J5.4 A COMPARISON OF AIRFLOW PATTERNS FROM THE QUIC MODEL AND AN ATMOSPHERIC WIND TUNNEL FOR A TWO-DIMENSIONAL BUILDING ARRAY AND A MULTI-CITY BLOCK REGION NEAR THE WORLD TRADE CENTER SITE.

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ABSTRACT

Dispersion of pollutants in densely populated urban areas is a research area of clear importance. Currently, few numerical tools exist capable of describing airflow and dispersion patterns in these complex regions in a time efficient manner. QUIC, Quick Urban & Industrial Complex, a fast-running flow and dispersion simulation program has shown promise in this area. QUIC flow patterns were compared against two wind tunnel data sets, namely: one for a simple two-dimensional building array; another for a complex group of buildings surrounding the World Trade Center in lower Manhattan. In both cases, QUIC satisfactorily simulated the flow patterns depicting channeling and recirculation patterns within particular street canyons.

1. INTRODUCTION

In the days and weeks following the collapse of the World Trade Center (WTC) buildings the site smoldered slowly releasing gases, smoke and fine particulates (fugitive dust) into the air. Understanding the movement and dispersion of these contaminants is important to our understanding of that particular event and to facilitate our development of tools and technologies to help prepare for pollutant releases in other situations. One such new technology is QUIC version 3.3, an empirically based mass-consistent diagnostic wind field model coupled with a Lagrangian particle based dispersion model. QUIC has shown promise in aiding our understanding of local urban flow and dispersion (Pardyjak et al. 2004, Pardyjak and Brown 2001). Although still in development, QUIC is increasingly capable of simulating flow and dispersion in complex urban situations (Bagal et al. 2004). This paper describes a comparison of velocity measurements from the QUIC model and the US EPA atmospheric wind tunnel for two cases: a simple two-dimensional building array; and an extremely complex group of buildings surrounding the WTC site in lower Manhattan. These two wind tunnel data sets provided the opportunity to compare the performance of the QUIC model for a relatively simple geometry as well as for an extremely complex urban area.

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2. DESCRIPTION OF THE MODELS

The two-dimensional building array and lower Manhattan physical models were constructed at the US EPA Fluid Modeling Facility and placed into the atmospheric wind tunnel (cross section of 3.7m wide by 2.3m high) with air flowing past at 4.23 m/s in the freestream (Snyder 1979). Ultimately, the velocity and turbulence data sets acquired provided a data base for model comparisons as well as direct information about flow and dispersion patterns in urban areas. In both cases, the velocity data were supplemented by extensive flow visualization (smoke) and dispersion estimates based on concentration measurements using hydrocarbon analyzers of a controlled ethane gas release (3000 cc/min).

Both building models were placed in a typical logarithmic boundary layer simulating neutral atmospheric conditions. The boundary layer was generated using three triangular Irwin spires (0.34m base width, 2.3m height) and a dense array of 19 mm high by 27 mm square roughness blocks (Irwin 1981). The simulated roughness height (z_0) for the approach flow to lower Manhattan was 0.4 m full scale. The boundary layer for both wind tunnel models was characterized by a 0.16 power law exponent with a reference wind speed of 3.0 m/s at a height of 15 cm. In the absence of the models, the boundary layer did not change appreciably

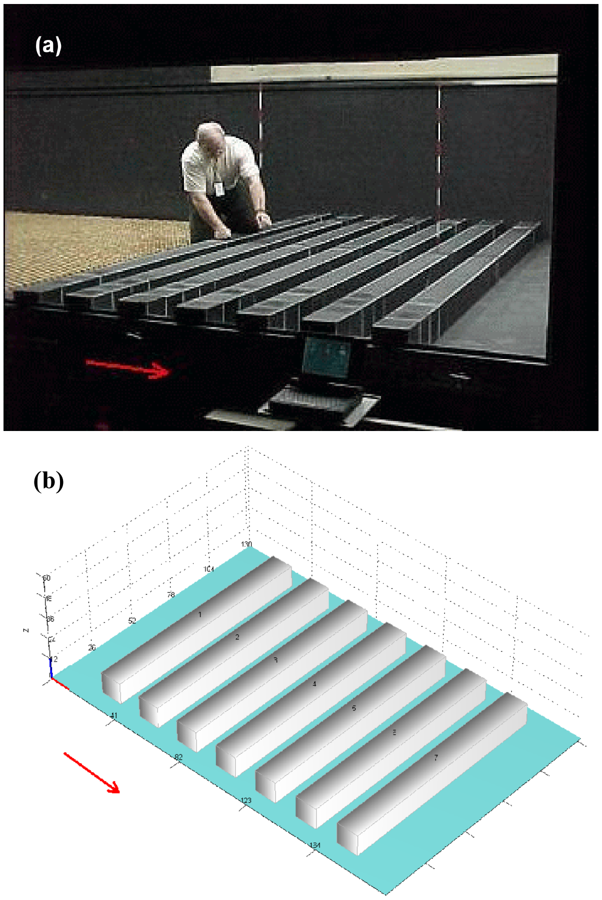

Figure 2. (a) A side view of the two-dimensional building array in place within the wind tunnel. Flow is from left to right (shown by the red arrow) and the buildings extend the entire width of the wind tunnel. (b) A side view of the model in QUIC (notice the ends of the blocks are unbounded). In QUIC, the data were collected along the centerline.

through the working section of the wind tunnel. For QUIC analysis, the input boundary layer was formulated as a power law, with the same parameters as the wind tunnel.

A simple two-dimensional building array was constructed of plywood using seven rectangular blocks (0.15m by 0.15m by 3.7m spaced 15 cm apart) oriented with the long axis of the buildings perpendicular to flow (Figure 1a). The blocks spanned the entire width of the wind tunnel. Vertical velocity profiles were measured using a pulsed-wire anemometer at three centimeter increments along a longitudinal section following the centerline of the wind tunnel. In QUIC the two-dimensional building array, seven regular rows of blocks spaced 15 cm apart oriented perpendicular to flow, was simulated with a mesh node present every 1.25 cm in the model. In contrast to the wind tunnel study, where the blocks extended across the entire width of the tunnel, in the QUIC simulation the ends of the blocks were not closed by a boundary wall (Figure 1b). Thus, air was able to flow laterally along the street canyons and out at the ends of the blocks.

The 1:600 scale model of lower Manhattan consisted of a circular region with a radius of about 2 km centered at a point on Broadway close to the WTC site. The buildings were fabricated using polyurethane foam based on digital building height measurements made available through the

Figure 2. A view of the WTC site from the west showing the extent of the modeled region.

Vexcel Corporation (USA) (Figure 2). Extensive measurements of velocity and turbulence were taken using a laser Doppler anemometer (LDA) at specific port locations which were distributed throughout the city, including the region surrounding the WTC (Figure 3a). The LDA eliminates the usual airflow disturbance prevalent when using probes. For vertical velocity and turbulence profiles, the LDA was mounted vertically below the wind tunnel and aimed through glass windows inset in the floor of the tunnel (Heist et al. 2004). Velocity measurements were made for two wind directions. The wind coming from the southwest and west at 225 and 270 degrees, respectively. These are both common wind directions for the New York City area in the fall months.

Due to computer limitations, only a small region of lower Manhattan could be modeled in QUIC. This encompassed a several block area extending from the western edge of the WTC site east to City Hall Park, including the Woolworth building (Figure 3b). At 241m the Woolworth building is one of the tallest in lower Manhattan. In

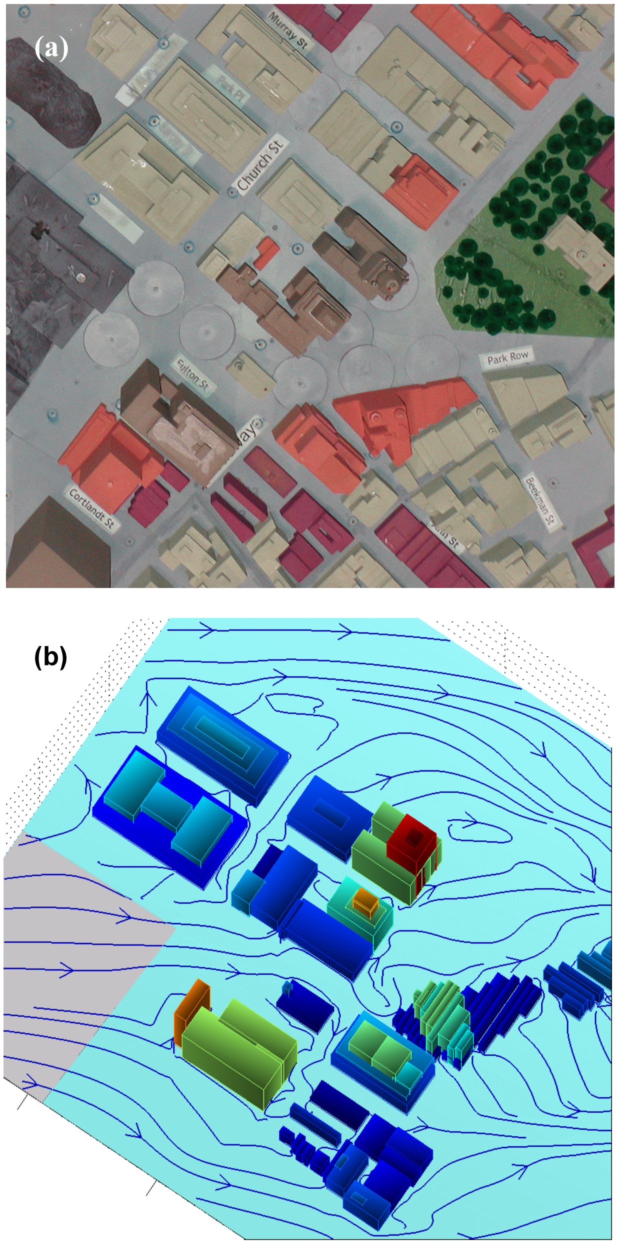

Figure 3. (a) An overhead view of the wind tunnel model showing the region simulated within QUIC. North is towards the top of the page. The small gray circular disks in the floor are locations where velocity and turbulence profiles were taken. The small blue circles show locations of surface concentration ports. The small white building in the green park is City Hall. The uppermost dark brown building is the Woolworth building. (b) The area around the WTC (light gray) modeled in QUIC including flow streamlines with westerly winds (left to right) at a height of nine meters above the ground. The peak of the Woolworth building is dark red.

QUIC, the resolution of the mesh size was three meters. The lateral size of the buildings were rounded to an even mesh increment., while heights were rounded to the nearest mesh increment. The building dimensions were derived from the same database used to build the physical model of lower Manhattan. QUIC requires that buildings be orthogonal to the coordinate system. Therefore the buildings were subdivided for the model into smaller segments. These dimensions were imported into QUIC with each of the 86 total building pieces categorized as an individual building. Upwind buildings and other roughness parameters present in the physical model which undoubtedly affect airflow patterns could not be simulated in QUIC due to computer limitations.

3. RESULTS

The flow around the two-dimensional building array was essentially skimming flow, passing over the tops of the blocks once it had accelerated over the first block. Regions of recirculation were present in each of the "canyons" between blocks (Figure 4a) and an upstream “rotor” was found along the upwind face of the first block (Figure 4b). These flow features were all well represented in the QUIC model. The directions of flow nearly always coinciding with those measured in the wind tunnel. The flow patterns around the most upwind block were particularly well described within QUIC. Additionally, the centers for the recirculation zones within the canyons coincided well. QUIC appeared to consistently underestimate the velocities within the canyons. This trend was most likely attributable to the three dimensional nature of the building array used in QUIC which allowed lateral movement of air within the canyons to the edges of the array. This flow feature was not evident in the wind tunnel simulations.

The flow in the wind tunnel model of lower Manhattan was complex, with significant areas of backflow and blockage around regions of the city (Figures 5a,b). As expected, building location and geometry obviously influenced flow fields and, thus, dispersion. Recirculation patterns and channeling down streets also was prevalent. For example, for westerly winds, notable channeling down Church St. (a street near the WTC oriented at 57 degrees to the wind, Figure 3a) was present at low heights (1.5m) compared to the heights of the surrounding buildings (around 60m) (Figure 5a). Above the buildings, and in the absence of tall buildings directly upwind, the flow vectors aligned with the freestream wind direction (Figure

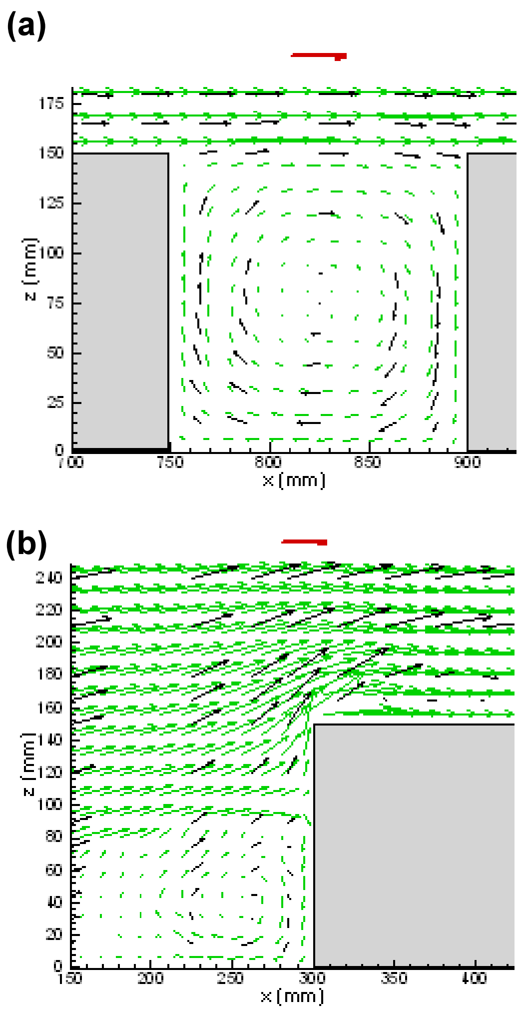

Figure 4. (a) Velocity vectors within the canyon between the second and third blocks (gray). (b) Velocity vectors near the upwind surface of the first block (gray) for the wind tunnel (black) and QUIC simulation (light green). The gray areas within the figures indicate areas where blocks are present 150 mm wide by 150 mm tall. The canyon between is 150 mm wide. The red vector at the top shows the direction of the wind, with the length equal to 3 m/s.

5b). Also apparent was flow up the leeward faces of tall buildings. Rapid vertical transport clearly influenced airflow. Also visible was channeling of flow along the eastern side of City Hall Park (the triangular green area to the east of the Woolworth building, Figure 3a). Generally, QUIC captured the major aspects of the flow in the area around the WTC site. It captured the channeling down Church St., and the change in flow direction to the north as it passed by St. Paul's Chapel and entered City Hall Park (Figures 3b, 6a, 6b).

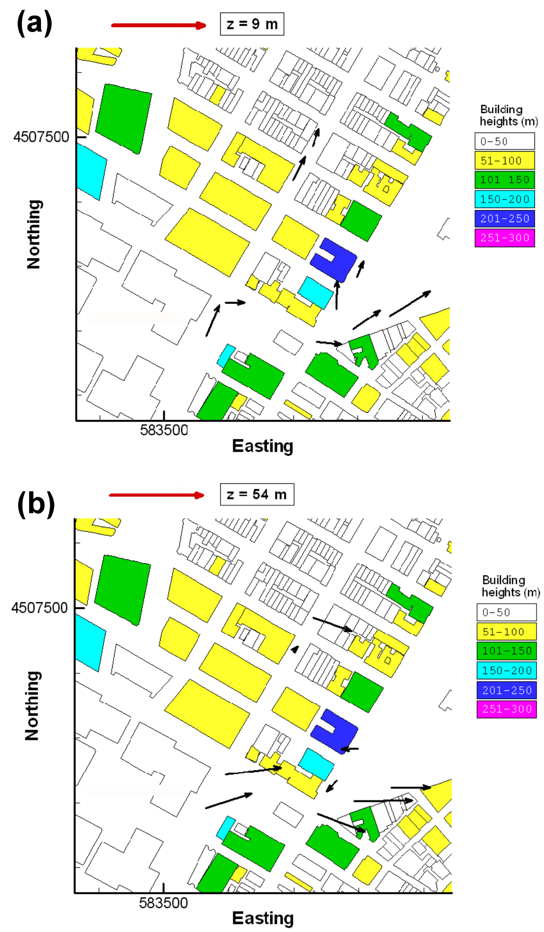

Figure 5. Velocity vectors at a full scale height of (a) 9 m and (b) 54 meters measured using the LDV from the wind tunnel model of lower Manhattan. The WTC site is the group of white footprints beneath the red vector. The wind (red vector) is from the west (270 degrees). The length of the red vector is 3 m/s. The dark blue footprint shows the location of the Woolworth building. The top two velocity vectors show flow channeling Northeast up Church street, with the flow going with the main wind once it reaches the tops of the buildings.

4. DISCUSSION

Understanding the nature of air movement in urban areas is critical to understanding of the dispersion of air pollutants. QUIC, was able to capture many of the major features of flow found in our wind tunnel simulations suggesting that it may be a useful tool for describing the dispersal of pollutants in urban areas. QUIC adequately described: abrupt changes in flow direction upon encountering bluff buildings; channeling of flow down streets; and recirculation patterns within

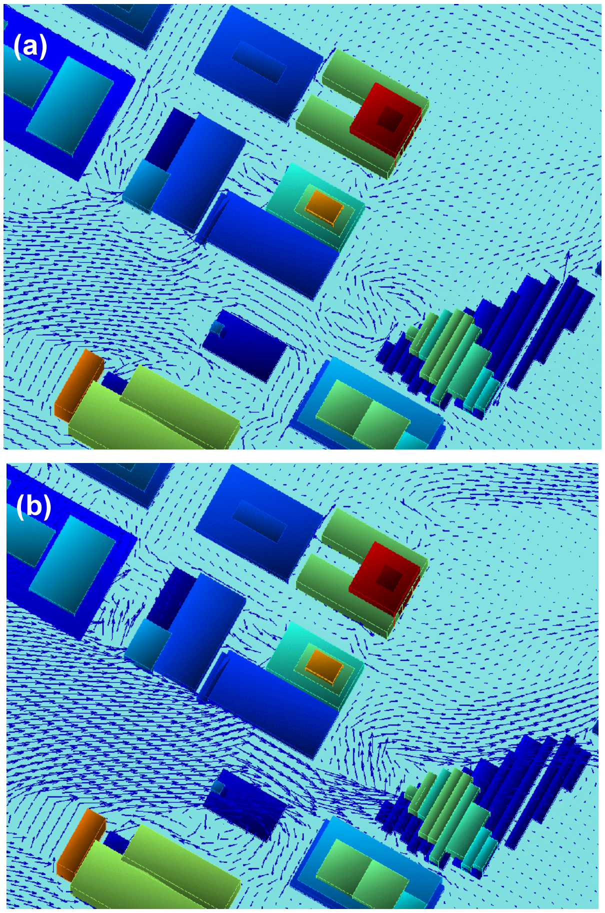

Figure 6. Velocity vectors (dark blue) created by QUIC for the westerly wind direction (270) at a full scale height of (a) 9 m and (b) 54 meters for the area of lower Manhattan near the WTC. Filled polygons show building locations. The WTC site is not shown, but would be to the lower left of the figures. The dark red box footprint shows the location of the Woolworth building. Vectors are shown every six meters and are scaled up by 1.5 in length.

street canyons. While flow patterns nearly always appeared to coincide between the wind tunnel and QUIC, the velocity magnitudes often differed.

For the lower Manhattan simulation, it is likely that buildings upwind of the WTC site that were not included in the QUIC simulation, account for some of the differences in flow between QUIC and the wind tunnel. However, other differences may be due to flow features not being incorporated into the QUIC model. For example, the flow phenomenon of rapid vertical dispersion, where street-level pollutants are transported vertically up the downwind faces of some tall buildings, was clearly evident in the physical model but was less well characterized by the QUIC model. In the lee of some of the tall buildings near the WTC, the velocities predicted by QUIC were not as strong or were in different directions from the vertical flow patterns that were measured in the wind tunnel.

Although not shown in this paper, for both the wind tunnel models and QUIC, smoke visualizations and tracer measurements suggested that dispersion appeared to strongly depend on the local wind fields created by the surrounding buildings. Notable regions of plume channeling down streets and recirculation within street canyons were evident. Initial dispersion appeared to strongly depend on source placement with respect to the surrounding buildings, local flow patterns, and the general wind direction.

Based on the results presented here, QUIC shows great promise in describing the intricate nature of urban flow. However, the complexities of flow and dispersion in urban areas continue to require diligent effort in model design as well as the creation of suitable data sets for comparison. Further comparisons with existing EPA data sets will allow greater examination of the flow and dispersion modeling capability of the QUIC model.

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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