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WIND-TUNNEL SIMULATIONS TO ASSESS DISPERSION AROUND THE WORLD TRADE CENTER SITE

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ABSTRACT

A wind-tunnel study was conducted of dispersion from the site of the destroyed World Trade Center (WTC) in New York City. A scale model of lower Manhattan, including a scaled representation of the rubble pile, was constructed. The first phases of the study involved smoke visualization and measurements of flow patterns with winds from the west; the second phase involved the measurement of dispersion patterns resulting from tracer releases from the rubble pile. Neither the initial explosions nor the collapses of the towers have been simulated but, instead, dispersion from the smoldering rubble pile was modeled for the time period around two to six weeks after the catastrophe.

Notable features included: strong horizontal recirculation patterns caused by a group of tall buildings not directly downwind acting as a single obstacle, vertical recirculation caused by a tall upwind building resulting in "pumping" of contaminants up the lee side to heights above the building top, and consistent alignment of flow directions with the street canyon axes at the lower levels, tending toward free-stream values at the upper elevations.

NOMENCLATURE

C	Concentration, ppm by volume
H	Length scale, m
U	Mean velocity, m/s
U_o	Reference or free-stream velocity, m/s
Re_s	Street canyon Reynolds number
W	Street canyon width

INTRODUCTION

The recent destruction of the World Trade Center (WTC) in New York City resulted in releases of large amounts of gaseous and particulate matter. With the large population of workers and residents in this area, these events have elevated the need for reliable models to predict concentrations of such contaminants within complex urban areas. This, in turn, magnifies the need for laboratory measurements of flow and dispersion in complex urban settings for the development and evaluation of such models. The primary goal of this study was to obtain, in the laboratory, a data base that may be used to develop specific guidelines for estimating near- and mid-range concentrations of smoke and pollutants emitted from the WTC site and, more generally, for comparison with estimates from computational fluid dynamics (CFD) models.

MODELING DETAILS

A photograph of the 1:600 scale model of the lower end of Manhattan Island installed in the Meteorological Wind Tunnel (3.7m wide, 2.3m high, 18m long, more fully described by Snyder, 1979) is shown in Fig. 1. It was constructed of rigid polyurethane foam mounted on a plywood base and centered 250m east and 115m south 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, a power-law index of 0.2, and a roughness length of 0.4m full scale at the end of the roughness blocks, which is expected to match reasonably well with the built-up urban/suburban area on the New Jersey (western) side of the river.

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

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 so as to simulate the distribution of emissions (smoke for visualization or neutrally buoyant ethane as a tracer for quantitative measurements of concentrations with flame ionization detectors). 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 around the city.

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Figure 1. View of scale model in wind tunnel, looking downstream (toward east).

For the quantitative flow measurements, a laser-Doppler anemometer (LDA) was used at a series of points located within various street canyons spread around 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

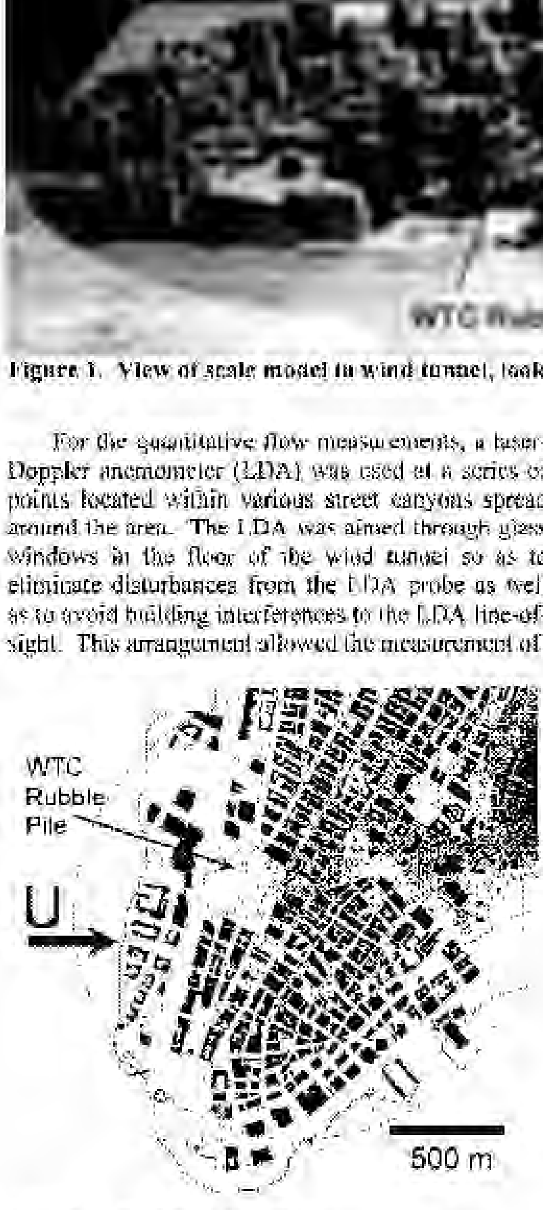

Figure 2. Plan view of model.

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, presenting 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. 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, so that, 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.

Initial measurements, as reported here, were for winds from the west (270°). Further studies are anticipated at additional wind directions.

PRESENTATION AND DISCUSSION OF RESULTS

One prominent feature observed from the flow visualization was entrainment of source material upwind to the lee of the World Financial Center (WFC) and its subsequent upwash or "pumping" of smoke up the lee side to the building top and even above, resulting in what appeared to be a continuous elevated release. Similar "pumping" action was observed from buildings to the south and somewhat downwind of the source. The results may be seen in Figure 3, where a laser-light sheet illuminated a horizontal plane just above one of the tallest buildings (the Chase Manhattan Building). The figure would appear 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.

Figure 3. Visualization of smoke in a horizontal plane just above the tallest building.

Another striking feature observed during the visualization was that puffs of smoke, albeit weak, were very frequently observed quite near the sidewall of the tunnel opposite Wall Street (located southwest of the WTC site). This was not-at-all expected, since it would require a half-angle plume spread in excess of 45°, and it appeared that it was the result of a large-scale horizontal recirculation of the flow. The large dense cluster of very tall buildings surrounding Wall Street acted much like a single obstruction, and the flow downwind from the WTC site was observed to curl around the lee side of this obstruction. Consequently, smoke carried by this recirculating flow was observed to infiltrate the street canyons in the vicinity of the financial district and even close to the tunnel wall.

Flow vectors at two different elevations over the city are shown in Figure 4. The low-level vectors (9m elevation) show strong channeling within the street canyons. Intermediate-level vectors (not shown) align more closely with the free-stream direction over the low-rise buildings but are strongly influenced by the taller buildings. The vectors at the highest elevation (90 m) clearly align with the free-stream direction except in the near vicinity of the very tallest buildings. This behavior is as expected.

Flow vectors in cross sections perpendicular to two street canyons are shown in Figure 5. These cross sections were located only 60m apart along the same street (Church), which is oriented about 20° off perpendicular to the free-stream wind direction, but they were separated by a cross street (Murray – see points "A" and "B" in Fig. 2). The two locations are more or less on the borderline between areas of low- and medium-rise buildings. In Figure 5a, located as shown by point "A" in Fig. 2, the upwind building is about the same height as the downwind one, and the spiraling flow within the street canyon is quite clear. The along-street component of the flow vector at the 9m elevation (shown in Fig. 4) is a little over twice as large as the cross-street component ($0.14U_o$ compared with $0.063U_o$). The tall protrusion on the downwind building is of small cross section and thus has little effect upon the overall flow structure.
By contrast, Figure 5b, located as shown by Point "B" in Figure 2, has a much taller upwind building and, whereas spiraling flow is not prominent here, upwash on the lee side of the upwind building is very strong over the full cross section. Continuity would suggest a fairly significant along-street component and, indeed, Figure 4 shows this to be $0.2U_o$.

The surface concentration pattern is shown in Figure 6, where the footprint appears to be strongly skewed toward the south, both in terms of the "centerline" of the plume and the large tail on the south side. This is further evidence of the influence of the dense cluster of tall buildings just southwest of the WTC site as mentioned earlier (Wall Street area).

Finally, cross sections of concentration were measured at 300, 600 and 1200m downwind of the WTC site. These are shown in Figure 7, 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, $100CU_oH^2/Q$, where C is the measured concentration, H is a reference length scale (150mm) indicative of, perhaps, 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 has not been felt at this downwind distance, since it is itself located very near this plane. The plume is 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 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

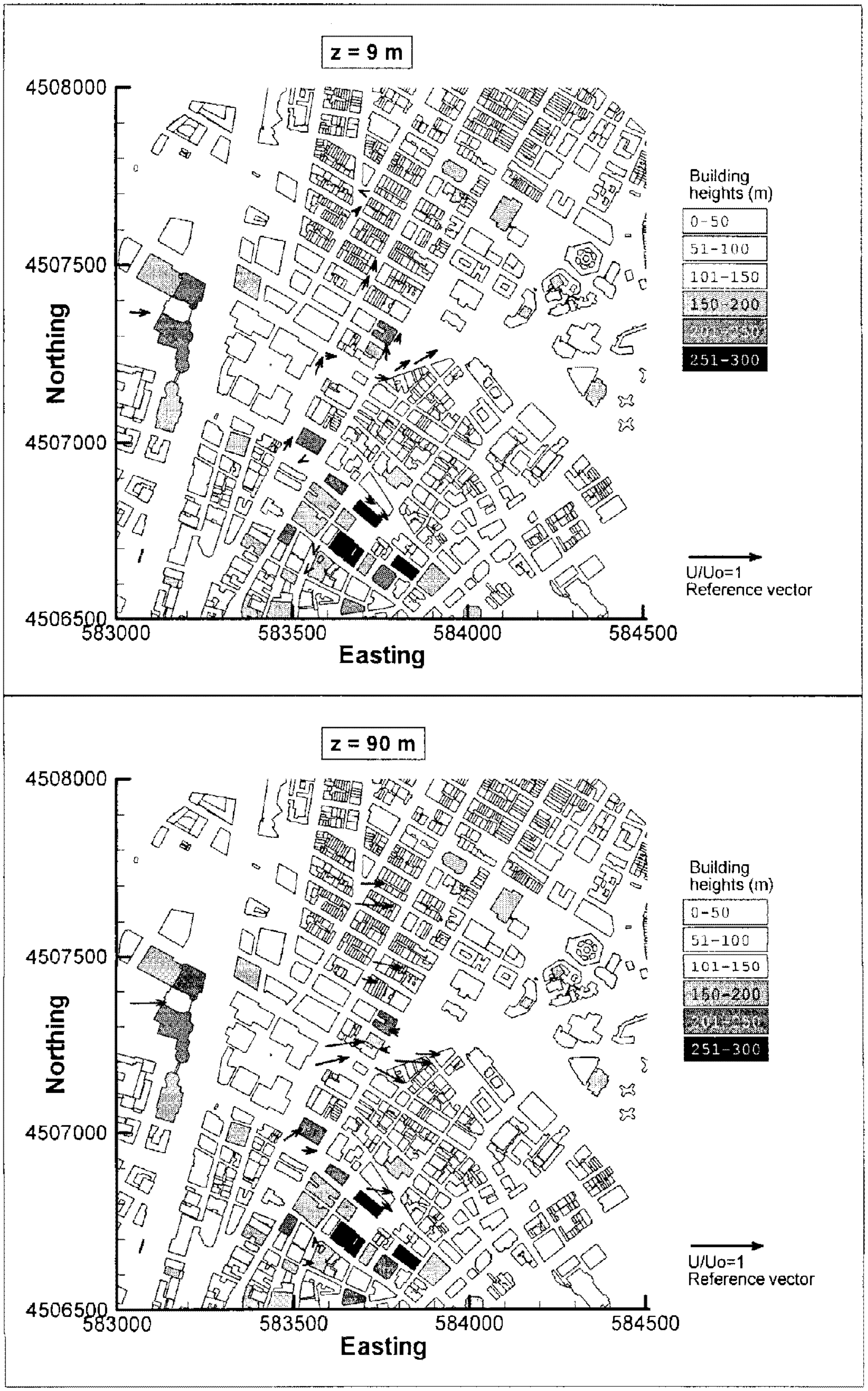

Figure 4. Plan view of flow vectors measured at two elevations above the model surface.

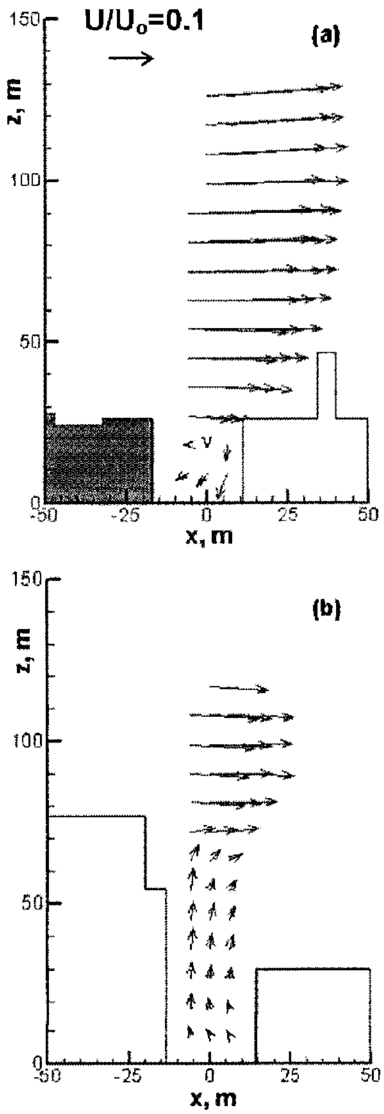

Figure 5. Flow vectors in street canyons.

concentration, indicated by the circled star, however, is on the centerline.

At 600m downwind, two lobes are still evident, but are more diffuse. The more notable feature is the lateral shift of the plume from a northward bias to a southward bias; the maximum measured concentration is 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 here, because buildings were in the way.

At 1200m downwind, only the north lobe is 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. Even more noticeable here is 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 is 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. Again, we believe this is an indication of the 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 is elevated approximately 80m above ground level. The dots forming vertical lines in this part of the figure indicate the locations where concentrations were measured.

CONCLUSIONS

These measurements show obviously very complex flow patterns over the densely packed buildings in lower Manhattan, both on the micro-level of the street canyons (spiraling flow, upwash and downwash behind buildings, and channeling within the canyons) as well as on the macro-level of the large-scale recirculation effected by the dense cluster of Wall-Street Buildings acting as a single obstacle.

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.

Flow measurements over two street-canyon cross sections in the same street showed quite different behavior. In one case, strong spiraling flow was observed, but in the other, longitudinal flow along the street with strong upwash on the lee side of the upwind building and over the full street width was far more prominent. Flow vectors at various positions around the city gave fairly strong and consistent indications of flow channeling within street canyons at low levels, tending systematically toward the free-stream direction just above the tops of the adjacent buildings.

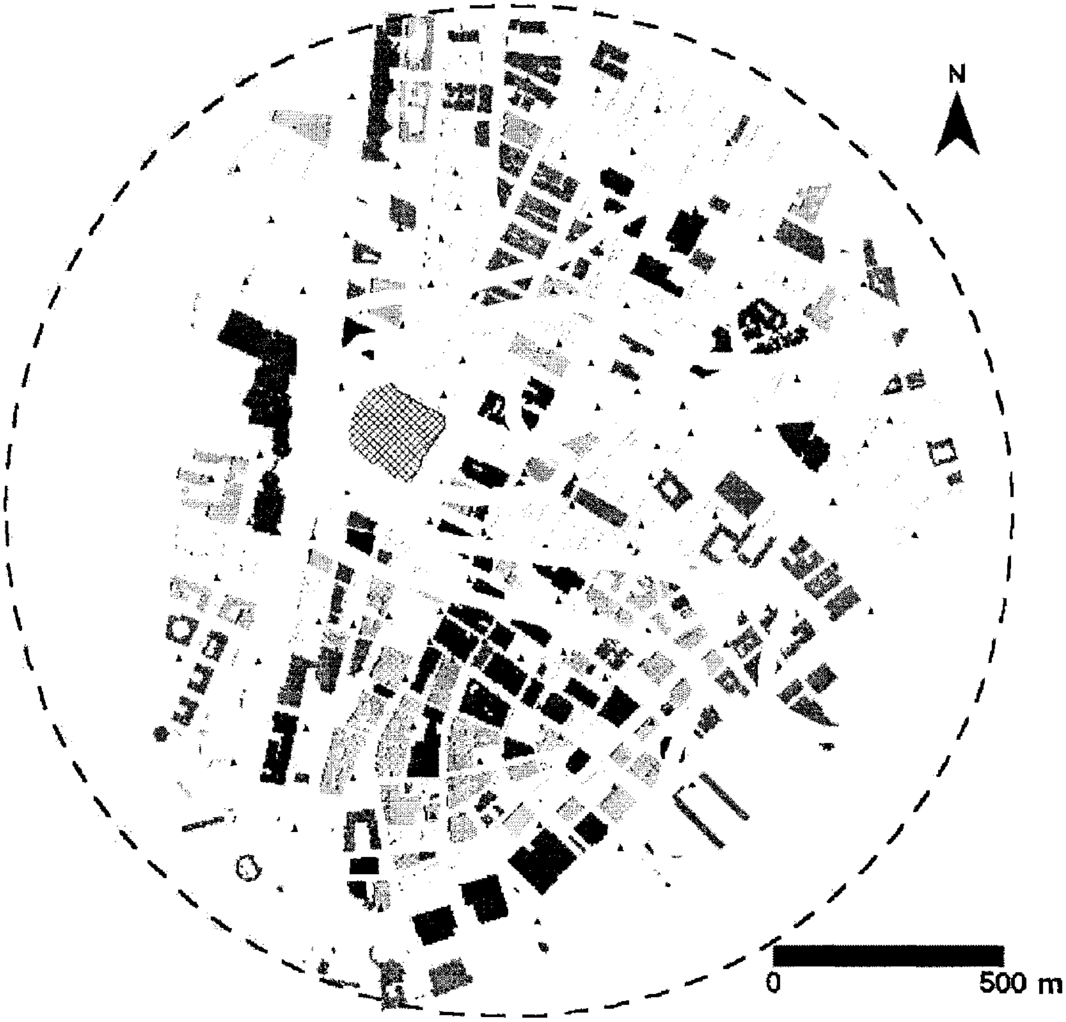

Figure 6. Surface concentration pattern over lower Manhattan.

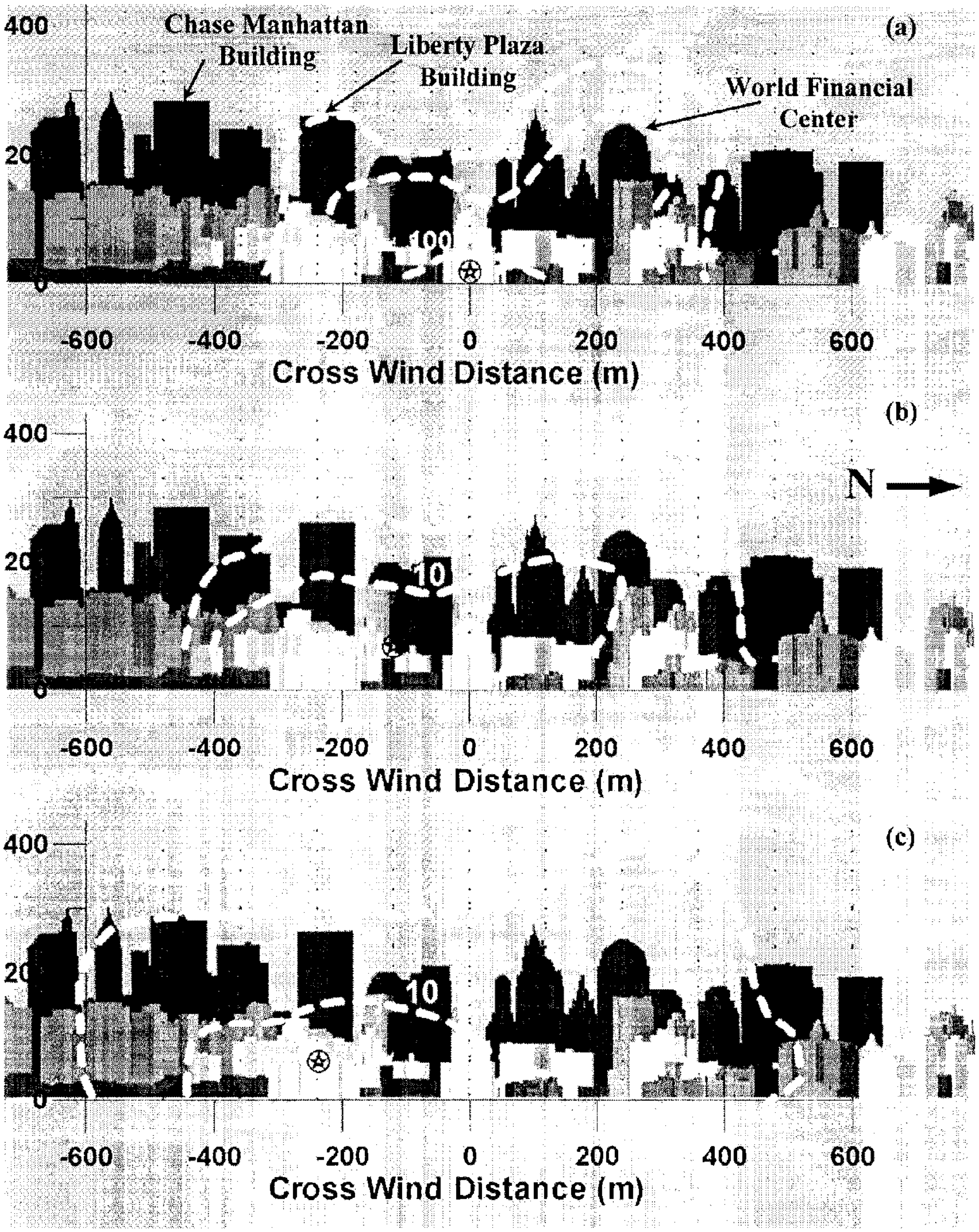

Figure 7. Plume cross sections at downwind distances of: a) 300m, b) 600m, and c) 1200m. View looking upstream against skyline of city. Shorter buildings indicated in lighter colors.

Concentration measurements showed a highly distorted plume downwind that was clearly influenced by the "pumping" 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.

Upon completion of the study, an extensive data set containing all of the three-dimensional mean velocity and turbulence data as well as concentration measurements will be made available for the development and evaluation of CFD and other types of models.

DISCLAIMER

This research has been supported by the US Environmental Protection Agency. It has been subjected to agency review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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