

L. Joel Peltier*

Sue Ellen Haupt

Applied Research Laboratory, The Pennsylvania State University, State College, PA

John C. Wyngaard

Meteorology Department, The Pennsylvania State University, State College, PA

1. INTRODUCTION

Computational fluid dynamics (CFD) offers the possibility to predict fine scale features of flow and dispersion in geometrically complicated urban environments where flow separations and complicated heat transfer exist. A number of CFD tools exist for this purpose. FAST3D-CT (Pullen, 2005) and CFDRC's Urban Dispersion Simulator (<http://www.cfdrc.com>) are examples.

Recent literature documents issues related to the computation of flows in urban areas (Britter and Hanna 2003). Relevant modeling efforts have ranged from flow in urban street canyons through modeling flow in large regions of cities for the purpose of matching monitored conditions (Warner, et al. 2004; Chang, et al. 2005, Haan, et al. 2001). Most of those studies have concentrated on the impact to the flow of the physical presence of the buildings (Yamada 2005). It has been shown that flow, and the resulting dispersion of an effluent, is modified in the building wake (Cowan, et al. 1997; Moon, et al. 1997; Palmer, et al. 2003; Baik, et al. 2003). Street canyons (Baik and Kim 1999) and building arrays (Hanna, et al. 2002; He, et al. 1997) have specific characteristics in near building flow computations. Experiments indicate that building arrays enhance dispersion (Yuan and Venkatram 2005).

The fidelity of the dispersion predictions relies primarily on the fidelity of the transporting wind field. In practice, the fidelity of CFD solutions for the wind field in an urban setting is limited by available computer resources (resolution), by incomplete knowledge of local geometry and local material properties, and by the reliability of the underlying turbulence- and dispersion-model closures.

The purpose of this study is to document turbulence closure effects on the transporting wind field. To consider how wind-field uncertainty affects dispersion is left to a follow-on study. Two CFD approaches are common in the literature. Large-eddy simulation (LES) related approaches attempt to simulate the largest turbulence scales directly gaining the scale-dependence of dispersion through simulation. FAST3D-CT is an example of an LES-type model. More traditional models predict the flow statistics. They solve the Reynolds-Averaged Navier-Stokes (RANS) equations, modeling turbulence through closures. Dispersion in the statistical wind field is also modeled. CFDRC's Urban Dispersion Simulator is a model of this type. We present results for both model types. Our LES-type variant is detached-eddy simulation (DES) that becomes LES in separated regions while remaining RANS elsewhere. Our RANS model is closed with the one equation Spalart-Allmaras model (Spalart, et al. 1997).

Section 2 describes the modeling approach with specifics on the geometry, the mesh, the CFD model, and the boundary and initial conditions. The resulting flows are presented and discussed in section 3. Section 4 summarizes the results and implications for future modeling studies.

Corresponding author address: L. Joel Peltier, Applied Research Laboratory, P.O. Box 30, Pennsylvania State University, State College, PA 16804; e-mail: peltierlj@psu.edu

2. MODELING APPROACH

Urban environments are characterized by a complicated interplay of massive flow separations from a regular class of geometric shapes - buildings. Buildings are characterized by relatively rough surfaces with sharp edges. The sharp edges determine the separation points for the flow. A second observation for urban turbulence is that the turbulence energy feed is at the large scale of the flow separation. This scale is proportional to the local building dimension. Wall-shear production of turbulence, at much smaller scales, is not the dominant source. The energy feed from large scale separations has the consequence that grid resolutions for urban CFD can be fairly coarse and still resolve the large-scale dynamics of the flow and may have the consequence that urban CFD may not be very sensitive to the fidelity of near-wall modeling.

Since the turbulence energy is input at building scales and separations are set by building geometry, either RANS or LES may be appropriate methodologies for urban CFD. The sensitivity of RANS models to separated flows and the sensitivity of LES models to near-wall turbulence may not be serious issues for urban CFD. That existing models of both classes perform reasonably well for urban CFD supports this idea.

Our study presents both both LES-type and RANS solutions for a model urban setting.

2.1 The Geometry

Our model geometry is the West Campus complex of Penn State University (PSUW). The group of buildings is shown in Fig. 1. This setting consists of 10 buildings in close proximity ranging from 1 story to 6 stories in height, as observed in Fig. 1. They are geographically separated from the Penn State Main campus, allowing localization of the model and simplification of upstream and lateral boundary conditions. The upstream fetch is open golf course yielding a low surface roughness.

In general, highly detailed geometries for urban settings are difficult to obtain. Building features that cannot be observed from above

are usually absent, as are local details on building materials. Our choice of the PSUW setting was partly motivated by our desire to create a highly detailed physical model. Ready pedestrian access to the west campus buildings has allowed us to easily verify/improve model features. We note that the roughness characteristics of the PSUW site are consistent with smaller US cities and towns, not the downtown regions of major US metropolitan areas.

2.2 The Mesh

An unstructured mesh is used for the simulations. The mesh is comprised of a mixture of tetrahedral, hexahedral, and pyramidal elements. The hexahedra are used to control near-wall spacing.

The mesh resolution on building surfaces is chosen to be 1.5m yielding about 2 grid cells per story. The far field resolution is coarsened to about 50m, and the transition between the buildings and the far field is controlled to cluster the mesh near the buildings. Figure 1 presents that computational surface mesh showing the grid clustering.

For the computations presented in this document, the near-wall spacing was chosen to be about 1m for all surfaces, including the ground at far field, yielding a total resolution of about 200,000 grid points or 800,000 grid cells. A mesh resolution study using finer near-wall spacing is underway to understand the sensitivity to near-wall resolution.

2.3 The CFD Model

We use the commercial flow code, AcuSolveTM, from ACUSIM Software, Inc. as our computational engine (see the AcuSolveTM manual, 2005). ACUSIM Software Inc. is a developer of robust, fast and accurate finite element flow solvers that can be seamlessly used by all levels of expertise, both as a standalone computational fluid dynamics flow solver and as an embedded CFD component integrated into customer specific engineering and scientific applications.

AcuSolveTM offers a number of turbulence modeling options. Detached-eddy simulation (DES) and Spalart-Allmaras (SA) RANS models are used in this work. DES is a simulation methodology that provides LES-like solutions for massively separated flows like the urban environment. The SA RANS model is a popular contemporary one-equation turbulence closure that yields reliable turbulence statistics for broad classes of turbulent flows.

2.4 Initial and Boundary Conditions

The flow computations were started from zero flow in the domain with a constant inflow velocity applied at the inflow boundary. A boundary layer was allowed to develop over an upstream fetch of about 0.25km before encountering the west campus model. No-slip was enforced on all solid surfaces. Surface roughness was not modeled. Constant pressure outflow conditions were used elsewhere.

A characteristic length of 1 story, ~ 3 m, was used with a freestream velocity of 10 m/s. The Reynolds number of the computations is $Re=2 \times 10^6$, using $\nu=1.5 \times 10^{-5}$ m²/s for air.

3. RESULTS & DISCUSSION

The PSUW geometry was simulated using both DES and RANS for identical flow conditions. DES is an eddy-resolving technique, so only one instant in the flow cycle is presented. RANS is a statistical technique. The flow statistics, however, are not stationary, so we present one instant in the statistical oscillation. Presently, flow statistics are being collected for both cases and will be discussed in future work.

3.1 Present Simulations

An ariel view of isosurfaces of dimensionless vorticity magnitude are presented in Figures 2 (RANS) and 3 (DES). The isolevel is 0.5 and the isosurfaces are colored by dimensionless vertical velocity. Red represents updrafts while blue represents downdrafts. The contour limits are ± 0.2 .

A visual comparison of the results shows that the DES simulation is supporting large-scale turbulence. An inspection of the Information Sciences and Technology building (IST – the long building on the top right side of those figures) in Fig. 3 suggests that a secondary instability is modeled with DES but not with RANS. Note the 6 “fingers” shedding from the top of the structure in Fig. 3 that are absent in Fig. 2. A roll vortex upstream of and parallel to that building is also apparent in the DES simulation (Fig. 3) that is not well formed in the RANS simulation (Fig. 2). Other fine scale details are apparent that are not seen in the RANS result. An interesting observation is how little turbulence structure is observed about the downstream buildings, that is, those embedded in the separated urban-like flow. Apparently the flow separations from the upstream structures insulate them from higher activity.

Pathlines are used in Figs. 4 (RANS) and 5 (DES) to visualize the turbulent activity. Again, the extra turbulent scale content can be seen in the “more chaotic” paths in the DES result. Even the RANS solutions, however demonstrate recirculation zones in front of, alongsides, and in the lee of buildings as well as in the regions of separated flow.

Contours of streamwise, cross-stream, and vertical velocities with pressure are presented in Figs. 6 (RANS) and 7 (DES). The DES results are characterized by relatively intense updrafts and downdrafts that are not observed as strongly in the flow statistic (ie. RANS). These structures are the large-scale features of resolved turbulence that will give grid supported dispersion of a contaminant.

3.2 On-going Simulations

Additional computations are ongoing to complete the study partially documented in this text. Flow statistics are being computed to compare the statistical RANS results to flow statistics collected from the DES. Because the DES uses the governing equations to partially resolve the large-scale turbulence, one expects the DES results to be “more true” to the physical flow. The comparison of the DES statistics to the RANS results, then, will suggest how well the RANS model is representing the statistical flow field.

Other computations are ongoing that consider the effect of near-wall resolution. As discussed, the energy feed at large scale for the urban flow may mean that the urban flow is not very sensitive to the fidelity of the near-wall representation. We are testing this postulate with the wall-resolved computations.

4. SUMMARY

Results from an eddy-resolving DES computation and a RANS computation are presented for a model urban setting. Qualitative comparisons are made that show the additional structure of the DES solution due to resolved turbulence eddies. We observe that RANS models the general features of the farfield well; however, resolve the fine scale features of the flow in the immediate vicinity of the buildings requires LES (implemented here through the DES algorithm). DES proves a method to blend those approaches in a way that leverages the advantages of each. It uses RANS modeling in the farfield, not requiring too fine of a grid there, and switches to LES in the detached regions which are not captured well by RANS.

This work is preliminary. It does, however, indicate that a DES approach is promising. We expect to explicitly model dispersion of a contaminant in the scenario in the near future.

Ongoing work is directed at determining sensitivity to near-wall resolution and at determining simulation/modeling fidelity to flow physics.

The results of this study are expected to help guide modeling work directed at urban dispersion.

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REFERENCES

AcuSolve Command Reference Manual v1.7 , ACUSIM Software Inc, Mountain View, CA, September 2005.

Baik, J.-J. and J.-J. Kim, 1999: A numerical study of flow and pollutant dispersion characteristics in urban street canyons, *J. Applied Meteorol.*, **38**, 1576-1589.

Baik, J.-J., J.-J. Kim, and H.J.S. Fernando, 2003: A CFD model for simulating urban flow and dispersion, *J. Applied Meteorol.*, **42**, 1636-1648.

Britter, R.E. and S. R. Hanna, 2003: Flow and dispersion in Urban Areas. *Annu. Rev. Fluid Mech*, **35**, 469-496.

Chang, J.C., S.R. Hanna, Z. Boybeyi, and P. Franzese, 2005: Use of Salt Lake City URBAN 2000 Field to evaluate the urban hazard prediction assessment capability (HPAC) dispersion model, *J. Applied Meteorol.*, **44**, 485-501.

Cowan, I.R., I.P. Castro, A.G. Robins, 1997: Numerical considerations for simulations of flow and dispersion around buildings, *J. Wind Eng. & Ind. Aerodynam*, **67/68**, 535-545.

Hanna, S.R., S. Tehranian, B. Carissimo, R.W. Macdonald, and R. Lohner, 2002: Comparisons of model simulations with observations of mean flow and turbulence within simple obstacle arrays, *Atmos. Environ.*, **36**, 5067-5079.

Haan, P.d., M.W. Rotach, and J. Werfeli, 2001: Modification of an operational dispersion model for urban applications. *J. Applied Meteorol.*, **40**, 864-879.

He, P., T. Katayama, T. Hayashi, J.-i. Tsutsumi, J. Tanimoto, and I. Hosooka, 1997: Numerical simulation of air flow in an urban area with regularly aligned blocks, *J. Wind Eng. & Ind. Aerodynam*, **67/68**, 281-291.

Moon, D. A. Albergel, F. Jasmin, and G. Thibaut, 1997: The use of the MERCURE CFD code to deal with an air pollution problem due to building wake effects, *J. Wind Eng. & Ind. Aerodynam*, **67/68**, 781-791.

Palmer, G., B. Vazquez, G. Knapp, N. Wright, 2005: The practical application of CFD to Wind engineering problems, Eighth International IBPSA Conference, Eindhoven, Netherlands.

Pullen, J., Boris, J.P., Young, T., Patnaik, G., and Iselin, J., 2005: A comparison of contaminant plume statistics from a Gaussian puff and urban CFD model for two large cities, *Atmos. Env.*, **39**, 1049–1068.

Spalart, P.R., W.-H. Jou, M. Strelets, and S.R. Allmaras, 1997: Comments on the Feasibility of LES for Wings, and on a Hybrid RANS/LES Approach, 1st AFOSR Int. Conf on DNS/LES, Rustin, LA. In *Advances in DNS/LES*, C.Liu & Z.Liu Eds., Greyden Press, Columbus, OH, 137-147.

Warner, S. N. Platt, and J.F. Heagy, 2004: Comparisons of transport and dispersion model prediction of the URBAN 2000 Field experiment, *J. Applied Meteorol.*, **43**, 829-846.

Yamada, T., 2005: Numerical simulations of air flows in and around a city in a coastal region, Proceedings of the Sixth Conference on Coastal Atmospheric and Oceanic Processes, San Diego, paper 5.6.

Yuan, J. and A. Venkatram, 2005: Dispersion within a model urban area, *Atmospheric Env.*, **39**, 4729-4743.

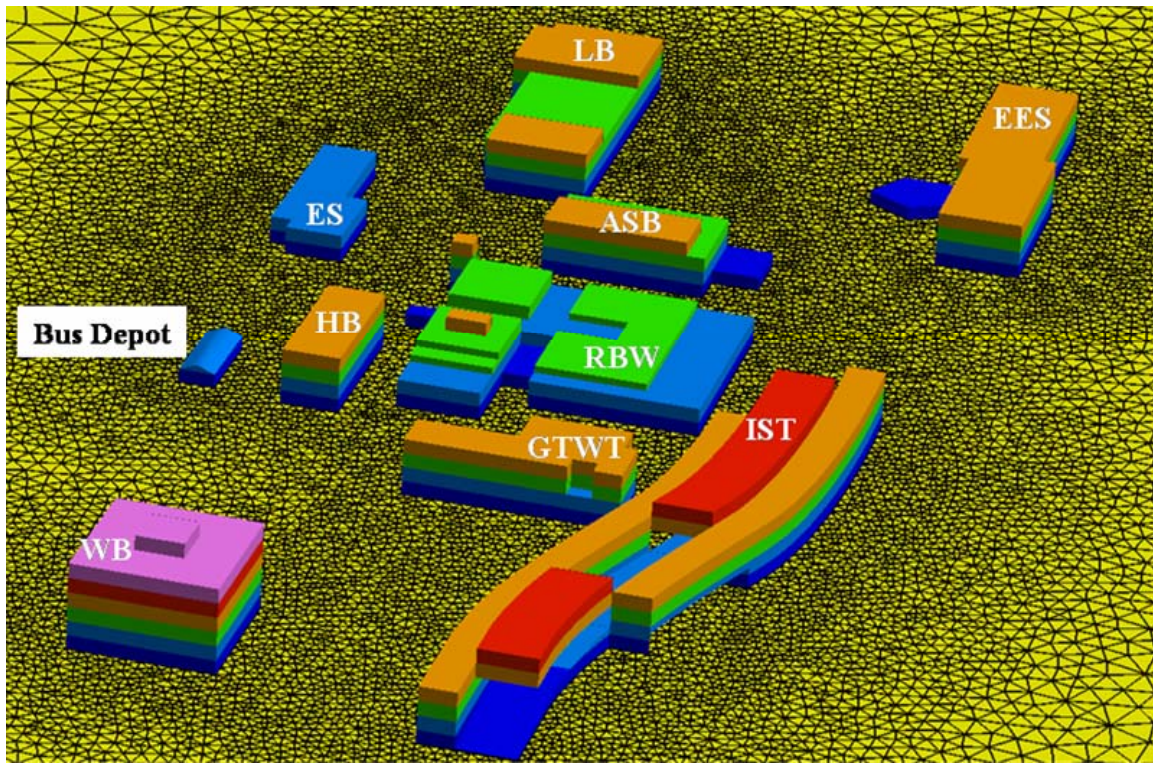


Figure 1 Penn State University West Campus: Information Sciences and Technology (IST), Walker Building (WB), Garfield Thomas Water Tunnel (GTWT), Research Building West (RBW), Hallowell Building (HB), Bus Depot, Engineering Services (ES), Earth-Engineering Sciences (EES), Applied Science Building (ASB), and the Leonhard Building (LB). Contours of Height: 1 band = 1 story.

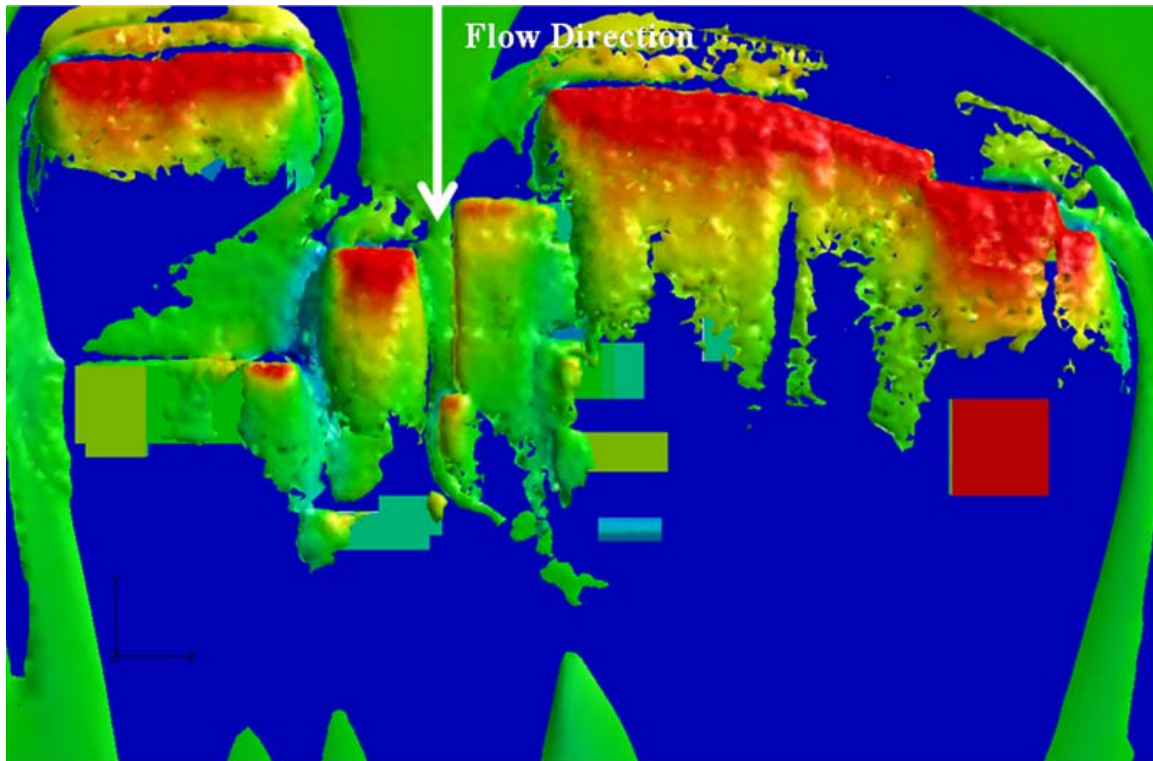


Figure 2 RANS results showing isosurfaces of vorticity magnitude (isolevel = 0.5) colored by vertical velocity. Updrafts are in red (> 0.2) and downdrafts are in blue (< -0.2).

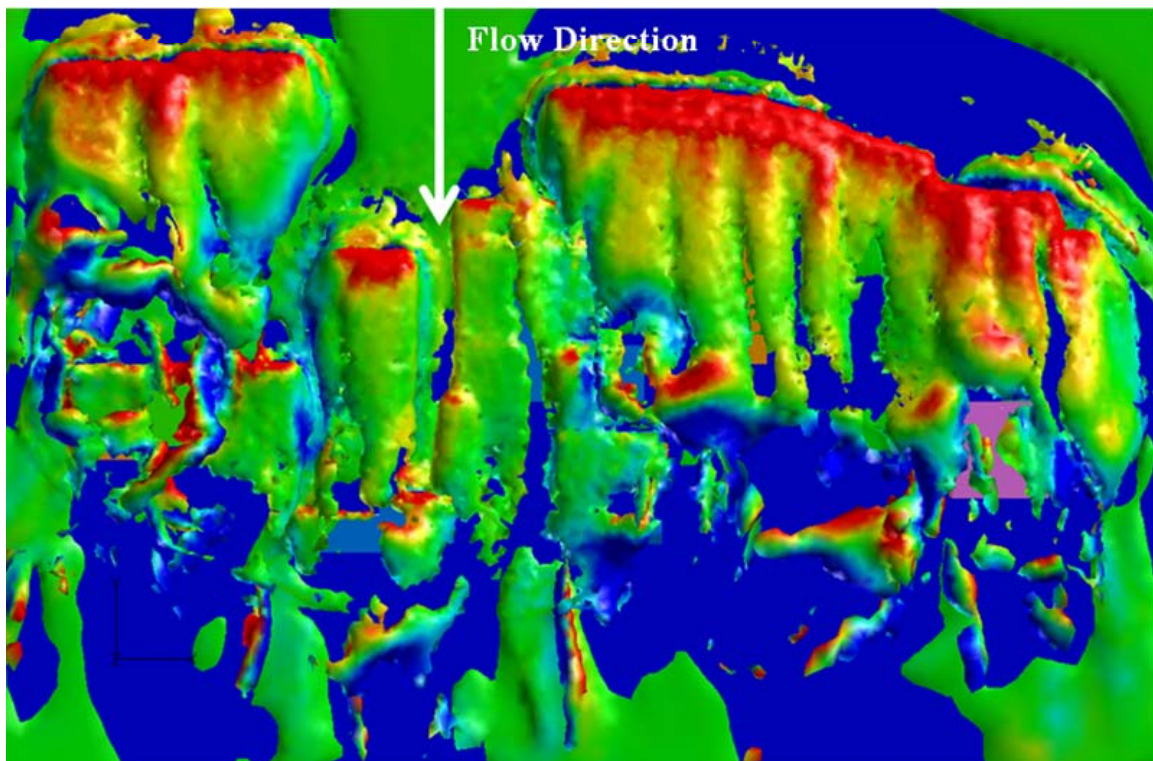


Figure 3 DES results showing isosurfaces of vorticity magnitude (isolevel = 0.5) colored by vertical velocity. Updrafts are in red (> 0.2) and downdrafts are in blue (< -0.2).

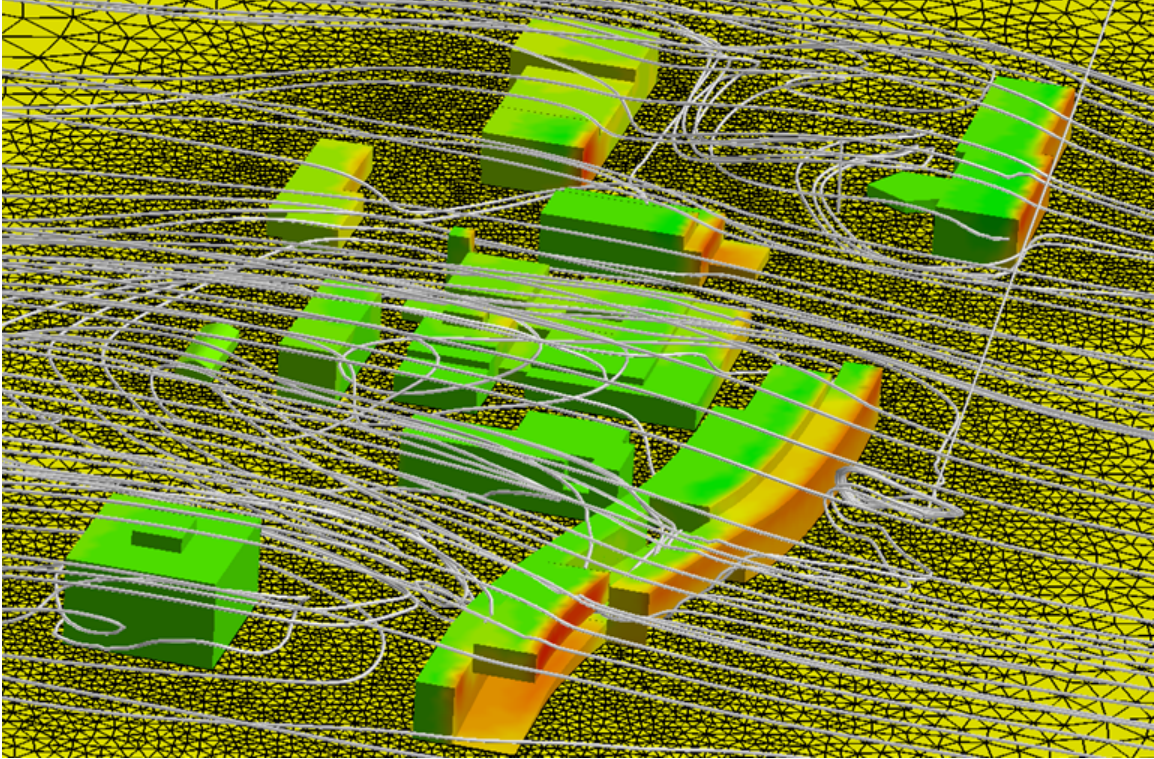


Figure 4. Pathlines from the RANS solution showing the resolved turbulence, flow separations and recirculations, with buildings colored by relative pressure (contour range $\Delta p = 1.4$).

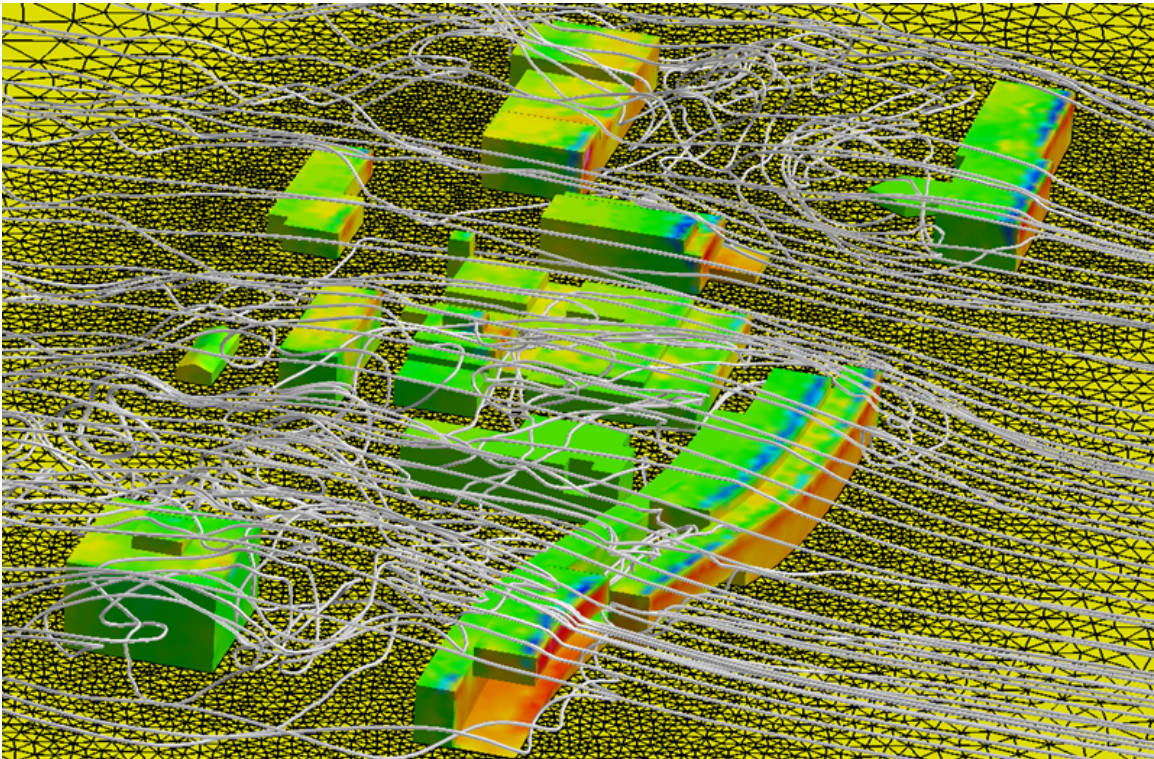


Figure 5. Pathlines from the DES solution showing the resolved turbulence, flow separations and recirculations, with buildings colored by relative pressure (contour range $\Delta p = 1.4$).

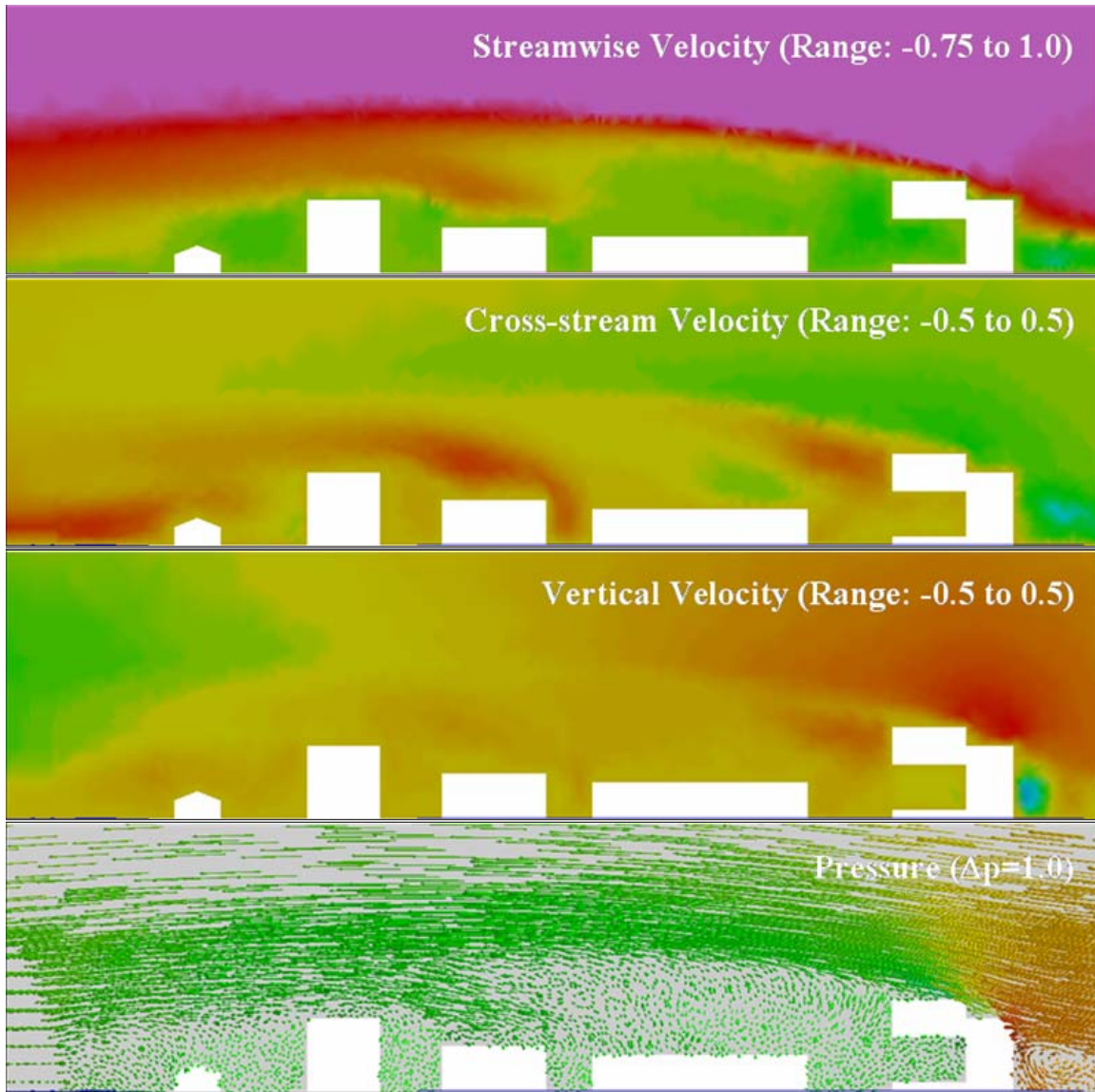


Figure 6 Velocity contours from the RANS solution showing the structure of the resolved turbulence on a plane: streamwise velocity (-0.75 to 1.0), cross-stream velocity (-0.5 to 0.5), vertical velocity (-0.5 to 0.5), and velocity vectors with background colored by pressure ($\Delta p=1.0$).

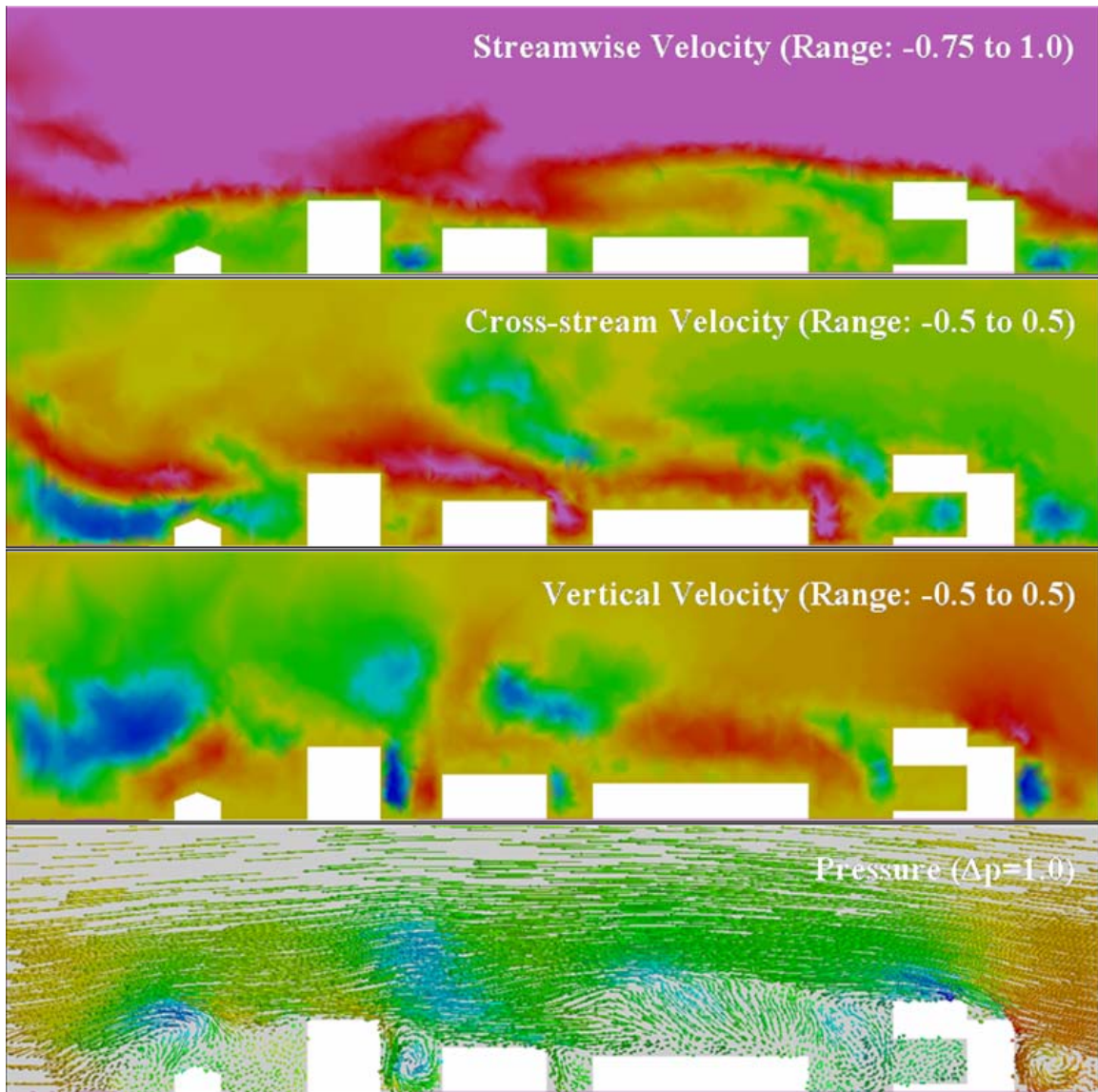


Figure 7 Velocity contours from the DES solution showing the structure of the resolved turbulence on a plane: streamwise velocity (-0.75 to 1.0), cross-stream velocity (-0.5 to 0.5), vertical velocity (-0.5 to 0.5), and velocity vectors with background colored by pressure ($\Delta p=1.0$).