#220. **URBAN EXPERIMENT RESULTS CHARACTERIZE BUILDING WAKES, AIDING AIRBORNE HAZARD APPLICATIONS**

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ABSTRACT

In the first decade of this century, the U.S. Army Research Laboratory (ARL) conducted three urban field studies aimed at characterizing the airflow and stability around a small cluster of urban buildings. The third study, *WSMR 2007 Urban Study* (*W07US*), utilized 12 towers/tripods and 52 sensors over a two-week period, to provide a detailed measurement set. From this data set, the building wake region was characterized under light and strong wind conditions. The observational results will be presented, along with a description of what the impact these patterns might have on airborne hazard scenarios. This paper will describe the *W07US* field study, representative low and high wind case studies, the observed building wake character from each case, the results of model simulations for these cases, and the relevancy of the field observations to potential emergency First Responder, operational scenarios.

1. BACKGROUND

When a toxic airborne release occurs in a populated area, one of the first questions asked by an emergency responder will be: what is the status of the local wind? Urban environments are well known to have unique air flows around buildings and various terrain obstacles. Models developed to display the airflow activities were founded on accumulated observations. In this paper, we will describe the character of building wake air flows through measured observations and model output, as well as the relevancy of the observations to potential operational scenarios of Emergency First Responders.

1.1 Urban Field Studies Designed around Wind Tunnel Results

In 1994, the National Oceanic and Atmospheric Association (NOAA)/ Environmental Protection Agency (EPA) published results from a wind flow study that varied building height (H) – width (W) – length (L) ratios of a single solid structure, to characterize repeatable airflow patterns around these simulated buildings. At a scale ratio of 200:1, the full-scale boundary layer simulated was typical of rural terrain with shrubs and small trees. Seven distinct features were identified and labeled through their various cases (Snyder and Lawson, Jr. 1994).

The U.S. Army Research Laboratory (ARL) utilized the NOAA/EPA results to strategically place meteorological measurements that would potentially verify the airflow features reported in the wind tunnel study. The subject building was aligned north-south, with similarly-sized solid structures to the north and south of the subject building. Prevailing winds for the site were westerly. Three progressively more complex urban field studies did indeed verify the wind tunnel flow patterns and more. The seven flow features verified included: Fetch, Velocity Acceleration, Velocity Deficit, Cavity Flow, Re-attachment Zone, Leeside Corner Eddies and Canyon Flow (Vaucher et al, 2008). A description of each pattern follows (see figure 1):

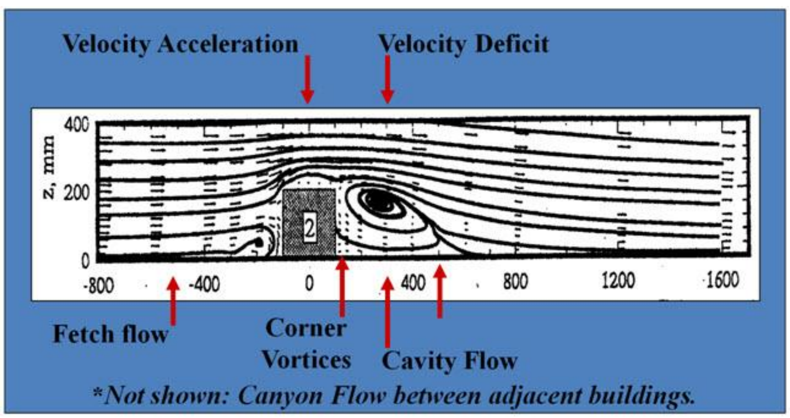

Figure 1. NOAA/EPA Wind Tunnel results captured airflow features.

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Using the subject building as a center reference, the Fetch wind is an upwind flow that has had no (minimal) interactions with the subject building. Once the flow reaches the building, the air rises over the building and is characterized by a slight acceleration. Consequently, this feature is called, “the Velocity Acceleration.” On the leeside (downwind) of the subject building, the airflow slows slightly and is called, “the Velocity Deficit.” With the building blocking the lower levels of flow, a shear is created that curls toward the ground. The net effect of this curl is an airflow direction reversal. This “Cavity Flow” feature will be described in greater detail later. Continuing away from the building on the leeside, the airflow re-attaches with the upper level’s uninterrupted flow, resuming the original Fetch character. This region is called “the Re-attachment Zone” or RAZ, for short.

Returning to the upwind (Fetch) side of the subject building, air that flows between buildings accelerates through the narrowed passageway. This effect is called “the Canyon Flow”, since the buildings create a canyon scenario with their impenetrable walls on either side of the open area. The acceleration of air can be explained using the Bernoulli Principle (or venturi effect). The last flow features are “the leeside corner eddies”, which are vortices on the leeside corners of the subject building.

1.2 WSMR 2007 Urban Study

In the first decade of this century, ARL urban field studies characterized the airflow and stability around a small cluster of urban buildings. The final study called, *White Sands Missile Range (WSMR) 2007 Urban Study* or “*W07US”*, provided the data for this subsequent investigation. The *W07US* utilized 12 towers/tripods and 52 sensors over a two-week period, to provide a detailed measurement set. The variables acquired included: pressure, temperature, relative humidity, wind speed, wind direction, and solar radiation. As stated earlier, the towers/tripods were strategically placed around the parameter of the subject building, based on the NOAA/EPA wind tunnel study. Thermodynamic data were sampled at 1-min averages. The dynamic data utilized high temporal resolution Ultrasonic sensors sampling winds (u, v, w) at 20 Hz. Figure 2 shows the general schematic of the urban field study. Instrumented towers included at least two and often three levels of wind sensors. For additional information on this study, see Vaucher et al, 2007.

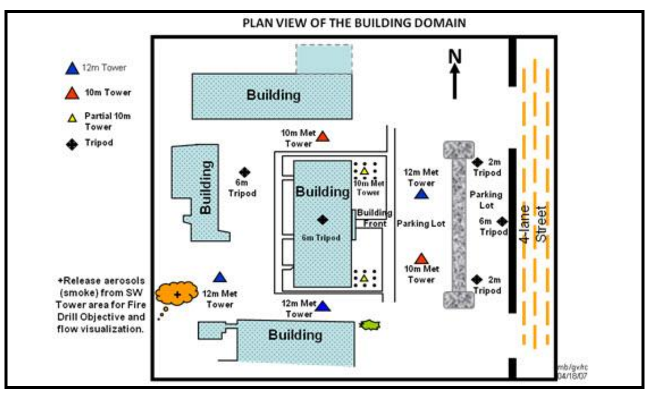

Figure 2. *W07US* test site layout. Black dots surrounding the partial 10 m towers were fence posts with tell-tail flags.

1.3 Cavity Flow

The regions of interested for this research were the Cavity Flow and the RAZ. As previously described, the Cavity Flow is best recognized by a flow reversal. To visualize the limits and character of this feature, the following summarizes the cavity height, cavity width, and cavity length observed in a wind tunnel (Snyder and Lawson, Jr., 1994). Note: Building length was the building dimension along the wind flow, and width was the building dimension facing the wind flow:

The cavity height was partly a function of the building dimensions. Wind tunnel studies have shown that when a building was a cube in shape (H=W=L), the cavity height was constrained to the building height. For wider buildings (W>H=L), stronger vertical velocities were observed on the leeside. In association with these velocities, the cavity height grew. For example, a cube produced a cavity height of H (building height); a building whose width was 10H, produced a cavity height of 3H/2.

For long buildings (L>H=W), the wind tunnel study showed a cavity height maximum (1.4H) when the building length was a minimum (e.g., a square flat plate standing on its edge). When the building length was greater than, or equal to, the building height, the cavity height effectively matched the building height.

For tall buildings (H > W), the cavity pattern initiated at the roof level, and formed a stagnation point below. This stagnation point was strongly dependent on the exponent of the power law describing the wind profile (Corke and Nagib, 1976). From the wind tunnel results, this point was about 2H/3.

The lateral extent of the cavity was bound by the two leeside corner eddies.[†]

The cavity length was independent of the building height, but did vary with building width. For example, for a cube, the cavity length was 1.4H. When the building width was 10H, the cavity length was 5.6H.

The subject building was purposefully selected to be wider than its height and length; therefore, stronger vertical velocities were expected on the leeside, as well as a variation in the cavity length. With fixed RAZ sampling sites, the latter variation could not be quantified. However, the orientation of the fixed site RAZ wind measurements was informative and thus, the concurrent RAZ data were included in this investigation.

2. CAVITY FLOW CASES

The original approach to this investigation used selected representative low and high wind periods, to frame the observed building wake character. The periods selected both occurred on 2007 March 23. In the course of analyzing these data, four distinct airflow scenarios came into focus, each appearing to be independent of wind velocity maximum or minimum. Consequently, the method for characterizing the wake region re-focused on these airflow scenarios. Each scenario will be described later in Section 2. First, an overview of the general atmospheric conditions for the March 23rd day will be presented.

2.1 Local Atmospheric Conditions for the Selected Cases

The general atmospheric conditions for 2007 March 23, were unstable. A Phase 1 weather warning for scattered thunderstorms began the day. Pre-dawn through about 1100 Local Time (LT) reported high humidity, which dried out until around 1400 LT, when conditions gradually returned to a moister environment by evening. A Phase 2 weather warning, called for severe thunderstorms with strong wind gusts over 55 mph, blinding rain and possible hail or funnel cloud activity for 1400 to 2100 LT.

Wind velocities from sunrise to noon were relatively low (wind speed <5 m/s) and variable. From 1200 LT–2200 LT, there was a consistent velocity increase. Peak velocities of over 22 m/s were recorded from the Roof anemometer (6 m above roof level). The variable wind direction converged into a west-northwesterly direction around 1400 LT. At 1900 LT, a distinct wind direction shift to west-southwesterly winds occurred. At 2200 LT, the wind velocities decreased rapidly and the wind direction was again variable. Temperatures for the day ranged from 8.2 °C to 21.8 °C. The solar radiation reached a peak value of 1109.3 W/m^2 at 1215 LT.

2.2 Four Airflow Cases

The low wind periods selected for study occurred between 1000–1100 LT and the high wind periods occurred between 1900–2200 LT. The criteria for these periods were based on the field study's sensor placement ideal, which called for a west to east airflow. To reduce the quantity of data analyzed, snapshot measurements were taken every 10 min and limited to a maximum of two vertical levels from the fetch, roof, canyon flow, and all leeside sampling towers/tripods. To visualize these measured values, the results were projected as arrows over a planar view of the test site. Figure 3 shows a sample of the low velocity results. The yellow arrows represent the top layer velocities at 10 m Above Ground Level (AGL) (6 m above the roof level for the rooftop sensor), and the red arrows map the lower level winds at 2.5 m AGL.

[†] ASIDE: Observations from the three ARL studies showed two distinct leeside corner eddy patterns. When a single tree, about the height of the building, was coincident with the building corner, the leeside corner eddies displayed well-defined, near-surface, circular flow. When these trees were removed, a much wider, complex vortex was mapped.

Figure 3. ***W07US*** **low velocity, Northwest fetch case with a leeside, low level, northerly circulation. Yellow vectors are 10 m AGL; Red vectors are 2.5 m AGL.**

Grouping Fetch orientations together, four airflow scenarios were observed: (1) a northwest fetch with a leeside low level northerly flow, (2) a southwest fetch with a leeside low level southerly flow, (3) a westerly fetch with a leeside low level convergence, and (4) a westerly fetch with a leeside low level convergence and cavity flow.

The following comments are based on field measurements only: Whether low or high velocity winds, the upper level winds flowing over the building maintained their original orientation even after the building. Whereas the low level winds on the leeside appeared to lose their westerly component and take on the secondary dominant orientation. For example: When the approaching air was Northwesterly, the leeside low level circulation was northerly (refer to figure 3) or even northeasterly, as see in the higher velocity cases (figure 4). When the airflow approached the subject building from the Southwest, the leeside lower level was southerly (figure 5).

Figure 4. ***W07US*** **high velocity, Northwest fetch case with a leeside, low level, north-northeasterly circulation. Yellow vectors are 10 m AGL; Red vectors are 2.5 m AGL.**

Figure 5. ***W07US*** **high velocity, Southwest fetch case with a leeside, low level, southerly circulation. Yellow vectors are 10 m AGL; Red vectors are 2.5 m AGL.**

For Westerly fetch flow, the leeside low level result had two orientations: (1) a cavity flow in the southeast tower data with an implied center convergence flow in the northeast tower data (figure 6), and (2) a center convergence flow created by the southeast and northeast 2.5 m AGL wind orientations (figure 7).

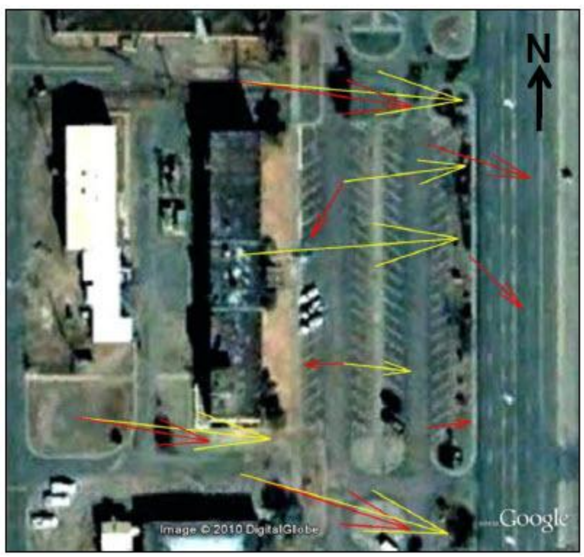

Figure 6. ***W07US*** **high velocity, Westerly fetch case with a leeside, low level, cavity flow in the southeast tower data and an implied center-convergence in the northeast tower data. Yellow vectors are 10 m AGL; Red vectors are 2.5 m AGL.**

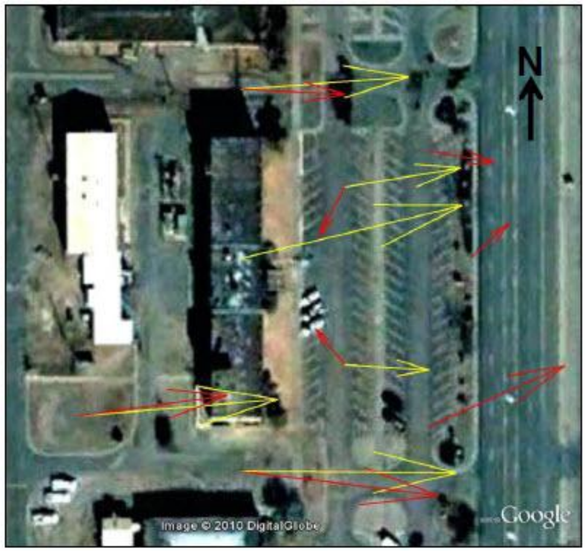

Figure 7. *W07US* high velocity, Westerly fetch case with a leeside, low level, center-convergence. Yellow vectors are 10 m AGL; Red vectors are 2.5 m AGL.

2.3 Model Simulations

The wind flow model simulations utilized an early building-scale version of the ARL Three-Dimensional Wind Flow (3DWF) Model created by Dr. Yansen Wang. This high resolution wind flow model is a diagnostic model that computes a three-dimensional wind field around surface obstacles in the boundary layer. The model presumes a conservation of mass, solves a variational/minimization problem, uses multi-grid (in the version used by this study) or Bi-Conjugate Gradient Stabilized methods (in a later version), and a parameterization of building wake and forest canopy flow.

The data input consisted of a Fetch profile that best represented the four scenarios described earlier. The output focused on the low level flow (a 2.5 m AGL horizontal slice). For the northwesterly and southwesterly flow cases, the model concurred with the low level circulation taking on the Fetch's secondary wind direction component. For the Northwesterly case, the leeside low level circulation took on a clockwise rotation. The Southwesterly case showed a counterclockwise rotation in the leeside low level flow. The outer border of this circulation was where the model and data painted a slightly different pattern for the Northwesterly case. The data implied a larger rotation, with a smaller leeside corner eddy. The Southwesterly case showed less of a contrast between model and data. The Westerly cases modeled a clean cavity flow (figure 8).

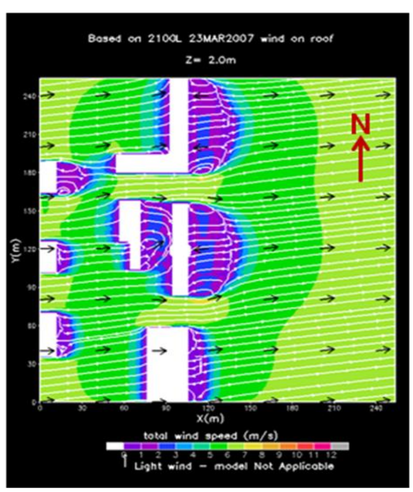

Figure 8. 3DWF-Westerly fetch results from Mar 23, 2100 LT simulation.

3. DISCUSSION

Variations between model results and data were expected, since the diagnostic model precedes the inclusion of local plant/foliage morphology. As explained earlier in the 'Aside', the impact of having the two leeside corner trees removed just before the field study execution was significant on the flow patterns. In fact, the dual tree removal may help explain the Westerly case (figure 7) convergence pattern, which will be discussed in the next section.

3.1 Building Effects on Leeside Low Level Flows

With the Westerly fetch flow, one would expect a clean cavity flow on the east side of the building. After a closer inspection, the Fetch flow at 10 m AGL had a slight northerly component, which was more evident in the 2.5 m AGL measurement (refer to figure 6). To the west of the subject building was a smaller-in-width building aligned on the north with the subject building. The air with the cleanest approach was on the south side of the subject building. Focusing on this south side, the southeast tower reported a well defined cavity flow. Upper and lower wind measurements were almost 180° apart. The south canyon flow was slightly northwesterly, indicating that the canyon outflow was not interfering with the wake of the building. Though, by the time the air reached the RAZ-southeast, there was a weak southwesterly wind, implying a spreading out of the canyon flow air.
Focusing on the north portion of the subject building, this air was channeled through a canyon and maintained the slight northwesterly orientation. Apparently, that northerly component coupled with an open eastern area was sufficient to re-orient the expected low level easterly cavity flow into a northeasterly flow. The leeside corner eddy rotation would be clockwise, complimenting this northeasterly orientation.

This curious Western Case wake pattern expands into a full leeside convergence for the second Westerly fetch scenario observed. For this case, the closer inspection revealed a slight southerly component in the Fetch flow (refer to figure 7). Once again, dividing the subject building into two portions, the south portion airflow begins with the west-southwesterly fetch, accelerates through the canyon maintaining this southerly element, and on to the RAZ-South where the winds bluntly show southwesterly flow. In contrast, the north portion of the building begins with the same west-southwesterly fetch, accelerates through the canyon maintaining the west-southwesterly flow in the upper level, but taking on a more westerly flow near the surface, then on to the RAZ-North where the winds show northwesterly flow. Observing the leeside low levels, the southeast and northeast towers indicate a low level convergence aimed at the front center of the subject building.

One potential explanation for this convergence is that what would have been a clean cavity flow is actually an extension of the north and south leeside corner eddies. Unlike the earlier two field studies, the test site no longer had trees on the leeside building corners to comb the air into well-behaved vortices that were confined to a short distance from the building (see figure 9). Without these trees, the eddy expanded laterally, even to the point of including what was a cavity flow zone. Clearly, more investigation is needed, to understand the ebbs and flows quantified within this dataset.

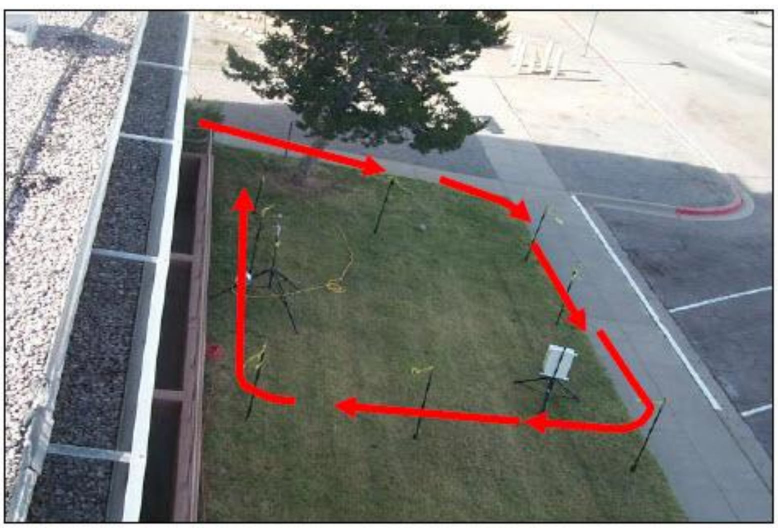

Figure 9. Northeast leeside corner eddy/vortex was visually mapped by tell-tail flags tied to fence posts during *WSMR 2005 Urban Study*. Notice proximity of the tree. This tree was removed just prior to *W07US*.

3.2 Relevance of Field Observations to Potential Operational Scenarios

The patterns observed within this study continue to confirm wind tunnel results and provide feedback for airflow model development. With respect to operational scenarios, the ARL has also been utilizing studies such as this one, to develop and refine tools for Emergency First Responders, such as the Local-Rapid Evaluation of Atmospheric Conditions (L-REAC^{TM}) System (Vaucher et al., 2009). The patterns discussed above are extremely relevant to the emergency responders dealing with airborne chemical/biological releases around urban buildings. For example, before determining how to approach a hazardous site without endangering the rescue crew, the upwind direction needs to be defined. Once crews are at the site, the extent of the cavity or leeside eddy flow is critical in helping them smartly place their emergency vehicles and triage areas. Within the subject building, the occupants need to know whether exiting the building will truly liberate them from the danger, or bring them right into the toxic environment (such as exiting into a hazard-filled, leeside convergence region). And finally, once the residents are outside of the building, where is the safest location for reconstituting the group to assess the effects of the hazard? To answer these concerns, knowledge of the local forcing factors in the urban environment needs to be provided. Full protection of personnel requires a combination of observations, modeling, and timely communications for rapid decisions.

4. SUMMARY AND CONCLUSIONS

Three progressively more complex urban field studies were conducted over the past 10 years that aimed at characterizing the airflow and stability around a small cluster of urban buildings. These studies were based on the NOAA/EPA wind tunnel results published in 1994. The third study, *WSMR 2007 Urban Study* (*W07US*), utilized 12 towers/tripods and 52 sensors over a two-week period, to provide a detailed measurement set. The field site was purposefully chosen to maximize the leeside flow variations described in the wind tunnel results. From the *W07US* dataset, the building wake region was characterized under light and strong wind conditions. Four building wake patterns were observed which were independent of wind velocity strengths.

The four building wake patterns observed were: (1) a southwest fetch with a leeside low level southerly flow, (2) a northwest fetch with a leeside low level northerly flow, (3) a westerly fetch with a leeside low level convergence, and (4) a westerly fetch with a leeside low level convergence and cavity flow. The leeside patterns for the northwesterly and southwesterly flows had similar attributes: the upper level winds continued in the direction of the Fetch winds; the lower level winds lost their west component, yet continued with the secondary component. For example, the northwesterly fetch produced a low level northerly flow on the leeside (clockwise). The southwesterly fetch produced a leeside, low level southerly flow (counterclockwise).

The westerly case generated two scenarios: (1) a cavity flow in the southeast tower with an implied center convergence flow in the northeast tower, and (2) a center convergence flow created by the southeast and northeast 2.5 m AGL wind orientations. Upon closer examination, the first scenario may have been a function of the upwind morphology. The second scenario's center convergence pattern may be an expansion of the leeside corner eddies. This latter pattern was unique to the earlier field studies that included leeside side corner trees as part of the field test site. These trees were removed just prior to the *W07US* field study.

Each of the four cases was simulated with the diagnostic model 3DWF. The results re-enforced the general patterns observed in the *W07US* field study. The field observation relevancy was described in context of an operational Emergency First Response application. Based on the above results, perhaps a better description for the cavity flow would be: a leeside flow in which a vertical discontinuity of the upper and lower winds is observed; this discontinuity can be as great as a vertical flow reversal.

5. ACKNOWLEDGEMENTS
The authors would like to thank the *W07US* field study participants for acquiring the detailed urban dataset, as well as Dr. Yansen Wang for use of his 3DWF-v1 Model, and NOAA/EPA, for the use of their Areal Location of Hazardous Atmospheres ALOHA model.

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