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Wind Tunnel Simulation of Flow and Pollutant Dispersal around the World Trade Center Site

by S.G. Perry, D.K. Heist, R.S. Thompson, W.H. Snyder, and R.E. Lawson, Jr.

INTRODUCTION

Over the past decade there has been renewed interest in the urban environment and the complex nature of emissions, transport, transformation, and fate of airborne pollutants therein. This interest in urban dispersion intensified after September 11, 2001, and the focus broadened from routine and accidental releases to include potential deliberate releases of hazardous substances into the atmosphere. The U.S. Environmental Protection Agency's (EPA) mission to protect human health and the environment has also been directed to include homeland security (i.e., to emphasize and expand its expertise and capability to prevent, where possible, and to detect and respond to, where necessary, accidental and intentional releases of toxic substances into the environment). Since numerical simulation models are important tools for assessing and responding to these types of releases, there is an ongoing need for both field and laboratory studies for model-development and model-evaluation purposes.

To evaluate and enhance numerical simulation capabilities[1] for lower Manhattan and other urban areas, and to support ongoing risk assessment and public health studies of the World Trade Center (WTC) disaster, EPA's Office of Research and Development (EPA-ORD) initiated a wind tunnel study of flow and pollutant dispersion in the complex lower Manhattan area. This included velocity and turbulence measurements throughout the street canyons of the city, and smoke visualization and tracer concentration measurements related to emissions from the WTC site following 9/11.

SCALE MODEL OF LOWER MANHATTAN

For examining flow fields and atmospheric transport and dispersion around the WTC site, a simulated atmospheric boundary layer (analogous to that expected in Manhattan for approach flow over New Jersey and the Hudson River) was developed within a low-speed Meteorological Wind Tunnel[2] at EPA's Fluid Modeling Facility in Research Triangle Park, NC. The 1:600 scale model of the southernmost 2 km of Manhattan Island, as installed in the wind tunnel test section, is shown in Figure 1. The buildings are constructed of rigid polyurethane foam and built to a 1-mm accuracy as specified by a digital database of the urban canopy. The buildings and other structures are mounted on a turntable, permitting characterization for different wind directions. Only results for the westerly (270°) wind direction will be discussed in this article. Other wind directions are also being studied. A detailed scale model of the rubble pile present at the WTC site for several months after the building collapse is also included in the model. An array of ports within the rubble provides for near-uniform release of both smoke and tracer gas. The wind tunnel flow speed well above the buildings (i.e., free-stream speed) was set to provide sufficient movement within the deepest and narrowest street canyons of the Manhattan model such that Reynolds number independence[3] was obtained (i.e., flow and turbulence in the model can be assumed similar to atmospheric flows at full scale in the city).

OBSERVATIONS OF SMOKE FROM WTC SITE

Smoke visualization provides a qualitative description of plume dispersion and highlights the general flow features. For this phase of the study, oil-fog smoke was released from the rubble pile (see Figure 2 of Vette et al.[4]), simulating emissions from both the below-surface fires that smoldered for months after the collapse and the activity-related fugitive particulate emissions related to the cleanup. One of the most prominent features observed for the westerly wind direction was the entrainment of source material by the tallest buildings around the WTC site. This upwash, or ventilation of smoke along the lee side of these buildings, brought material up to and above the building tops, providing initial vertical mixing and elevated release of the WTC pollutants. Figure 2 displays vertical ventilation from the World Financial Center (WFC; northwest of WTC), the Liberty Plaza (south of WTC), and the Chase Manhattan (southeast of WTC) buildings, where the horizontal laser sheet illuminates three elevated plumes. Additionally, large clusters of tall buildings, as found in the Wall St. area to the south and east of the WTC site, function as single large obstructions to the flow. During the smoke visualization, plume material moving eastward was observed to deflect toward the south around the Wall St. area.

Figure 1. Scale model of lower Manhattan in the wind tunnel looking downstream (east).

TRACER CONCENTRATION PATTERNS

For quantitative dispersion measurements, neutrally buoyant ethane tracer gas was released from the same ports as the smoke release. More than 130 hydrocarbon sampling ports were installed on the model surface (at street level) to facilitate measurement of the ground-level concentration distributions. Additionally, sampling ports were mounted on a traverse system to obtain both vertical and horizontal concentration profiles throughout the city.

The surface-level concentration distribution for the 270° wind is displayed in Figure 3. The plume moves initially toward the east, and eventually wraps around the Wall St. cluster of buildings. Near the WTC site, the plume shows significant crosswind and even upwind spread due to the mixing and updrafts caused by the buildings surrounding the site. The values of concentration in Figures 3 and 4 are nondimensionalized as 100 CUH^2/Q, where C is tracer concentration, U is free-stream speed, H is the urban height scale (90 m full scale) indicative of the average building height, and Q is the volumetric source flow rate.

In addition to the surface measurements, vertical slices of

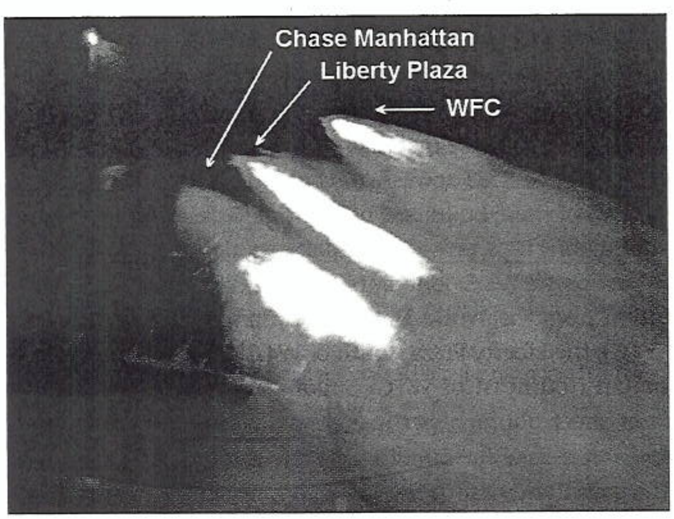

Figure 2. Smoke released from the scale model of the rubble pile at the WTC site enhanced by horizontal sheet of laser light at elevation just above tops of tallest buildings.

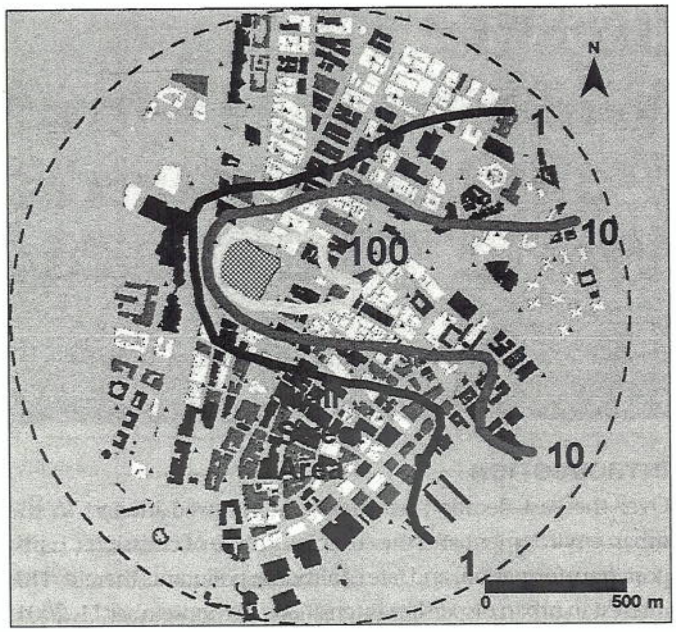

Figure 3. Surface concentration pattern in the scale model of lower Manhattan.

plume concentration were measured at 300, 600, and 1200 m (full scale) downwind from the WTC site. Figure 4 depicts these cross sections against the background of the city skyline, as viewed from a downwind position looking into the

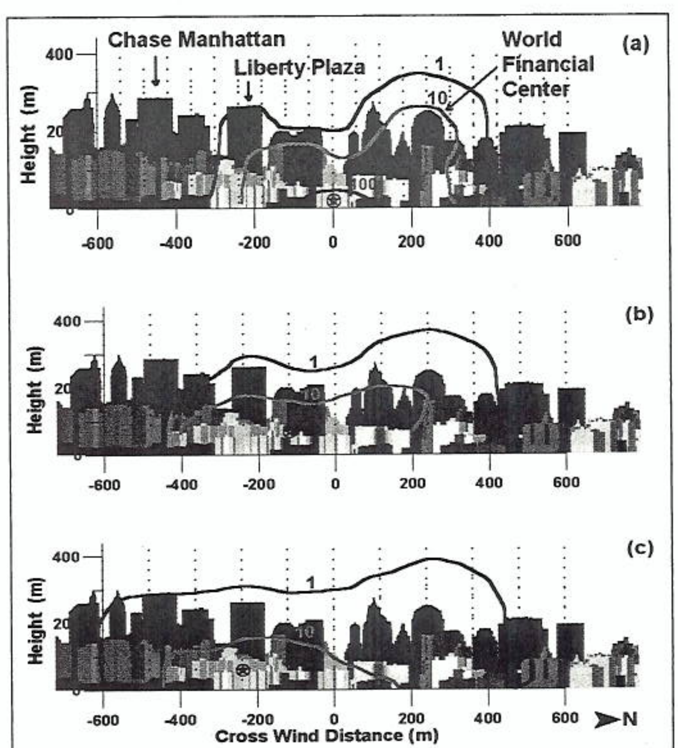

Figure 4. Plume cross sections at downwind distances of (a) 300 m, (b) 600 m, and (c) 1200 m from the rubble pile. The view is directly upstream against skyline of the city. Colors indicate categories of building heights.

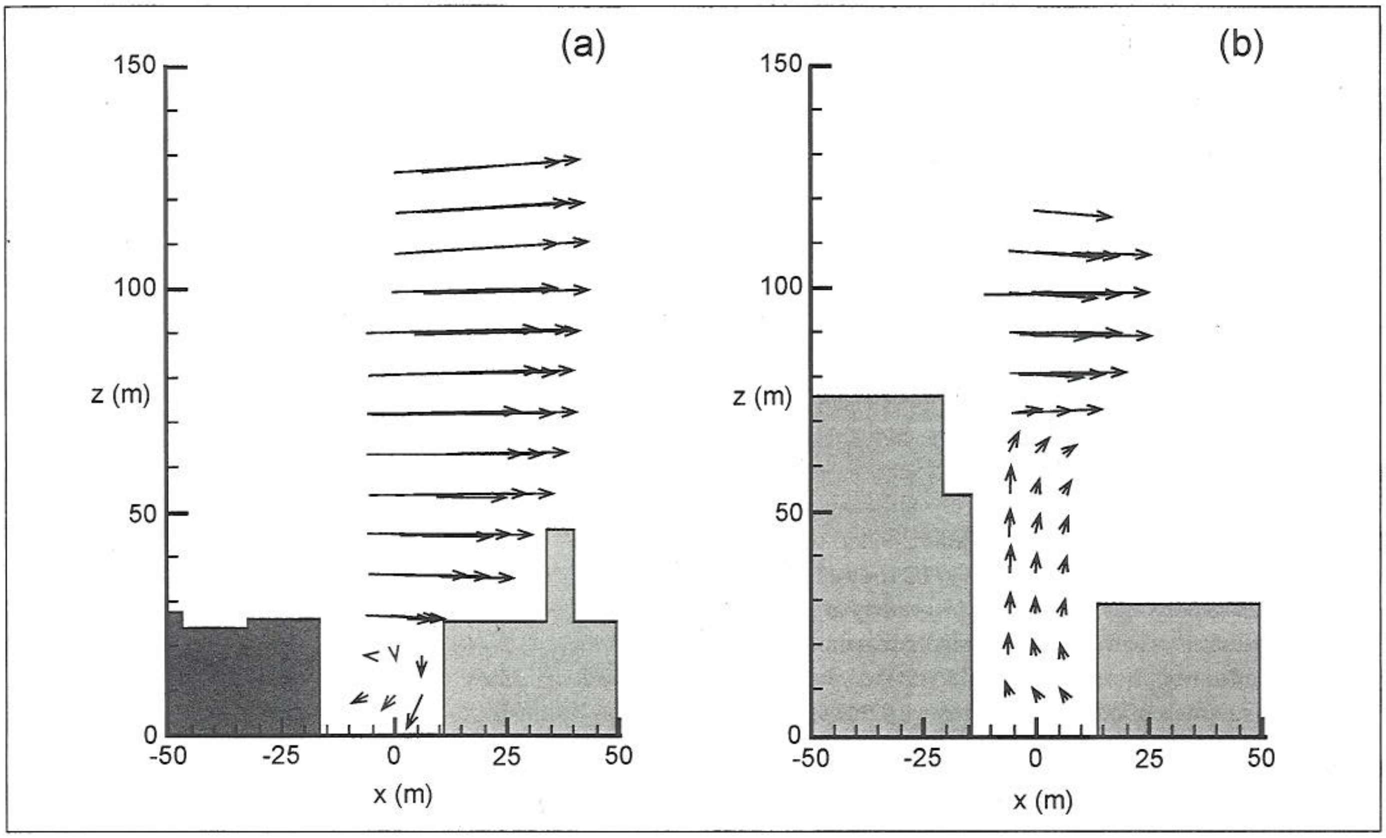

Figure 5. Air flow patterns along Church St. approximately 3–4 blocks northeast of the WTC site, illustrating complex flows in street canyons.

wind (looking westward). The measurements support the observations of the smoke visualization. At 300 m (approximately three city blocks) downwind, the plume cross section (Figure 4a) exhibits a double lobe in the 10 and 1 contours, reflecting the near-source upwash of material from the Liberty Plaza building to the south and the World Financial Center building to the northwest. At 600 m (Figure 4b), the double lobe is still apparent but the plume and its peak concentration have shifted toward the south. This is the beginning of the blocking and deflection effect of the tall, dense cluster of buildings in the Wall St. area. At 1200 m (Figure 4c), the plume continues to grow and shift toward the south. This represents the plume distribution that is leaving Manhattan and is available for transport to downwind locations (e.g., Brooklyn, Long Island).

AIR FLOW PATTERNS IN LOWER MANHATTAN

Understanding the local dispersion of contaminants within the complex urban canopy of lower Manhattan requires flow characterization within and above the wide variety of street canyon geometries. Velocity and turbulence fields were sampled using Laser Doppler Velocimetry (LDV), a noninvasive technique where, in this study, laser beams were projected through optical quality windows in the floor of the wind tunnel. LDV windows were installed in 20 different street-canyon locations, representing 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 canyons surrounded by tall buildings). The measurements show that the flow generally follows the street canyons at elevations below the local roof lines, even in streets that are aligned as much as 60° from the free-stream wind direction. As elevation increases, the flow tends to align with the free-stream direction except in the vicinity of the taller buildings.

One of the street canyons that was examined in some detail is three to four blocks northeast of the WTC site on Church St. This location is on the borderline between areas of low- and medium-rise buildings. Flow in planes perpendicular to Church St. is shown in Figure 5. These cross sections are located only 60 m (one block) apart along Church St. and are separated by a cross street (Murray St.). In Figure 5a, with the upwind and downwind buildings at approximately the same height, the flow appears to recirculate within the street canyon. There is also a velocity component along the street (not shown) such that the flow actually spirals up the street. In contrast, only one block away, a much taller building stands upwind and no spiraling or recirculating flow is evident (Figure 5b); instead, upwash on the lee side of the upwind building is very strong over the entire width of the street. This example of the complexity of the flow fields in lower Manhattan and the variability over very short distances illustrates the challenge that modelers have in quantifying the dispersion and fate of airborne pollutants in major urban areas.

SUMMARY

Wind tunnel measurements of velocities and dispersion have demonstrated the complexity of the flow field in and above the street canyons of lower Manhattan. However, there are several generalities of the flow and pollutant dispersion that can be deduced from this study and consequently considered for testing against numerical modeling approaches. The manner in which areas of densely-packed buildings act as obstructions to the flow and the manner in which tall buildings can quickly move pollutants near the surface to high elevations are just two examples. Aside from improving numerical modeling tools for general air pollution and homeland security type applications, laboratory data can be useful for developing guidelines for emergency responders making critical evacuation decisions.

At the time of this writing, the WTC wind tunnel study is continuing with measurements for additional wind directions. The study will be extended beyond the WTC source to include other release locations and release types in a variety of street canyons and intersections within the lower Manhattan model. Other release scenarios (e.g., from moving vehicles or a specific location) in scale models of other urban areas with different urban landscapes (e.g., Washington, DC) are being considered for future laboratory studies.

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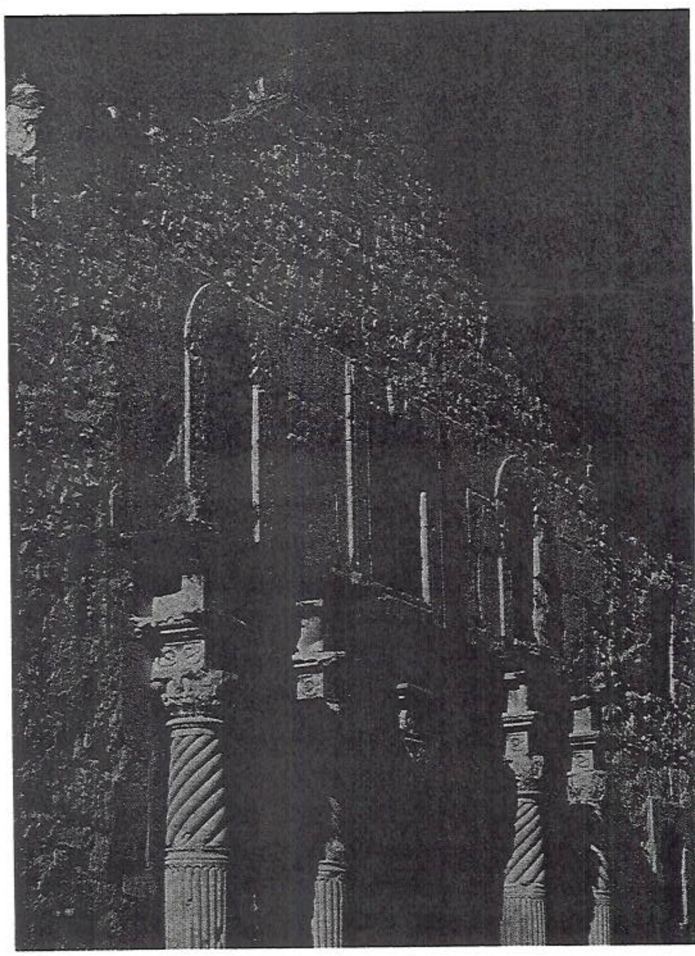

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