J6.4 NEAR-BUILDING TURBULENT INTENSITIES, FLUXES, AND VORTICES

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1. INTRODUCTION

A series of urban field studies were conducted to detect, identify and characterize turbulent and mean flow features and behavior that are generated by interacting with a single building. These field measurement activities occured during 2003 through 2005 by scientists and engineers of the US Army Research Laboratory (ARL). Development of new models and the improvement of existing micro-scale model/codes drive the need for better understanding of these processes and phenomena in both space and time. First-order, microscale wind models for the surface layer require parameterizations of both vertical and horizontal eddies to generate various processes and effects as airflow interacts with building arrays. Recently micrometeorological boundary layer modeling at ARL has expanded from airflow over complex terrain and within and above vegetative canopies to now include flow in and about urbanized areas (Cionco, 2000). Research also has addressed the coupling of mesoscale models to these first order microscale models (Cionco and Luces, 2002 and 2004).

This paper addresses turbulent flow and the computation of the characteristics, fluxes, and vortices that developed about and above a single building. The sensor placement and over all design was constructed to locate and measure formation, intensity, and dissipation of flow features reported by wind tunnel, water channel, and field experimentalists. Our previous studies (Cionco, Vaucher, and Yee, 2004) documented the vertical eddy flow reversal and several other mean flow features found by others researchers. Our recent study expanded our scope to also measure and identify horizontal eddies that are generated just downwind of the model building's corners

For 2005, our study was designed to document the behavior of turbulent flow and eddy structure as well as the mean flow conditions. Our objectives focused on the turbulent behavior of the flow field and detecting and identifying the presence, location, and persistence of: 1.) the flow reversal as a vertical eddy in the cavity zone downwind of the building; 2.) velocity deficits and enhancements downwind from the reference tower due to the influence of the building; 3.) accelerated flow over the roof top; 4.) the reattachment zone downwind of the building; 5.) horizontal eddy structures just downwind of the building's corners, and 6.) channeled and accelerated flows between the building and adjacent buildings. Preliminary results derived from computations and analyses of turbulence properties and characteristics and behavior patterns as the flow is influenced by the presence of our model building also are part of this paper. Our study of Turbulence and Airflow About a Building, EXperiment 2005 is referred to as TAABEX'05.

2. BACKGROUND

After several decades of limited non-air quality research for urban domains, boundary layer and micro-meteorologists have recently returned their focus to urban meteorology and diffusion in the field, laboratory facilities, and ultra-high resolution numerical simulation studies. The scope of these newer studies ranges from the full urban boundary layer to the central business district and on to single buildings addressing both airflow and dispersion processes in time and space. A main source of information and guidance on urban climate processes can found in numerous publications by Oke (such as 1987) and his colleagues.

Most notable is the increase in atmospheric airflow and diffusion field studies in a variety of urban scenarios. Studies such as Urban 2000 (Allwine et al, 2002), ESCOMPTE (Cros Et al, 2002), BUBBLE (Rotach, 2002), DAPPLE (Dobre et al, 2004), and Joint Urban 2003 (Allwine et al, 2004) as well as earlier studies such as by DePaul and Sheih (1984) in a Chicago street canyon have added considerable knowledge for international researchers.

Controlled studies in nature where containers, boxes, and panels are placed on flat, open terrain in geometrical arrays have been conducted as crossover studies with qualities of both the atmospheric and laboratory approaches. . Studies such as MUST (Biltoft et al, 2001) conducted by government and university scientists occurred during the time of the 9/11 attack while Roth and Ueda (1998) and others were conducting wind tunnel studies over roughened surfaces.

A larger number of laboratory studies have been on-going for more than 30 years for both flow and dispersion focused on clusters of simulated urban structures as well as single model buildings of varying lengths, widths, heights, and spatial arrays. Several wind tunnel and water channel flow and diffusion studies such as those more recently by Snyder and Lawson (1994), Roth and Ueda (1998), Macdonald (2000), Brown et al (2001), Leitl and Schatzmann et al (2004), and much earlier studies by Cermak et al (1974), Hoydish & Dabberdt (1988) and numerous others have add to the reservoir of knowledge. Studies such as those by Snyder and Lawson as well as others clearly show flow patterns of flow reversal as a vertical eddy downwind of a single building and horizontal eddies developing downwind of both corners of a single building.

CFD modelers also address flow patterns within model urban domains. Most recently, CFD simulations by Coirier and Kim (2005) and Lundquist and Chan (2005) clearly show horizontal eddies forming downwind of and between buildings. Others such as Huber et al (2004) and Baik and Kim (1999) generate single and double vertical eddies in model street canyons for modest sized model buildings. Others have shown also how the vertical eddy adjusts itself upward for taller buildings and deeper canyons. Huber's CFD simulations match the flow fields measured in a wind tunnel by Snyder and Lawson (1994) for several rows of model buildings in the first street canyon and so on downwind.

Several studies of diffusion patterns about model buildings have also been to determine how aerosol plumes travel around corners and about the downwind side of model buildings. Cermak et al studies showed that aerosol concentrations tended to be higher behind the building where the corner eddies formed, while Hoydysh and Dabberdt found lesser concentration in the same area.

3. DESCRIPTION OF TAABEX'05

A description of the TAABEX design, field site, sensors, and meteorological conditions follows.

3.1 TAABEX Design

The ARL studies were conducted with one building such that the 'street canyon' does not have the opposing structures of the JU2003 street canyon study described by Brown (Brown et al, 2004). Based upon guidance derived from wind tunnel studies by Snyder and Lawson (1994) and the success of our original study, multiple towers were located on each side of the model building as well as on the rooftop.

Dimensions of the building under study and its orientation are important factors in determining where to place measurement sites. In that our model building is wider (W) than it is deeper (L) in relation to building height (H), a ratio of W/H was calculated to be 6.6. For our study, W is the cross-stream face of the model building. Snyder and Lawson addressed building W/H ratios of 2 to 10. They also considered a variety of L/H ratios not covered in this discussion. Knowing our ratio and analyzing the wind tunnel results, we were able to locate each tower and tripod on the first try for each purpose. Snyder and Lawson and others show the development of a vertical eddy directly downwind as well as the formation of horizontal eddies just beyond the downwind corners of a building. Brown et al (2004) and Kastner-Klein and colleagues (2004) also confirmed the presence of these corner vortices in a street canyon for a building ratio of 5. Figure 1a locates the positions of the flow features with respect to a model and therefore the designated placements of the towers and tripods. Figure 1b displays the horizontal corner eddy locations and behavior as documented in wind tunnels.

One tower was located upwind of the model building for the reference measurements. Another tower was located downwind of the building in the cavity zone. Two towers were placed on each side of the building near adjacent buildings (out of necessity). The tower on the roof was placed away from the leading edge at the center of the roof area and upward into the general flow zone. Three additional tripods with sensors were also located in the downwind reattachment zone and just beyond the downwind corners of the building. The use of fast response wind sensors permits the collection of turbulence data that are used in the computation of turbulence properties and indices and mean flow values. See Figure 2 for a plan view of the relative positioning of each tower with the three additional tripods of wind sensors added for the final study. Note that the placements and sizes of the buildings are not exactly to scale in the Figure 2.

3.2 Field Site Description

The field site is located on near flat terrain. There is a slight loss of a few meters of elevation from west to east. The model building is rectangular with the following dimensions: width = 72.7m (north-south), length = 12.8 m (west-east), and height = 11m at the Southeast corner of the building. The surrounding buildings also are simple rectangular shapes located at different distances from the model building. Figure 2 depicts the layout for the model buildings and towers. Table 1 provides linear distances and orientation of each tower and tripods in relation to the walls of the model building for both the original and final study placements. Note that the Southwest, Rooftop, Northeast, and Reattachment sites were lined up along the prevailing flow trajectory (from 225 degrees towards 45 degrees). The other towers and tripods are parallel to their adjacent wall.

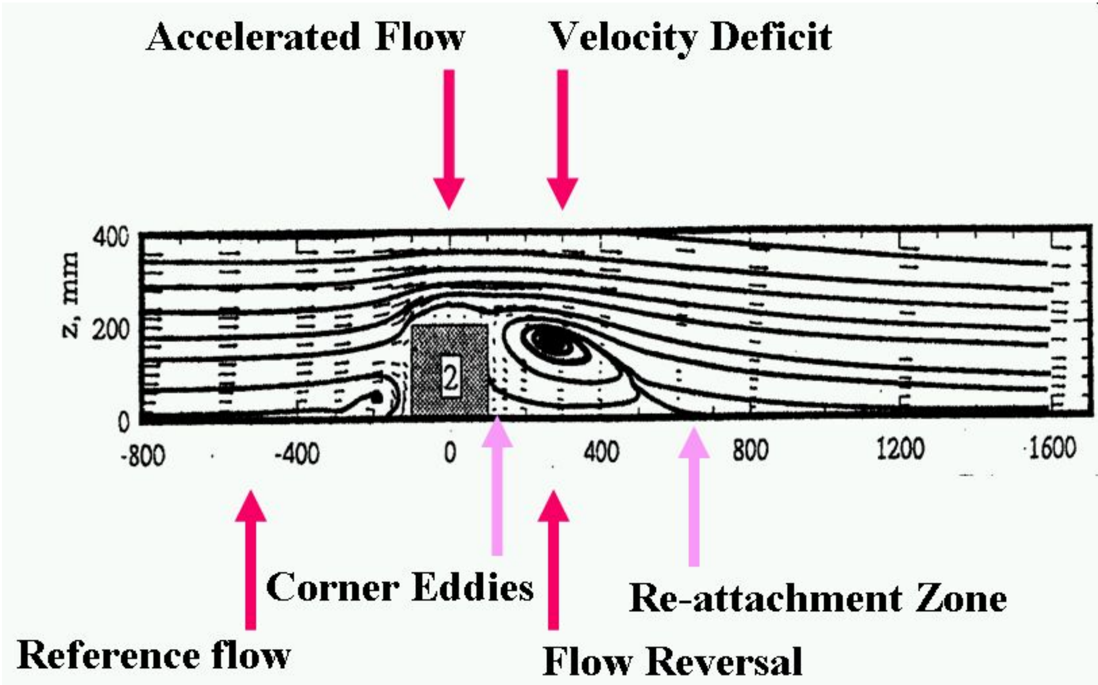


Figure 1a. Placement of towers and tripods of sonics about the building (2) to detect these flow features

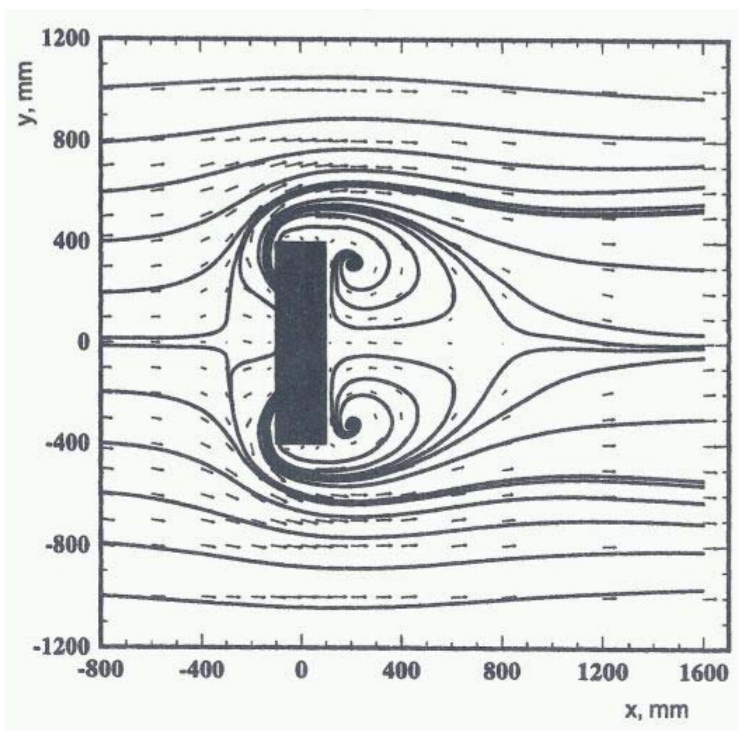


Figure 1b. Ideal behavior of corner eddies downwind of a single building where W > H

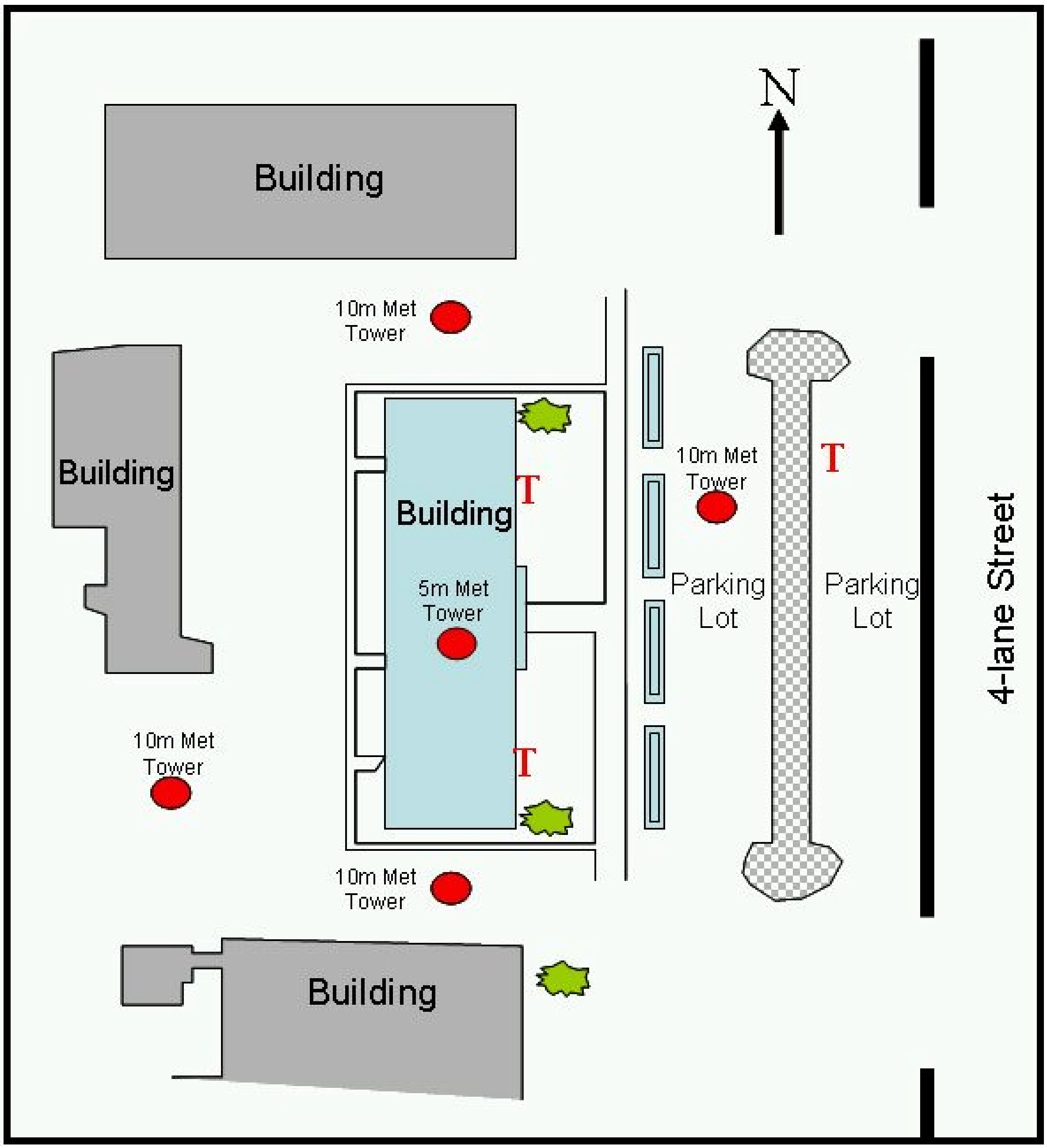


Figure 2. Plan view of tower and tripods (T) placements about the building

Table 1. Distances of meteorological towers and tripods in relation to the respective walls of the model building and the center point of the roof area

TOWER NAME	DISTANCE (m)	ORIENTATION
SOUTHWEST (REFERENCE)	33m	225^0 FROM THE CENTER OF THE ROOF AREA
ROOF TOP	+5m ABOVE THE ROOF	AT CENTER OF THE ROOF AREA
NORTHEAST (CAVITY ZONE)	42m	45^0 FROM THE CENTER OF THE ROOF AREA
REATTACHMENT ZONE	20.0m Downwind of NE Twr	45^0 FROM THE CENTER OF THE ROOF AREA
NORTH SIDE	10.4m	PARRALLEL TO NORTH WALL WEST-EAST
SOUTH SIDE	11m	PARRALLEL TO SOUTH WALL WEST-EAST
NE CORNER (EDDY)	2.3M FROM WALL 7.45M FROM EDGE	JUST BEYOND WALL AND INWARD FROM THE CORNER
SE CORNER (EDDY)	2.4M FROM WALL 7.45M FROM EDGE	-JUST BEYOND WALL -INWARD FROM THE CORNER

3.3 Sensors and equipment

During the 2003 field study, wind birds and thermodynamic sensors were used to document mean values and conditions. In that the 2005 study directly addressed turbulent flow and eddy behavior about the same building, fast response anemometers units were used to measure the three wind components (u,v,w), ambient temperature T, and the speed of sound. The wind unit is an R. M. Young sonic anemometer-thermometer, model 81000 here after referred to as sonics or sonic anemometers.

Three levels of sonic anemometers were mounted at 2.5, 5.0, and 10.0m on four ground-based 10m towers and also at 5.0m on the roof-mounted mast. Three additional sonic anemometers were mounted on tripods at 2.0m and placed just beyond the downwind corners of the building and some greater distance downwind in the reattachment zone. The sampling rate of each sonic was 20HZ. All data were organized as one hour records to stay within the limits of the data logging system and storage units. Table 2 provides a list of the sensors and their locations and vertical levels.

Table 2. List of sensors, locations, and levels for each tower and tripod

TOWERS	SENSOR	LEVEL (M)	VARIABLES
SOUTHWEST (Reference)	R. M. YOUNG 81000	2.5, 5.0,AND 10.0M	uvw,T and speed of sound
ROOF TOP	R. M. YOUNG 81000	5.0M only	uvw,T and speed of sound
NORTHEAST (Cavity ZONE)	R. M. YOUNG 81000	2.5, 5.0,AND 10.0M	uvw,T and speed of sound
REATTACHMENT ZONE	R. M. YOUNG 81000	2..0M only	uvw,T and speed of sound
NORTH SIDE	R. M. YOUNG 81000	2.5, 5.0,AND 10.0M	uvw,T and speed of sound
SOUTH SIDE	R. M. YOUNG 81000	2.5, 5.0,AND 10.0M	uvw,T and speed of sound
NE CORNER	R. M. YOUNG 81000	2.0M only	uvw,T and speed of sound
SE CORNER	R. M. YOUNG 81000	2.0M only	uvw,T and speed of sound

3.4 Meteorological conditions

The field study was set up to take advantage of the very predictable Southwesterly flow regime during springtime (March) in the desert Southwest region of USA when upper level troughs pass through the area resulting in tight pressure gradients. Wind speed tends to be moderate to strong during this time ranging 4 to 20 m/s during the day and 10m/s or less and short periods of calm through the night hours. Wind directions, except for nocturnal periods of calm and near calm, consistently are Southwesterly and Westerly. Sky conditions for the most part are clear, but occasional periods of fair weather clouds traversing the domain did occur. Precipitation was not in the forecast, nor was it an issue. A considerable volume of daily upper and surface data was collected and archived during TAABEX'05. Daily forecasts were also made to support the field operations based upon numerous analyses available on the INTERNET provided by a wide variety of organizations.

4. VORTEX BEHAVIOR AND COMPUTATIONAL RESULTS

Earlier results on the mean flow behavior about the model building have been reported by Cionco et al (2004). Flow features such as accelerated flow above the rooftop, velocity deficits downwind from the reference tower about the building, and channeled and accelerated flows between adjacent buildings as well as the flow reversal in the vertical downwind of the building. During the 2005 study, the same tower set up was used with some enhancements for the final study. In order to capture the horizontal eddy structures forming just downwind of the corners of the model building, additional sonics were deployed on two tripods at the 2.0m level. In that the re-occurrence of similar features was readily discernable, our focus will be on detecting and further quantifying the vertical and horizontal eddy structures. Time histories of wind speed and direction at each of the three levels of the upwind (SW) and downwind (NE) towers for the March 23, 2005 diurnal period are the example data set for discussion.

Computations and analyses of turbulent indices and fluxes are based upon values of the three components of the wind, u, v, and w, and the ambient temperature given the speed of sound for 30 March 2005.

4.1 Flow reversal in the cavity zone

Clearly the reversal of airflow in the cavity zone downwind of the building appeared during the final study as well. A comparison of the reference upwind tower (SW) data to the downwind tower (NE) data depicts the time and space development of the vertical eddy structure following a night time of unfavorable light and variable conditions. Figure 3 is the data trace for the upwind tower and Figure 4 is the data trace for the downwind tower. The time histories start at 0000 Hrs and end at 2359 Hrs where the 10m data is coded red, the 5m data is coded green, and the 2.5m data is coded blue. Between 0000Hrs and about 0230Hrs, the winds were clearly light and variable at both towers. Just before 0300HRS, the wind speed increased to 3 to 5m/s and up valley flow was established from the Southeast direction at each of the three levels. The organized Southeasterly flow remains until about 0830Hrs a short time after the transition of stabilities occurred at both of the towers. From 0830Hrs on, West winds (270 degrees) were established at the Reference tower at all levels and the wind speeds were mostly in the 5 to 10m/s range through the period to midnight.

Referring to Figure 4, the data at each level depicts behavioral differences. At the 10m level both speed and direction mirrored the upwind 10m data except that speeds are somewhat diminished (similar to the velocity deficit noted in the original study). Wind direction remained from the West (270 degrees) at 10m, but at the 2.5m level wind direction varied from South through East strongly suggesting a flow reversal from 10m to 2.5m. The 5m data basically supported this flow reversal in that the directions vary from Southeast through North Northwest from moment to moment appearing to reflect the cull region of a vortex.

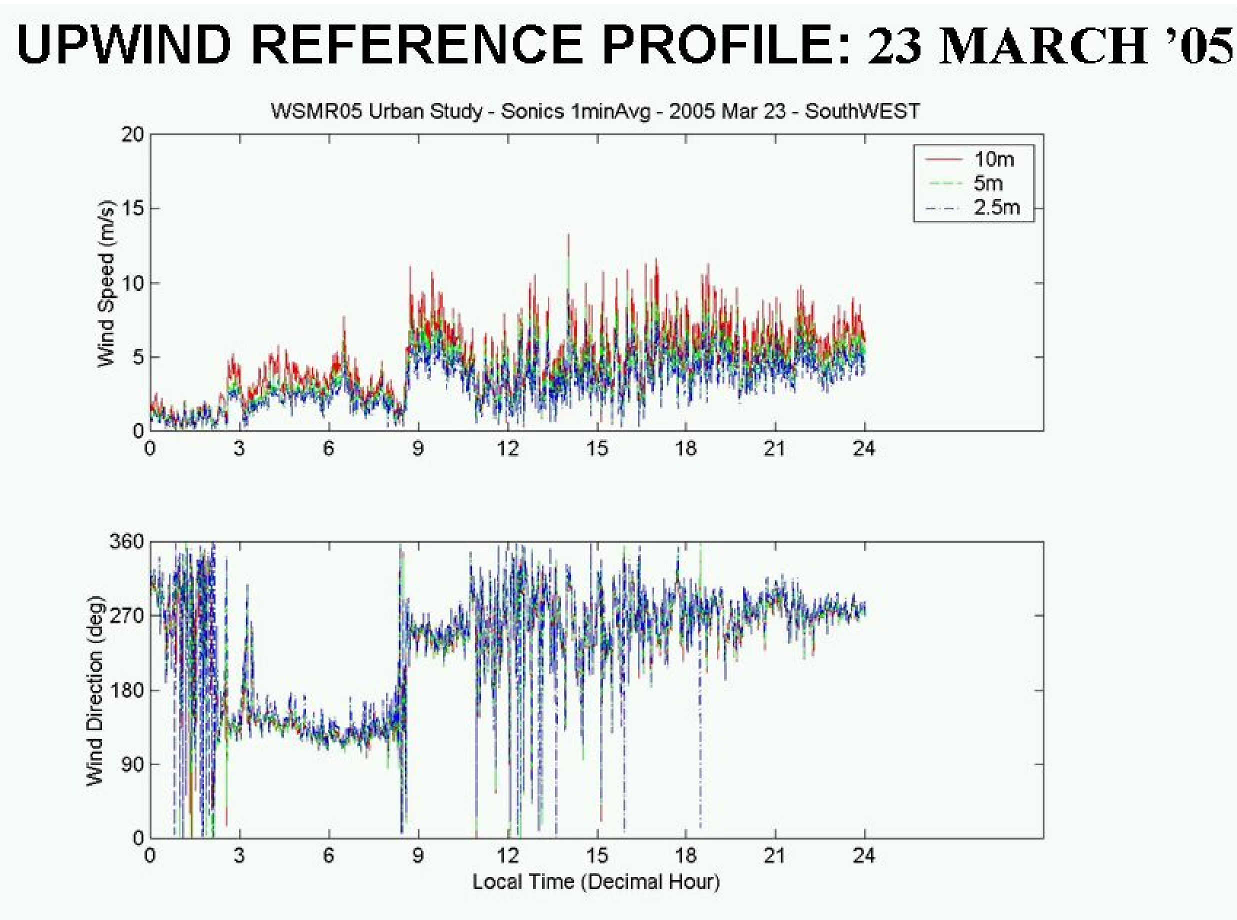


Figure 3. Time histories of wind speed and direction for 23 March 2005 at the upwind reference tower Note the stronger westerly flow setting in after 0830Hrs at all levels.

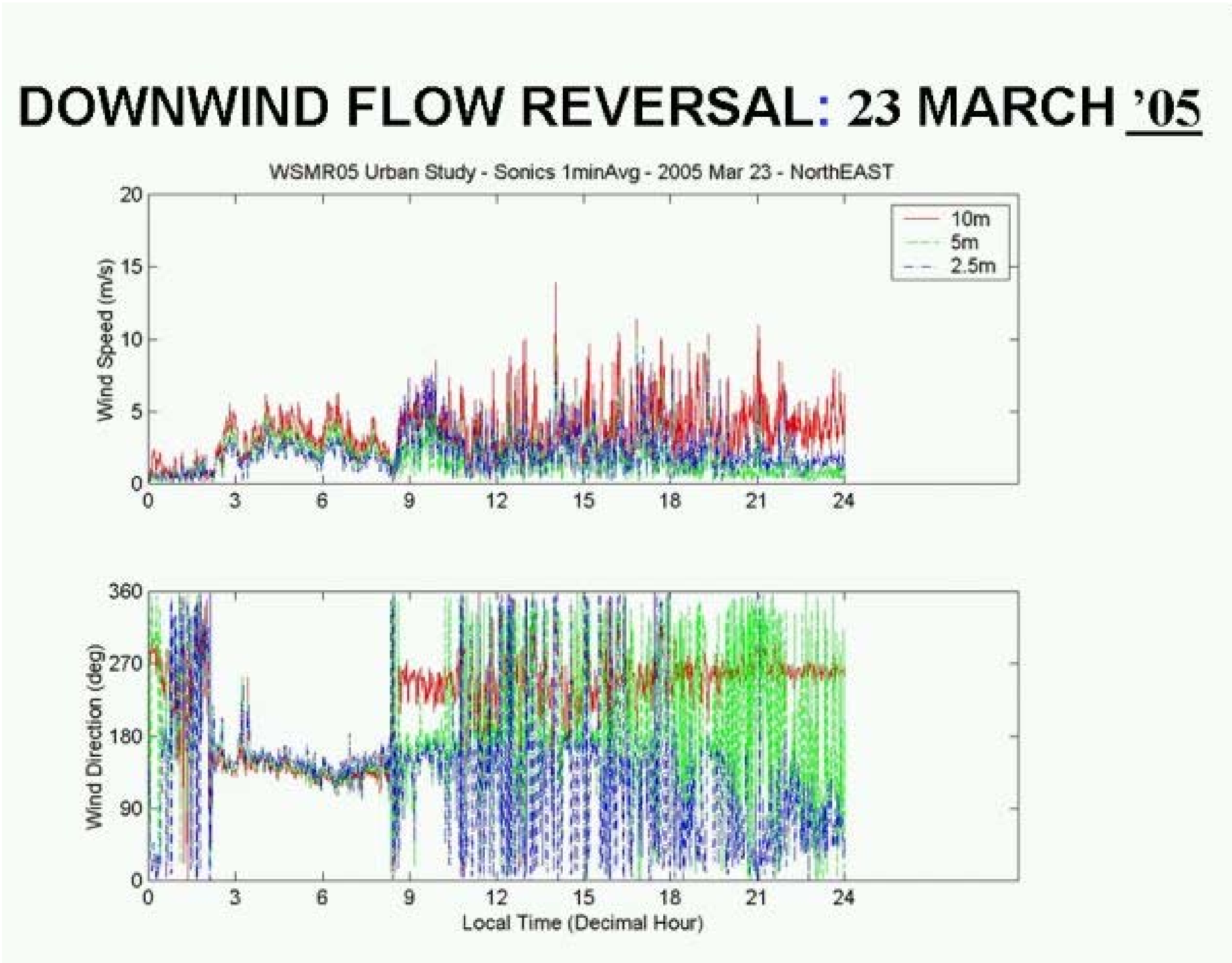


Figure 4. Time histories of wind speed and direction for 23 March 2005 at the downwind side of the building for comparison to Figure 3 After 0830Hrs, the 10m level direction remains from the west while the 2.5m direction (blue) reverses direction to easterly varying from northeast to southeast indicting an eddy structure at the downwind tower. Level 5.0m becomes quite variable in the null region.

4.2 Detection of corner eddies

Reviewing the time histories for the same times for the tripod sites will reveal if horizontal eddy structures are forming downwind of the building's corners as suggested by the flow pattern found in physical modeling experiments as shown in Figure 1b. Figure 5 displays data (at 2.0m level) for the two tripod-mounted sonics located in the vicinity of the North and South downwind corners of the model building and the tripod-mounted sonic located further downwind in the Reattachment zone. See Figure 2 to locate the three tripods noted by a red T. Note that the previous color designations change with this figure. The red data trace is for the North corner area, the green data trace is for the South corner area, and blue data trace is for the sonic in the Reattachment zone further downwind to the East. These sonics also measured the light and variable conditions from 0000Hrs to 0230Hrs as noted in Figures 3 and 4. Unfortunately, the data signal from the South corner sonic before 0900 Hrs was not recovered and therefore not plotted. As the wind speeds increased from 0230Hrs to 0830Hrs, Southerly flow at the North corner sonic persisted while the Reattachment sonic measured a Southeasterly flow as did the Reference and Northeast towers (see Figures 3 and 4). From 0830Hrs onward, as the Westerly flow established itself, eddies were generated just beyond the corners of the building. Figure 6 is a photograph from the rooftop showing eight stakes with tell-tales on them being streamlined by the Westerly flow turning the corner southward and curling towards the building and then northward for a full 'circular' pattern. A set of red arrows are placed on the image to depict the essence of the flow. A similar photo (not given here) of the South corner tell-tales and arrows showed the same eddy pattern at the same time. Figure 5 clearly shows that the North corner sonic was recording a South wind as the vortex completes its circular motion. Similarly, the South corner sonic recorded a North component as the vortex moves in the opposite direction. For the same time period, the Reattachment sonic was far enough away from the building (per guidance from Figure 1a) that it experienced the same Westerly flow as noted at the upwind Reference tower in Figure 3. Clearly the corner vortices were detected and the Reattachment zone was established at the same time the vertical eddy also was established.

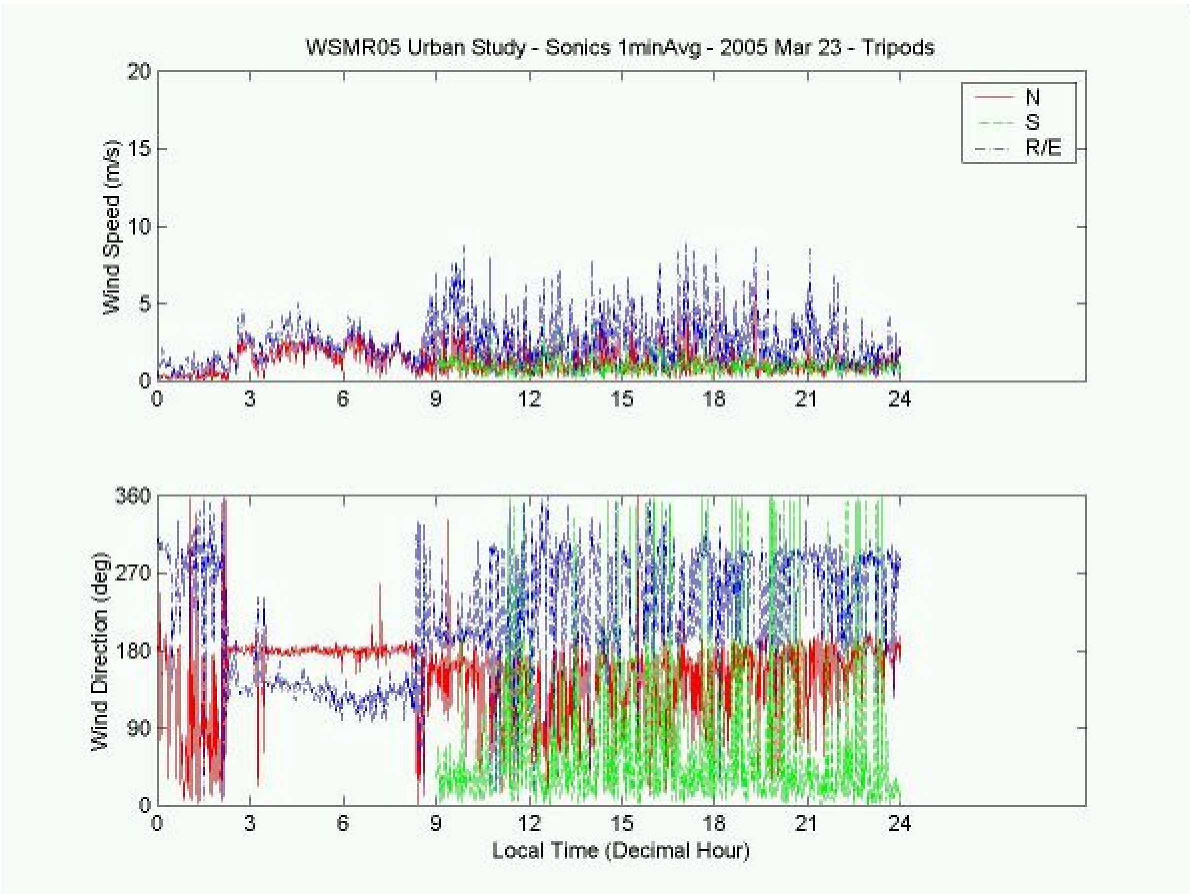
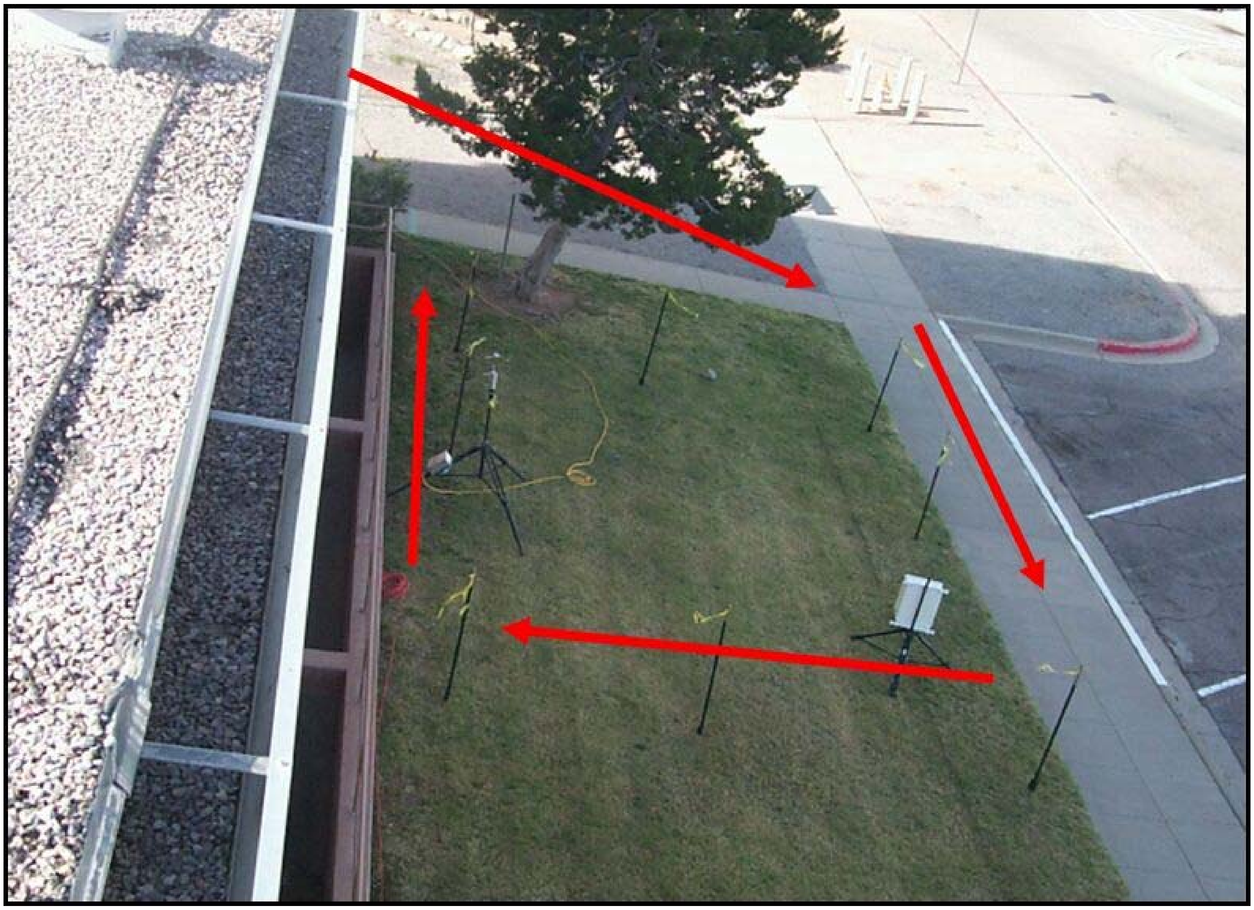


Figure 5. Time histories for 23 March 2005 of the two corner tripods (N and S) and the Reattachment zone site (R/E). The Reattachment flow agrees with the upwind reference tower 10m level, while each of the corner directions reverse to curl around the corners and flow in opposite directions from which they came.

Figure 6.(below on next page). A photograph from the rooftop looking down on the North corner of the building's downwind side. The yellow tell-tale streamers streamline with the flow to define the 'circular' path of the eddy. The red arrows are placed to instruct the reader. The sonic was placed in the return flow near the wall



4.3 Time variability of the vector field

A three hour period of data on 30 March 2005 was selected to display the time variability of the main flow and the downwind effects of the model building. The period starts at 1000Hrs and ends at 1300Hrs. the vectors are representative of 5 minute averages at each site and at all levels. The Southwest , Roof Top, North, South and Reattachment vectors all have virtually the same direction. Some accelerated flow is notable above the rooftop and the North and South side locations. By contrast, the downwind Northeast tower shows the opposing flow vector directions from 10m to 2.5m levels and another direction in the null region at 5m. The 10m level of the Northeast tower is still detecting the general Westerly flow that the other locations are experiencing. At the same time, the eddy structures beyond the North and South corners are clearly in place as the flow curls around the corners full circle. The Reattachment zone vectors tend to follow the flow noted at the upwind reference tower. A composite plot of vectors given in Figure 7 as five-minute averages for all sites and levels for a three-hour period shows how consistent the winds maintain their orderliness and persistence as well as their eddy structures.

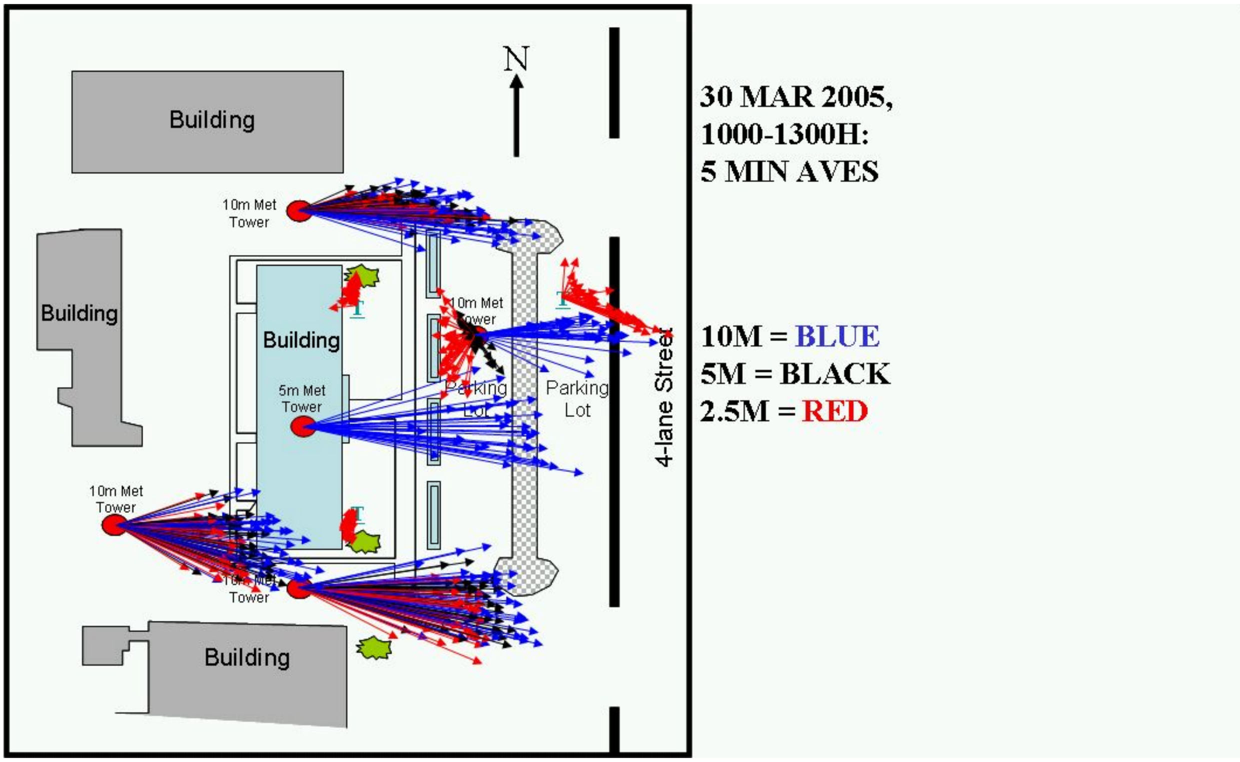


Figure 7. A three-hour composite of 5 minute vectors at each site and at all levels are given for 30 March 2005 from 1000 to 13000Hrs. The main flow is steady and persistent while the downwind eddies clearly display their reversals caused by the model building.

4.4 Preliminary calculations of turbulence values

Sonic data from 30 March 2005 are used in a preliminary computation of turbulence indices and fluxes and mean flow values and parameters. These data correspond to the same data set used for the vector plot in Figure 7. Wind and temperature fluxes, variances, TKE, and mean values of wind speed and direction, temperature, friction velocity, heat flux, and Z/L specifically were computed. The turbulence intensity indices were calculated for the individual wind components and the combined horizontal components for sites both upwind and downwind of the building. Although all of the permutations of the wind components and temperature were calculated, only the momentum and heat flux are given herein along with Z/L, TKE and the intensities. The mean values derived from the wind components and temperature data were wind speed, direction, Ustar, and the ambient temperature. Tables 3a and b provided the results for the 10m levels of the towers aligned downwind (SW to NE) and then the sites that indicate the flow from upwind traversing downwind around the model building including the corner eddies. Note that in Table 3b, *i (u' +v')* is the combined intensity of turbulence index for the horizontal wind components. The resultant values do show that the building perturbed the parameters in notable ways. More computations will be made for the 5m and 2.5m levels as well soon.
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10m	SW	Roof	NE	Reattachment
u'w'	-0.942	-11.693	-3.115	-0.758
w'T'	0.333	5.678	0.470	0.239
z/l	-0.056	-0.012	-0.013	-0.010
TKE	6.059	35.090	8.011	5.198
i(u')	0.274	0.508	0.624	1.052
i(v')	0.264	0.728	0.437	1.010
i(w')	0.264	0.398	0.334	0.567

Table 3a. Variations of the turbulence parameters at the 10m levels of each of the downwind towers for a three hour period (1000 to 13000Hrs) on 30 March 2005

10m and Tripod	SW	N	N-Corner	S	S-Corner
WS (m/s)	8.461	7.297	1.063	8.461	1.020
DIR (degrees)	274.258	271.450	159.959	274.258	32.669
Ustar	0.983	0.984	0.236	0.983	0.269
T (Celsius)	15.003	14.396	17.776	15.003	16.977
i(u'+v')	0.449	0.461	1.335	0.383	1.390

Table 3b. Variations of mean quantities at the upwind tower 10m level versus the data at the 2.5m levels of side towers and the 2m levels of the three tripods

5.0 SUMMARY

Clearly, the success of our previous studies provided sufficient motivation to pursue this expanded design. We were able to detect and identify: eddies forming beyond both downwind corners of the model building, velocity deficits and enhancements downwind, the development of a reversal of flow vertically in the cavity zone, the reattachment zone, accelerated flow over the building, and channeling between our adjacent buildings. We also saw that the corner vortices were generated and the reattachment flow was detected at the same time the vertical eddy also was established.

The preliminary computations of the turbulence quantities show that the building sufficiently perturbed the flow and raised the intensity levels. Our preliminary analyses of the data show that one building influences the behavior of turbulent eddies and the flow field.

In the near future, more in-depth analyses will more provide insight to conditions of how and when eddies generate and degenerate. Follow-on analyses will address how ranges of wind speed and directions and changes in atmospheric stability play roles in the airflow's interactions with the single building. The variations of the turbulence quantities will also be pursued. Later, studies of the diffusive behavior of aerosol plumes and puffs about a single building should be pursued in order to provide better guidance for on-site first responders and consequence assessment analyses.

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