7.5 EVIDENCE OF ENHANCED VERTICAL DISPERSION IN THE WAKES OF TALL BUILDINGS IN WIND TUNNEL SIMULATIONS OF LOWER MANHATTAN

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ABSTRACT

Observations of flow and dispersion in urban areas with tall buildings have revealed a phenomenon whereby contaminants can be transported vertically up the lee sides of tall buildings due to the vertical flow in the wake of the building. This phenomenon, which contributes to what is sometimes called "rapid vertical dispersion", has important consequences for the dispersion of pollutants in urban areas and its understanding may be crucial to improving urban dispersion models. This venting effect was observed in a wind-tunnel study of dispersion from the site of the destroyed World Trade Center (WTC) in New York City, using a scale model of lower Manhattan, including a scaled representation of the rubble pile.

Enhanced vertical dispersion was seen on the downwind side of several tall buildings in the highly urban area surrounding the WTC site using a smoke tracer. The flow responsible for this vertical dispersion was measured with laser Doppler velocimetry, and its effects on the plume were demonstrated with concentration measurements of an ethane tracer released from the rubble pile. Notably, the World Financial Center buildings, which stood upwind of the WTC site for westerly winds, caused an initial vertical dispersion of the plume before it began to move downwind. This vertical dispersion was caused by a vertical flow in the wake of these buildings and resulted in rapid transport of contaminants to heights above the building tops. The enhancement of the dispersion of the WTC plume due to tall building wake effects is analyzed and compared with Gaussian plume model predictions.

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1. INTRODUCTION

To evaluate and enhance our numerical simulation capabilities for lower Manhattan and other urban areas and to support ongoing risk assessment and public health studies of the World Trade Center disaster, EPA's Office of Research and Development initiated a wind-tunnel study of flow and pollutant dispersion in the complex Lower Manhattan area. The wind-tunnel study was conducted using a scale model of lower Manhattan, including a scaled representation of the World Trade Center (WTC) rubble pile. Neither the initial explosions on September 11, 2001 nor the collapses of the towers have been simulated. Instead, dispersion from the smoldering rubble pile was modeled for the time period approximately two to six weeks after the catastrophe.

A prominent characteristic of the flow through this highly urban area of lower Manhattan is the tendency for some tall buildings to create wakes that transport contaminants from street level to the building rooftops. This phenomenon was observed in each of the three phases of the study: flow visualization, velocity measurements, and tracer concentration measurements.

2. EXPERIMENT

A photograph of the 1:600 scale model of the lower end of Manhattan Island installed in the EPA's Meteorological Wind Tunnel (3.7m wide, 2.3m high, 18m long, more fully described by Snyder, 1979) is shown in Fig. 1. The model was constructed of rigid polyurethane foam mounted on a plywood base and centered 250m east and 115m south (full scale) of the center of the WTC site. It encompasses all of the southern tip of Manhattan Island.

A simulated atmospheric boundary layer (abl) was developed using three Irwin (1981) spires and roughness blocks (18mm high, 27mm square) with 25% area coverage. These blocks ended at roughly the western edge of the Hudson River, which is about 1 km wide at this point. Measurements showed the full-scale (600:1) equivalent of this abl would have a depth of 1100m, and a roughness length of 0.4m full scale at the end of the roughness

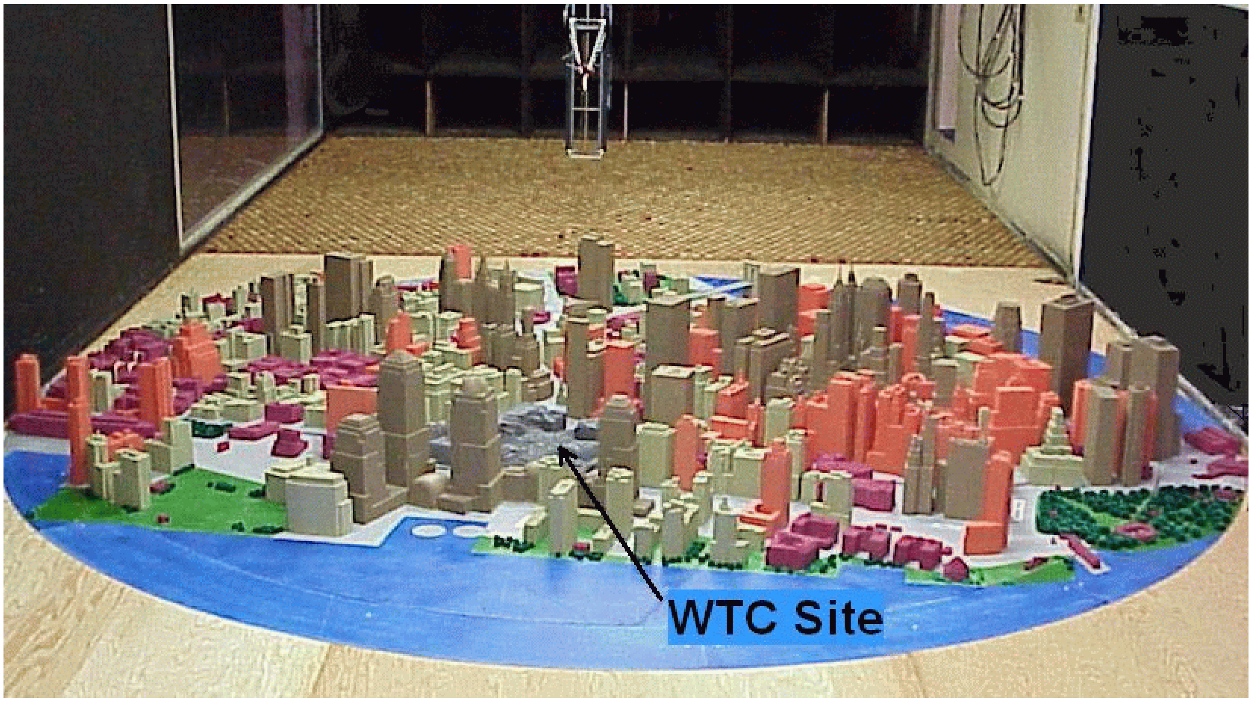

Figure 1. View of scale model in wind tunnel for the 270° wind direction case, looking downstream (toward east).

blocks, which is consistent with the built-up urban/suburban area on the New Jersey (western) side of the river. Detailed measurements were made for winds from the west (270°) and the southwest (225°), although results shown in this paper only from the 270° case.

The free-stream velocity (U_o) was set at 4.23 m/s, providing a street-canyon Reynolds number ($Re_s=U_oW/\nu$) of approximately 10,000 for the smallest street-canyon width (35mm or 21m full scale). W is the street canyon width and ν is the dynamic viscosity of air. Independent measurements of flow in idealized two-dimensional street canyons suggested that Reynolds-number independence would be achieved if Re_s exceeded 4200.

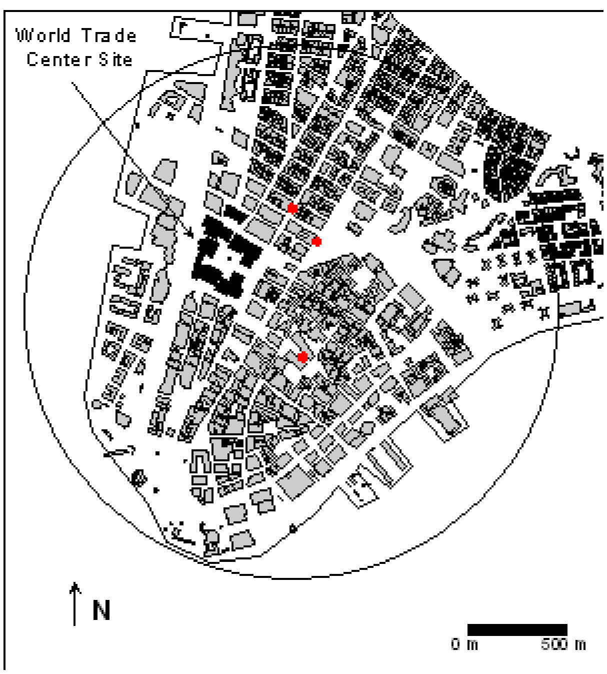

Figure 2. Plan view of study area. Red asterisks indicate selected LDV measurement sites.

A plan view of the model is shown in Figure 2. A roughly square array of 9 discrete tubes was used to release effluent from the smoldering rubble pile to simulate the distribution of emissions. Neutrally buoyant ethane was used as a tracer for quantitative measurements of concentrations with flame ionization detectors. Flow visualization was performed using a theatrical smoke generator and a laser light sheet used to illuminate cross sections of the plume.

For the quantitative flow measurements, a laser-Doppler anemometer (LDA) was used at a series of points located within various street canyons throughout the area. The LDA was aimed through glass windows in the floor of the wind tunnel so as to eliminate disturbances from the LDA probe as well as to avoid building interferences to the LDA line-of-sight. This arrangement allowed the measurement of horizontal components of velocity. A small mirror placed at 45° to the LDA viewing direction and supported by small-diameter rods extending through the window enabled the additional measurement of vertical components as well as vertical traversing (Snyder & Castro, 1998).

Eight basic locations were selected for LDA measurements, providing a cross section of the different types of local building topographies in the region (e.g., low-rise buildings with narrow streets, open space surrounded by tall buildings, narrow canyon surrounded by tall buildings, etc.) and covering a range of distances and directions from the WTC site. Fortunately, a number of the selected measurement locations were on the downstream side of relatively tall buildings. Therefore, the velocity measurements provided quantitative information on the vertical transport of pollutants in those situations.

Each of these measurement locations included at least a pair of ports or windows for access by the LDA and, in some locations, as many as 5 ports. The separation between the pairs was 100mm and, in general, pairs were oriented along the street axes. The 100mm separation was the same as the beam extension beyond the 45° mirror on the LDA. Therefore, by using the mirror when the LDA head was in one port of the pair and removing it when in the other, vertical profiles of both horizontal and vertical velocities could be measured along the same line, generally at the center of the street canyon. Also, by rotating the LDA probe with mirror attached, it was possible to measure off-axis profiles, thus providing cross-sectional information on the flow structure within the canyon.

A large number (133) of sampling ports were installed on the model surface to facilitate the measurement of ground-level concentration distributions. Sampling "rakes" on a traverse system allowed lateral and vertical concentration profiles to be measured at virtually any position in the model city. Samples acquired in this way were analyzed

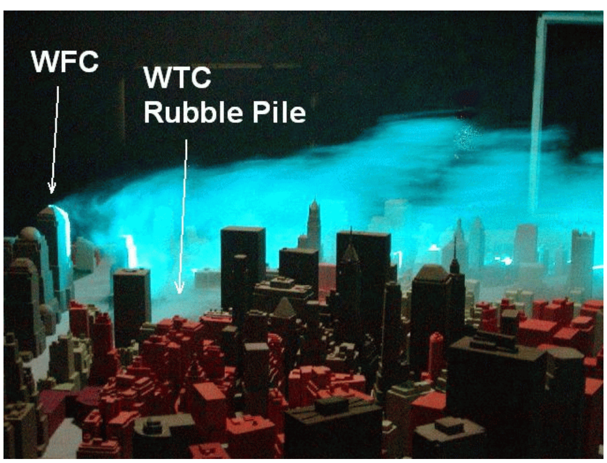

Figure 3. Visualization of smoke in a vertical plane parallel to the direction of the freestream flow (from left to right).

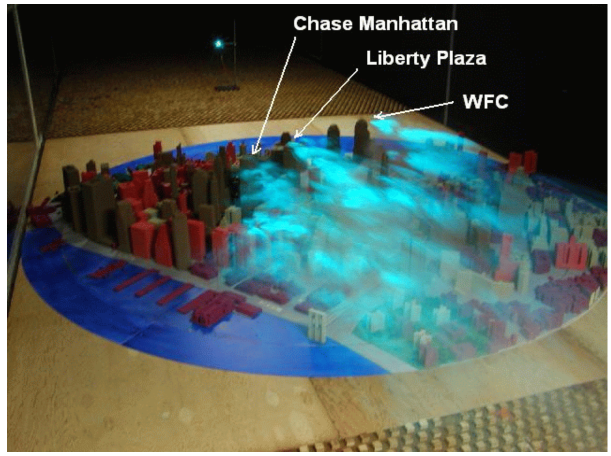

Figure 4. Visualization of smoke in a horizontal plane just above the height of the tallest buildings using a laser light sheet.

with Hydrocarbon Analyzers equipped with flame ionization detectors to determine mean concentrations of the tracer material.

3. FLOW VISUALIZATION

One prominent feature observed from the flow visualization was entrainment of source material upwind into the lee of the World Financial Center (WFC). The subsequent upwash or "pumping" of smoke up the lee side to the building top and even above, resulted in what appeared to be a continuous elevated release. This effect can be seen clearly in Figure 3 where the plume from the WTC site reaches the top of the WFC building before it leaves the immediate area of the rubble pile. Similar "pumping" action was observed from buildings to the south and somewhat downwind of the source. These results may be seen in Figure 4, where a laser-light sheet illuminated a horizontal plane just above one of the tallest buildings (the Chase Manhattan Building). The figure appears to show 3 distinct "plumes". The one on the right originated from the WFC (213m high), the middle one from the Liberty Plaza Building (236m), and the (somewhat more diffuse) one on the left from the Chase Manhattan Building (274m). These are the three tallest buildings in the vicinity of the WTC site.

4. VELOCITY VECTORS

The vertical transport of pollutants in the wakes of tall buildings can be attributed to relatively strong updrafts which have been quantified for a number of prominent buildings in the lower Manhattan study area. Using LDA, the velocity fields were measured

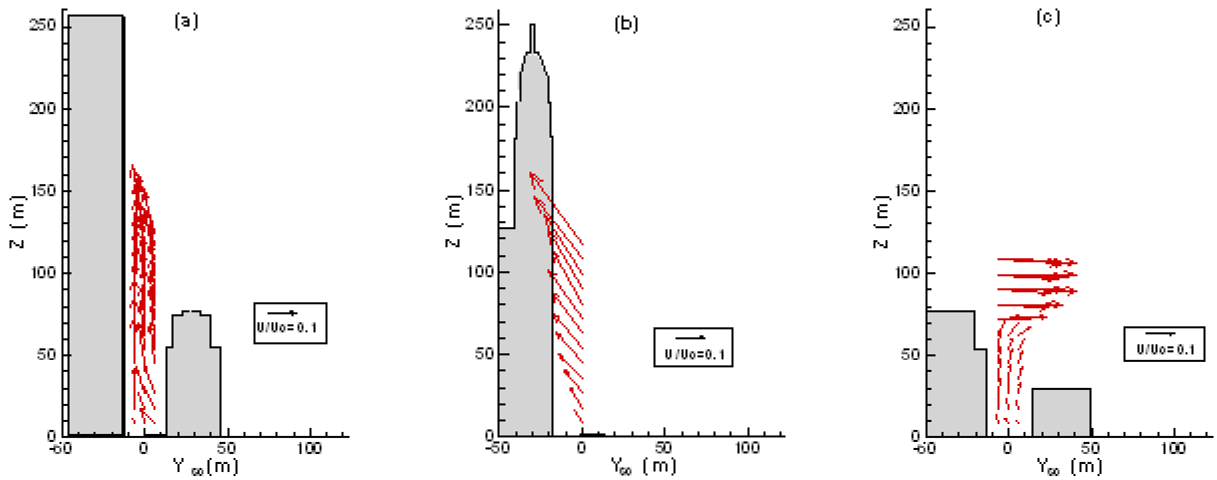

Figure 5. Velocity vectors on the downwind side of tall buildings (shown in silhouette on the left side of each figure. a) Chase Manhattan building (Federal Reserve building on right), b) Woolworth building, c) unknown building approximately 300m northeast of WTC site.

at many locations across the area, several of which were on the downstream side of tall buildings (indicated with asterisks in Figure 2). In general, the air moves vertically up the lee side of tall buildings with a velocity that can easily exceed 10% of the freestream velocity aloft (Figure 5).

The Chase Manhattan building (located approximately 500m southeast of WTC site) is one of the tallest buildings in the Wall Street area with a rectangular block-like shape that projects above the neighboring buildings. The flow on the lee side of that building rises dramatically (Figure 5a)

Figure 5b shows the flow behind the Woolworth building located approximately 300m east-northeast of the WTC site. This building, although quite tall (241m), tapers toward to the top, thereby reducing its influence on the flow around it. Nevertheless, the flow on the lee side of the building exhibits the same tendency to transport material from ground level to the top of the building that was seen at Chase Manhattan building.

Figure 5c shows a much shorter building, located approximately 300m northeast of the WTC site on the edge of an area where most of the buildings are low-rise. Although the building on the left in Figure 5c is not tall compared to the Woolworth Building or the Chase Manhattan building, it does stand taller than the buildings in its immediate vicinity. The flow vectors in the figure indicate that even behind this building, the flow is drawn up the lee side to the top of the building before being swept downstream by the flow aloft.

5. TRACER MEASUREMENTS

The effect of the tall building upwash can be seen in the tracer measurements of the simulated WTC plume. Cross sections of concentration were measured at 300, 600 and 1200m downwind of the WTC site. These are shown in Figure 6, where isoconcentration contours against a background of the city skyline viewed from downstream provide some indications about the plume size and behavior. (The values of the isoconcentrations are nondimensional, $100CU_oH2/Q$, where C is the measured concentration, H is a reference length scale (150mm) indicative of an average building height, and Q is the volumetric source flow rate.)

At the 300m distance (Fig. 7a), the most notable feature of the cross section is the two lobes of higher concentrations on the sides, with a valley of lower concentrations in the middle. This is rather clear evidence of the "pumping" of effluent up the lee sides of the World Financial Center and the Liberty Plaza Building. The influence of the Chase Manhattan Building was not a factor at this downwind distance, since it is located very near this plane. The plume was strongly asymmetrical, with the north lobe being much wider and higher in elevation than the south lobe. Also at this downwind distance, the plume appears to be shifted slightly to

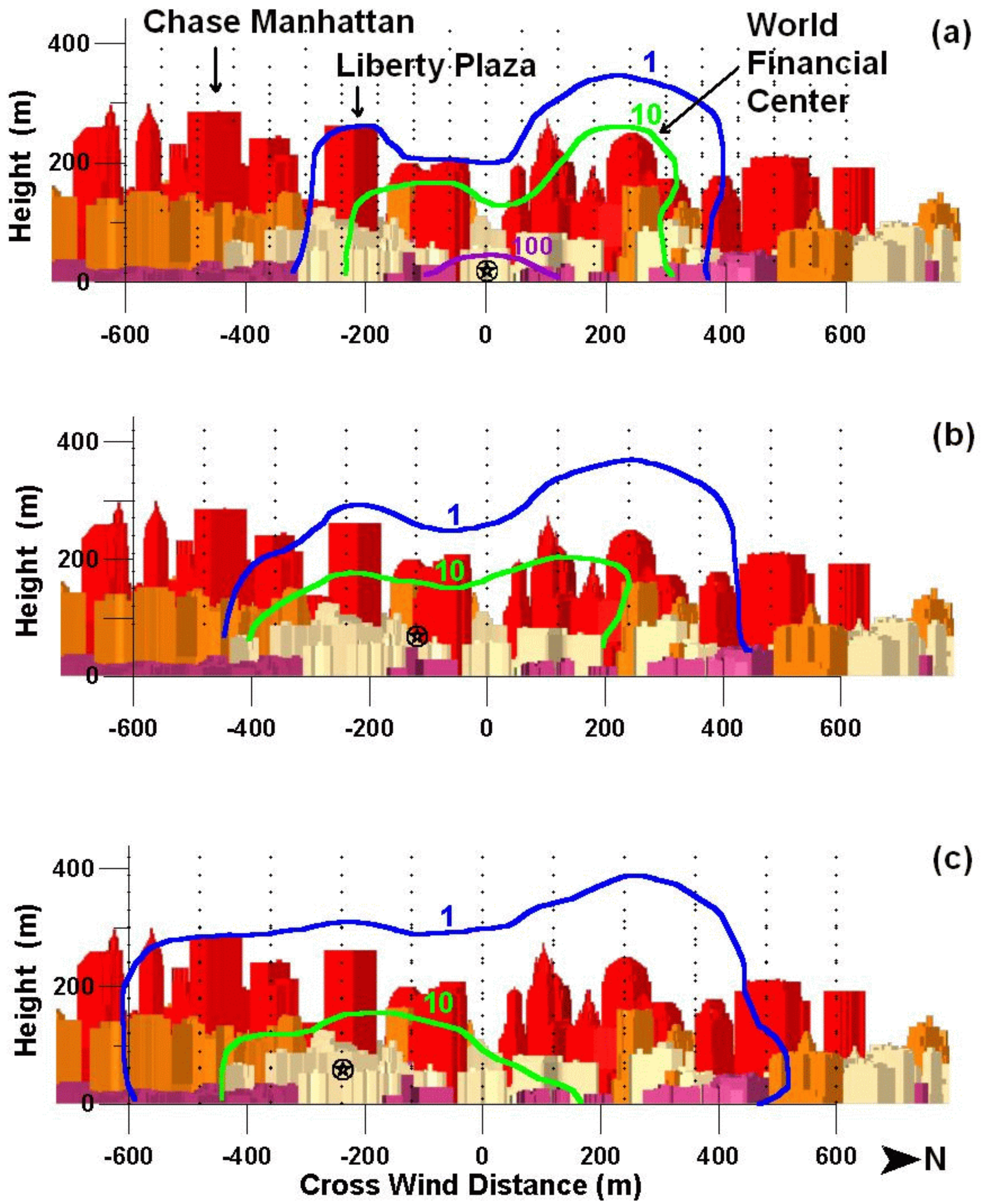

Figure 6. Plume cross sections at downwind distances of: a) 300m, b) 600m, and c) 1200m. View looking upstream against skyline of city. Shorter buildings indicated in lighter colors.

the north side of a line aligned with the free-stream wind and through the center of the WTC site (henceforth referred to as the centerline). The largest concentration, indicated by the circled star, however, is on the centerline.

At 600m downwind, two lobes were still evident, but were more diffuse. A notable feature was the lateral shift of the plume from a northward bias to a southward bias; the maximum measured concentration was located over 100m south of the centerline. The maximum concentration is shown elevated above ground level at this distance, but it may have been lower; no measurements were made at lower elevations at this downstream location, because buildings were in the way.

At 1200m downwind, only the north lobe was pronounced; a roughly horizontal concentration contour on the south side suggests that the middle and south plumes observed in Fig. 3 have essentially merged at this downwind distance. Also noticeable here was the strong spread of the plume to the south side, with the "10"-contour reaching only 170m to the north of the centerline, but 440m south of the centerline. The maximum concentration was located about 240m south of the centerline, indicating an angular shift of the plume by approximately 11° from a line directly downwind of the source. We believe this is an indication of a recirculation caused by the dense cluster of tall buildings in the vicinity of Wall Street (centered at approximately 500m south of the centerline through the source). At this distance, the maximum concentration was elevated approximately

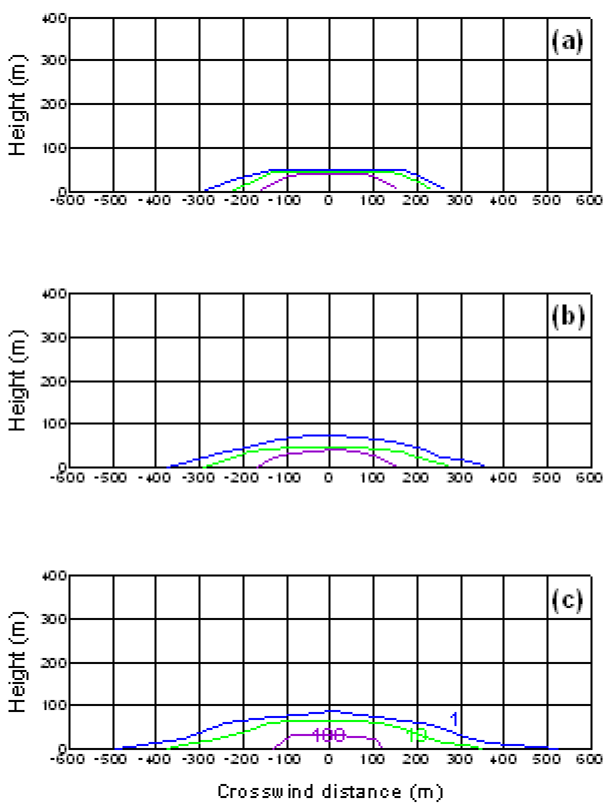

Figure 7. Gaussian plume model results using AERMOD. Plume cross sections at downwind distances of: a) 300m, b) 600m, and c) 1200m. View looking upstream.

80m above ground level. The dots forming vertical lines in this part of the figure indicate the locations where concentrations were measured.

Comparisons with AERMOD, a steady-state Gaussian plume model (Cimorelli, 2003), reveal that building effects, especially vertical venting on the lee sides of tall buildings and increased mechanical turbulence due to the urban surface characteristics, have a significant impact on the growth of plumes originating from ground level sources. AERMOD was run assuming neutral atmospheric conditions with the same approach flow and source characteristics as existed in the meteorological wind tunnel experiments.

6. CONCLUSIONS

Flow visualization showed that three of the tallest buildings surrounding the WTC site caused strong transport of contaminants up their lee sides, with results that looked like "chimneys" outputting smoke plumes above their tops. The World Financial Center was actually upstream of the WTC site, so that effluent was first entrained into the building wake, then transported to the building top. The Chase Manhattan Building was well off to the south and well downwind of the source, but nevertheless displayed similar behavior.

Velocity measurements confirmed that the vertical transport of pollutants in the building wakes was likely attributable to the mean vertical velocity produced on the lee side of these tall buildings. These velocities can easily reach magnitudes of 10% of the freestream velocity aloft.

Concentration measurements showed a highly distorted plume downwind that was clearly influenced by the venting action of the tall buildings and by the blockage effect of the dense cluster of tall buildings surrounding Wall Street. The locus of maximum concentrations did not follow the free-stream wind direction, but rather deviated by an angle in excess of 10° from a line pointing directly downwind. Further, the lateral distributions showed a bifurcation of the upper levels of the plume (high concentrations on the two sides with lower concentrations in the middle) that clearly resulted from the upwash behind the tall buildings.

DISCLAIMER

This paper has been reviewed in accordance with the United States Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

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