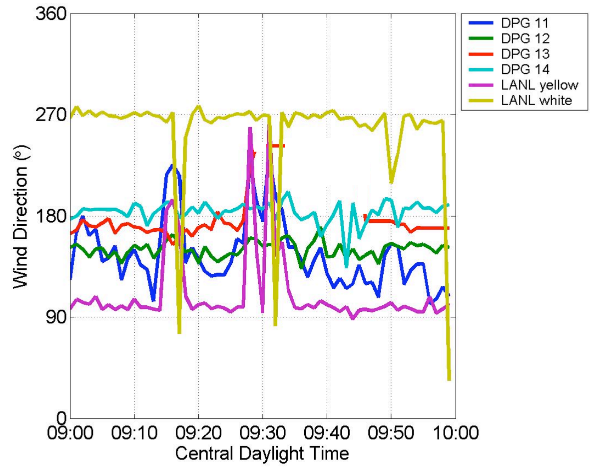

Figure 11. Wind direction measured at six different points in or near the Park Ave. – Broadway intersection in Oklahoma City. Note that sensors all within a street width of one another are measuring very different wind directions.

k) Intersections.

Winds in intersections and at street ends are thought to be very complicated. Winds at each of the four corners can all be blowing in different directions. This is illustrated in Fig. 11 which shows wind directions measured within and near an intersection during the Oklahoma City Joint Urban 2003 field experiment. Intermittent horizontally-rotating eddies that spiral upwards are thought to exist near the end of the street canyon and have been identified in wind tunnel smoke visualization experiments (e.g., Hoydysh et al., 1974). These corner vortices are thought to change the nature of transport and dispersion in street canyons (e.g., Cermak et al., 1974; Hoydysh and Dabberdt, 1988; and Hayden et al., 2002). In addition, subtle changes to the winds in the intersections may impact the nature of the flow in the adjoining street canyon (e.g., intermittent channeling, in-canyon vortex development). Hoydysh and Dabberdt (1998) found that concentrations within the same street intersection but on opposite sides of the street can vary by an order of magnitude. It is clear that transport and dispersion in intersections and near street canyon ends are very complicated and will be difficult to parameterize.

l) Impact of roof features.

Wind-tunnel experiments have confirmed that small-scale building features can influence transport and dispersion. For example, Rafailidis (1997) showed that peaked roofs resulted in significantly different concentrations in the street canyon as compared to those with flat roofs and had a stronger influence than building spacing. Kastner-Klein and Plate (1999) showed that peaked roofs interspersed with flat roofs – and which was upstream of the other - dramatically changed the concentration patterns in the street canyon. A wind-tunnel experiment by Cermak et al. (1974) showed that a rooftop structure on one corner of a street intersection changed street-level concentrations by a factor of two. Few fast response urban dispersion models currently have the fidelity to account for these effects.

m) Turbulence specification in the urban canopy.

At some stage, all but the most simple models require information on the turbulent velocity and/or length scales (e.g., u*, l_m). Plume or puff dispersion models often utilize the friction velocity to estimate plume spread parameters or to compute velocity profiles, random-walk models need to have the normal and shear stresses defined, and computational fluid dynamics models must satisfy boundary conditions which are often parameterized using a law-of-the-wall which is u* dependent. In general, fast response models need a parameterized form of these turbulent scales. Recently, there has been focused research done on whether similarity theories hold above the

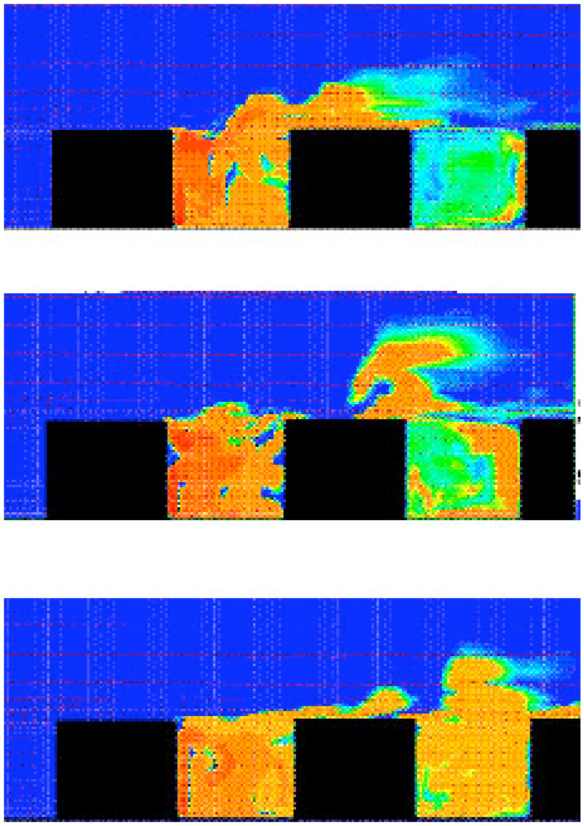

Figure 12. Snapshots of concentration contours from large eddy simulation of plume dispersal in street canyons. Release is in the 1st canyon near the back-wall and winds are from the left. Material is intermittently ejected and injected into street canyons by large building-induced eddies. From Smith et al. (2002).

urban canopy (e.g., Roth, 2000), but much less has been accomplished within the canopy layer. Exceptions include, for example, the work by Christen et al. (2002), Kastner-Klein and Rotach (2004), and Nelson et al. (2004). Further studies are needed in this area in order to advance the next generation of urban dispersion models.

n) Gradient-mixing vs. non-local mixing.

Many fast-response dispersion models utilize the concepts of gradient mixing, either implicitly or explicitly. For transport and dispersion around buildings, large eddies can act to physically transport contaminants from one point in space to another. For example, in the lee of a building, a cavity develops that intermittently flops laterally from side-to-side, resulting in significant mixing of materials released in the downwind cavity. Or, for a release in a street canyon, material intermittently is ejected out of the canyon resulting in periods of low and high concentrations in the canyon (Fig. 12). This "non-local" mixing is not adequately accounted for by gradient mixing theories. In the world of CFD, the distinct advantage of large-eddy simulation is the fact that it can account for non-local mixing since it explicitly models these intermittent vortices (large eddies) that develop around buildings. For fast response modeling, non-local mixing theories, however, are not well established and much uncertainty remains in their implementation. Initial work on implementation of non-local mixing ideas into random-walk modeling can be found in Williams et al. (2004) at this conference.

o) Tree effects.

In many cities, trees account for a large fraction of the canopy cover and can alter the heat and moisture budget (e.g., Oke, 1989). In addition, trees can slow down winds through drag, trap contaminants below leaf level, etc. Tree trunks may actually increase turbulence intensity near the ground (Gayev and Savory, 1999). An outdoor dispersion experiment around an isolated building could only be replicated by a CFD model when the drag from a row of Eucalyptus trees were accounted for in the simulation (Calhoun et al., 2000). In some instances, fast response models may need to account for trees to improve urban dispersion prediction capabilities.

p) Traffic effects.

Moving vehicles create turbulence and may alter the near-surface winds. Wind-tunnel experiments by Kastner-Klein et al. (2003) have shown that traffic can significantly impact ground-level and near-wall concentrations within a street canyon. Gaussian dispersion models were developed to account for vehicle-induced mixing through an initial vehicle wake plume spread parameter (e.g., Benson, 1992). As discussed in Kastner-Klein and Clark (2004), the scheme of Di Sabatino et al. (2003) is being implemented into the QUIC urban dispersion model. Although in principal it may be possible to approximate the effects of traffic on dispersion, it will be difficult to obtain data on traffic density and average vehicle speed for specific streets in a city of interest.

q) Real-time behavior.

As alluded to in prior sections, the real-time nature of the flow around buildings is less understood (and more difficult to model) than the steady-state behavior. For many airborne hazardous release scenarios, intermittent phenomena (e.g., peak concentrations) may be extremely important due to the health, lethality, or flammability properties of particular agents.

r) Atmospheric stability and heating of building surfaces.

Another key issue is atmospheric stability. Although cities have been shown to minimize stability effects, dispersion measurements show that plume spread is dependent on stability (e.g., McElroy, 1997). It is not clear whether this is a mesoscale feature due to the upstream air advected into and above the city, or if this is microscale feature resulting from different rates of heating (and cooling) of urban surfaces. CFD modeling studies have shown that heating of individual building walls radically changes the vertical structure of the flow within a street canyon (e.g., Mestayer et al., 1995; Kim and Baik, 1998) and around an isolated building (Smith et al., 2000). Large eddy simulations by Smith (1999) of dispersion during the daytime in the Washington DC Mall area showed large impacts due to heating at the surface. The plume was lofted into the air by convective eddies, whereas when the surface heating scheme was deactivated the plume traveled near the ground (Fig. 13).

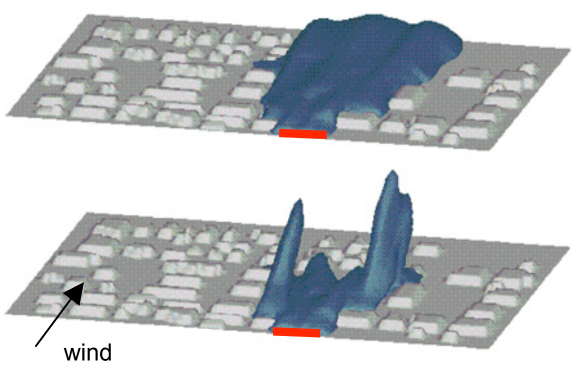

Figure 13. Iso-surfaces of plume for case of no surface heating (top) and surface heating turned on (bottom) in HIGRAD large eddy simulation of a line source release (red line).

4. Conclusions

Fast running urban dispersion models are needed for applications involving toxic agent releases in cities. In order to obtain accurate predictions of both plume concentrations and plume location, explicitly accounting for the effects of buildings is important. The complex flows that develop in and around buildings presents a serious challenge for fast response model developers, i.e., having a simplified model with enough fidelity to account for the complexities of transport and dispersion in cities. Specific challenges and difficulties were highlighted in this paper, including issues regarding turbulent mixing, mean flow prediction, and building geometry effects. There are certainly other challenging issues for successful urban dispersion modeling (e.g., indoor-outdoor modeling, porosity of parking structures, interaction with meteorological scales, impact of moisture and rain). A number of groups are making progress in this area, but much work remains to be done.

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