Fast Pressure Calculations on Buildings to Improve Outdoor-to-Indoor Transport & Dispersion

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Austin, TX

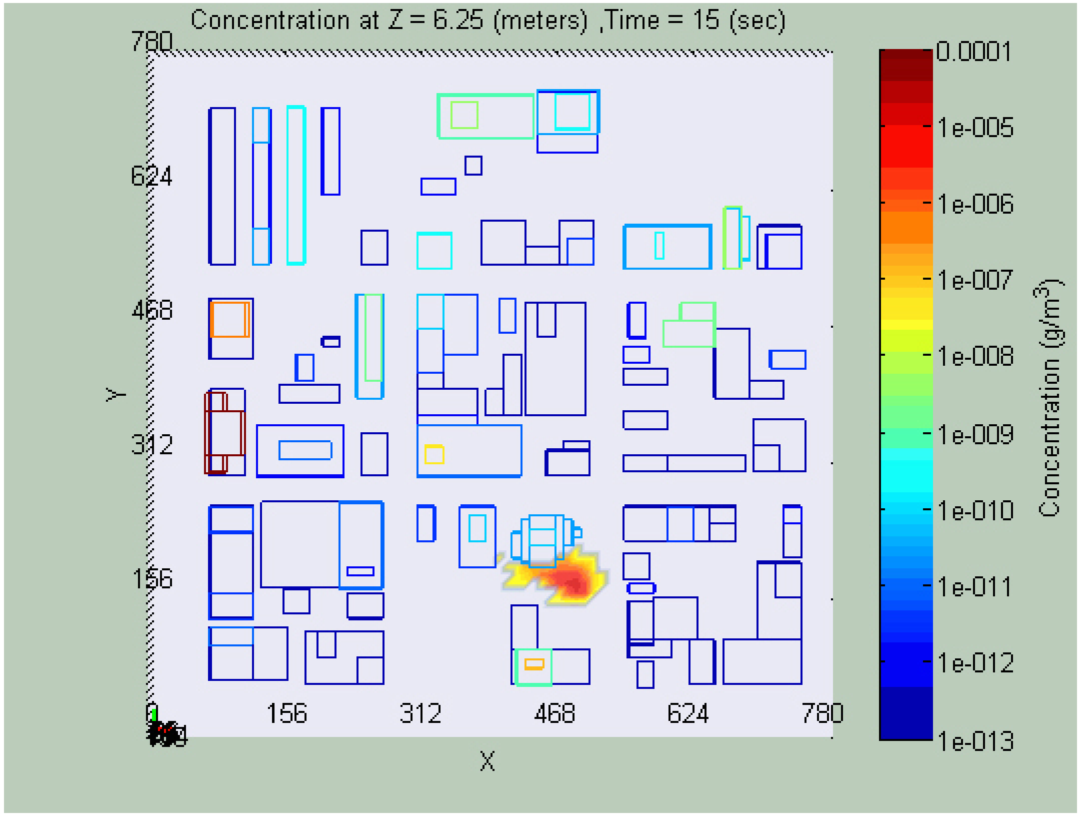
Presentation Outline

- **Why Pressure Important for T&D Applications**
  - Pressure Distribution on Buildings Influences Air Exchange Rate
- **Modeling Tools**
  - QUIC-URB Wind Model
  - QUIC Pressure Solver
- **Model Evaluation**
- **How the fast wind & pressure models could be used to improve Indoor T&D calculations**

Motivation

- **Outdoor Releases Infiltrate into Buildings**

5 minute duration outdoor release



½ hour QUIC Salt Lake City simulation

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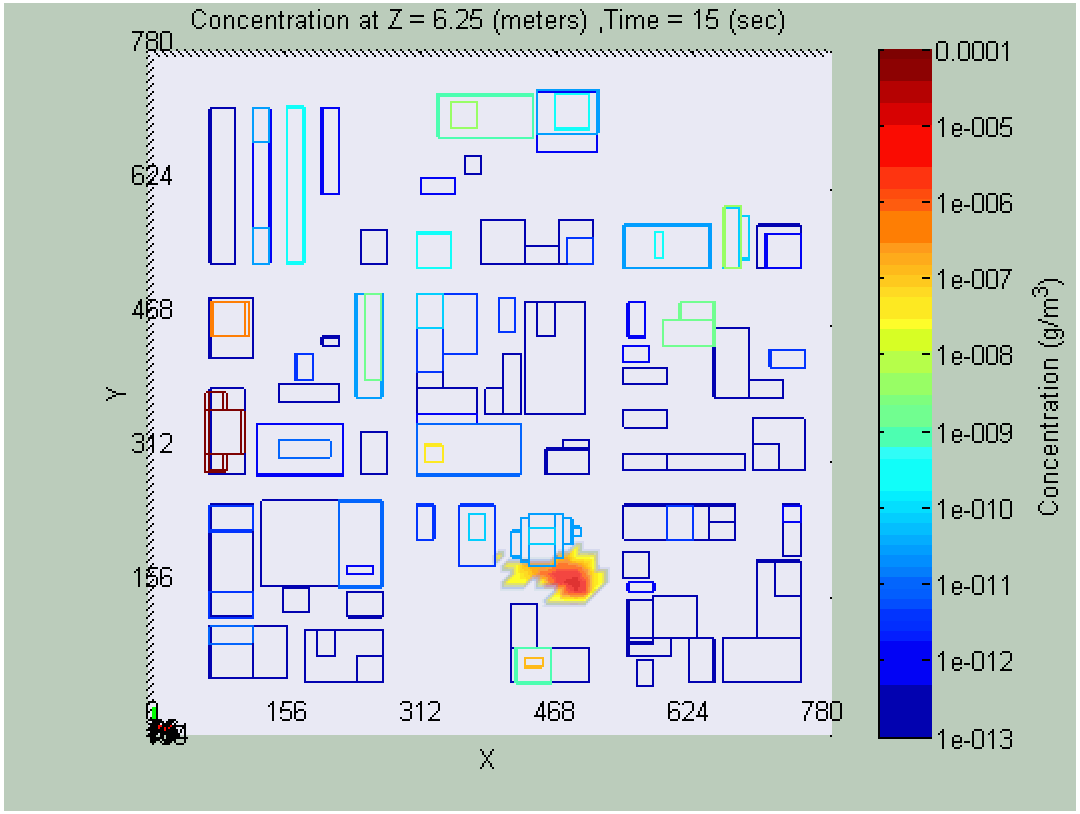

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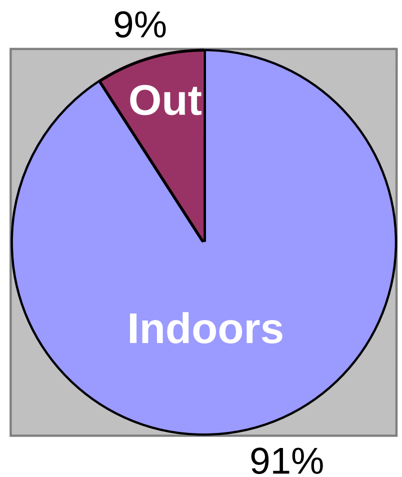
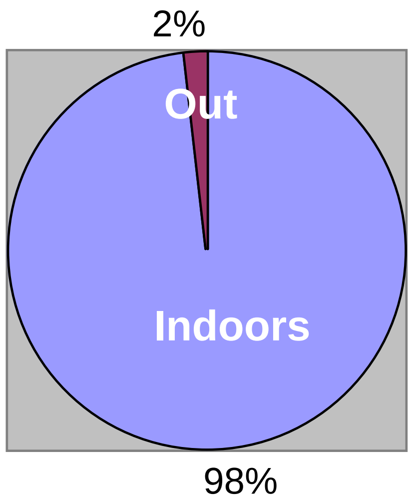
- Outdoor Releases Infiltrate into Buildings
- **Population mostly resides Indoors**

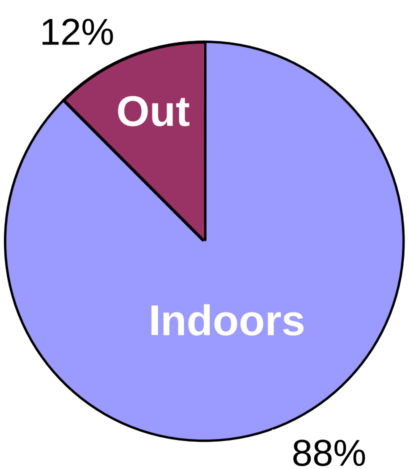
Daytime Residential



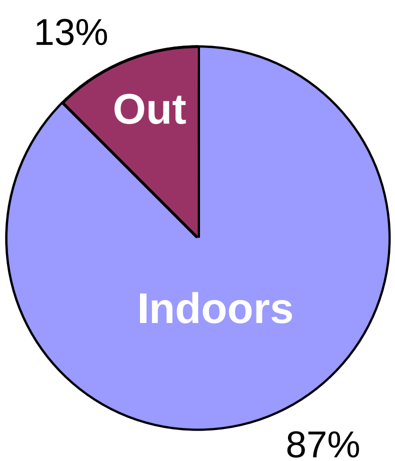
Nighttime Residential



Daytime Workers



Nighttime Workers



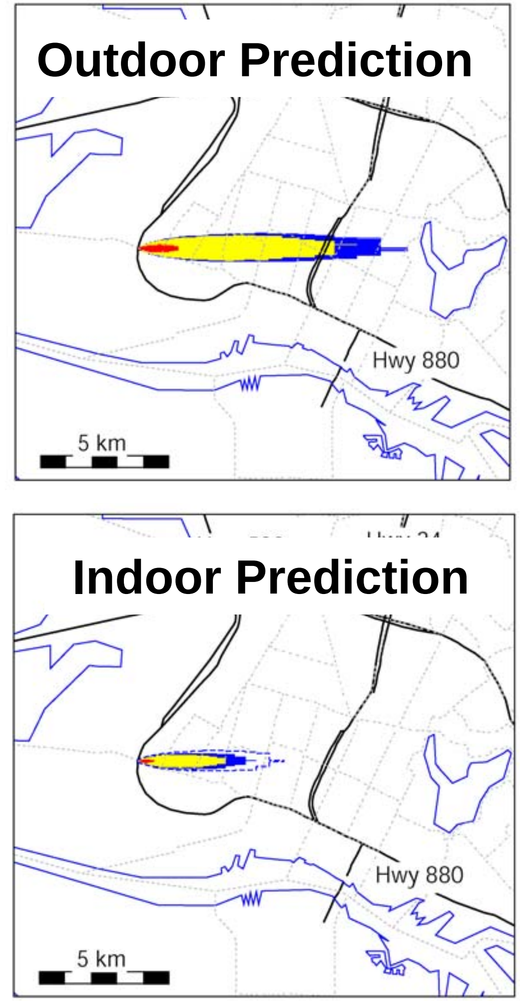
LANL USA Day-Night Indoor-Outdoor Pop DB

McPherson, T., A. Ivey, and M. Brown, 2004: Determination of the spatial and temporal distribution of population for air toxics exposure assessments, AMS 5th Symp on Urban Environment, Vancouver, BC.

Motivation

- **Outdoor Releases Infiltrate into Buildings**
- **Population mostly resides Indoors**
- **Exposure estimates can be much smaller if building "protection" considered**

Gadgil, 2005
GMU T&D
Workshop

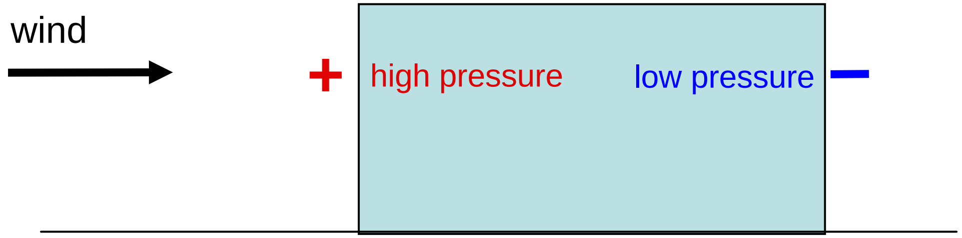


Transient Effects	Irreversible Effects	Life Theatening

Acute **E**xposure **G**uideline **L**evels

Motivation

- Outdoor Releases Infiltrate into Buildings
- Population mostly resides Indoors
- Exposure estimates sensitive to building "protection"
- **Air exchange for naturally-ventilated buildings is proportional to wind-induced pressure on building walls**



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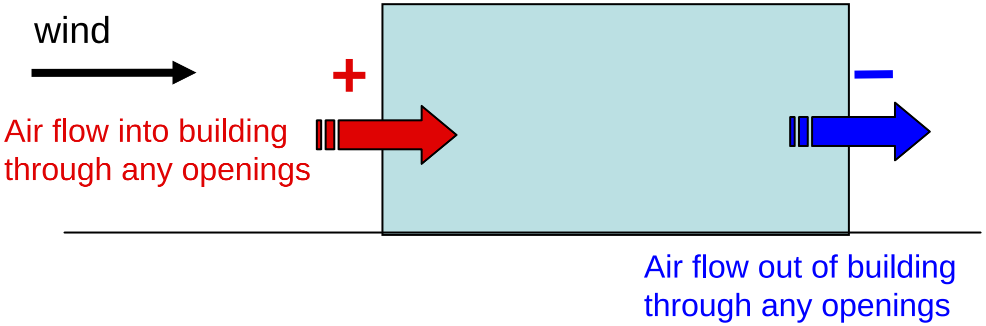

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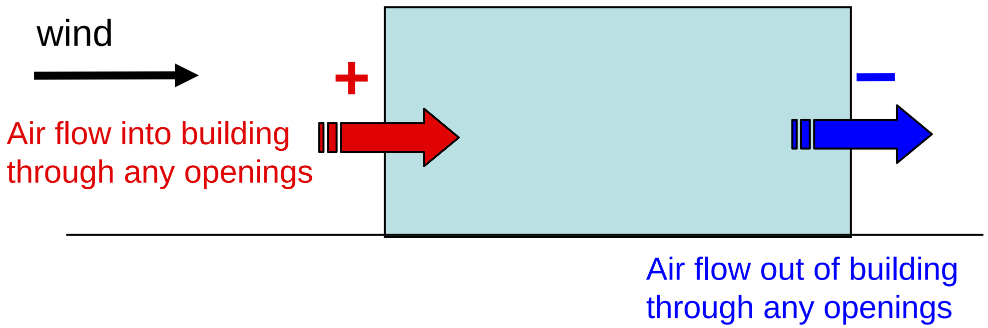

Chan et al. (2005) – Most residential buildings in US do not have mechanical ventilation systems

Motivation

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- **Population mostly resides Indoors**
- **Air exchange for naturally-ventilated buildings is proportional to wind-induced pressure on building walls**

Pressures on surface used as boundary conditions in CFD and multi-zone models, e.g., **COMIS**

Orifice equation

$$Q_f = ELA_{bldg} * (2 * \Delta P_{bldg} / \rho)^{1/2}$$

Q_f = volumetric airflow rate
ELA = effective leakage area of bldg

In practice

$$Q_f = k * \Delta P^{n} \qquad 0.6 < n < 0.7$$

Motivation

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The Urban Dispersion Model (UDM)

The Air Exchange Rate (AER) is due to a Buoyancy (“stack”) Pressure and a Wind-Induced Pressure.

Ignoring the stack pressure effect (e.g., $T_{indoor}=T_{outdoor}$)

$$\boxed{AER_{bldg} = (AER_{ref} / \Delta P_{ref}^{2/3})*\Delta P_{bldg}^{2/3}}$$

<u>Indoor Concentration</u>

$$\chi_i(t)=e^{\frac{-t}{\tau}}\left[\chi_{out}(t_s)+\int_{t_s}^{t}\frac{\chi_{out}(t')}{\tau}e^{\frac{-t}{\tau}}dt'\right]$$

where

$$\tau=\frac{3600}{AER}$$

Wind & Pressure Solvers

Idea:

Use Fast Solvers To Compute **Pressure Field** on Buildings and Provide as Input to **Indoor Models**

3D Buildings

Inflow Wind Profile

QUIC-URB

3D Wind Field

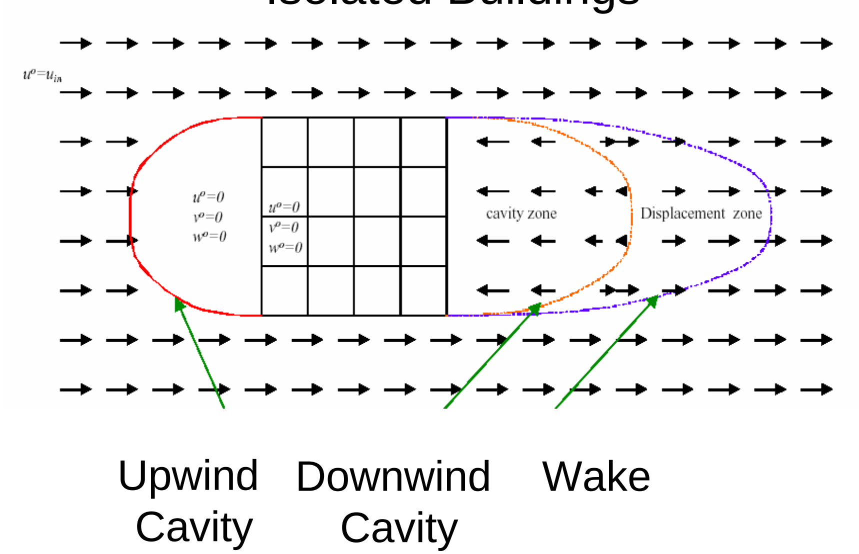
QUIC-Pressure Solver

3D Pressure Field

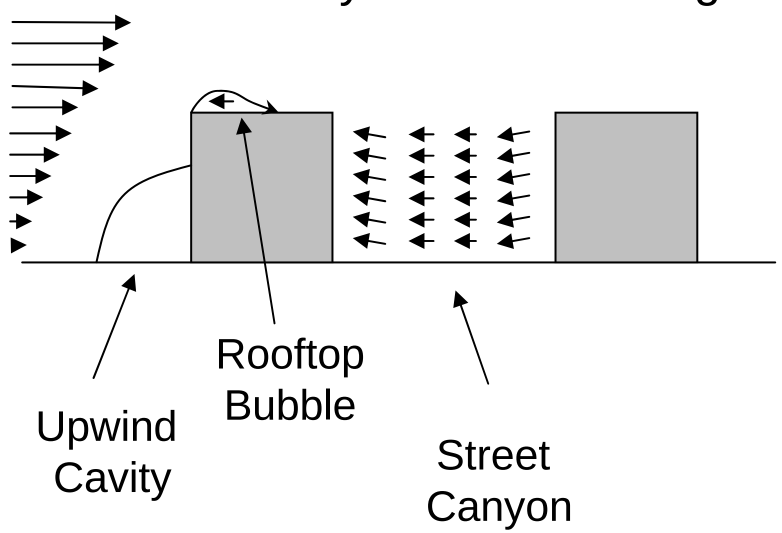
QUIC-URB Wind Solver

- Based on dissertation of Röckle (1990)
- 3D winds obtained from diagnostic/empirical method
- Initial winds based on building spacing and geometry
- Then mass conservation imposed (Sherman,1978)

Isolated Buildings



Densely Packed Buildings



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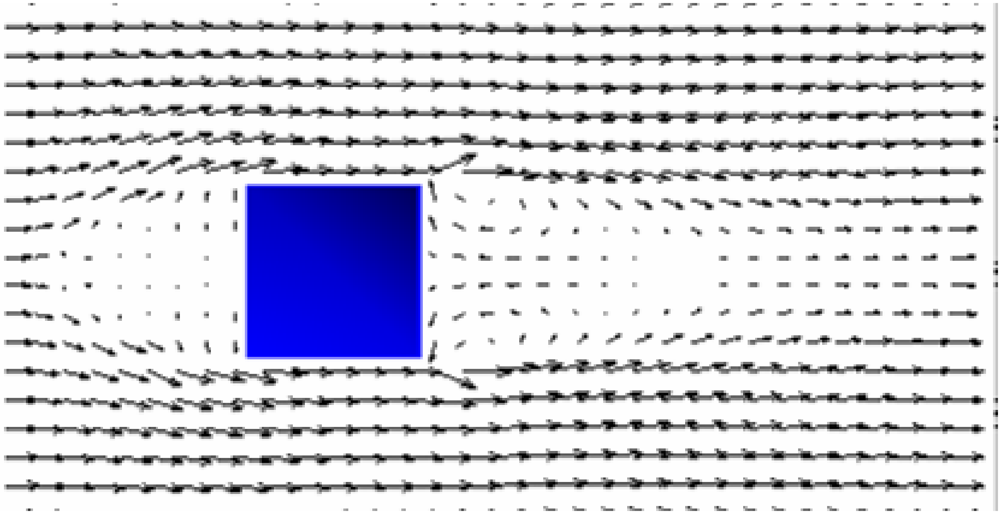

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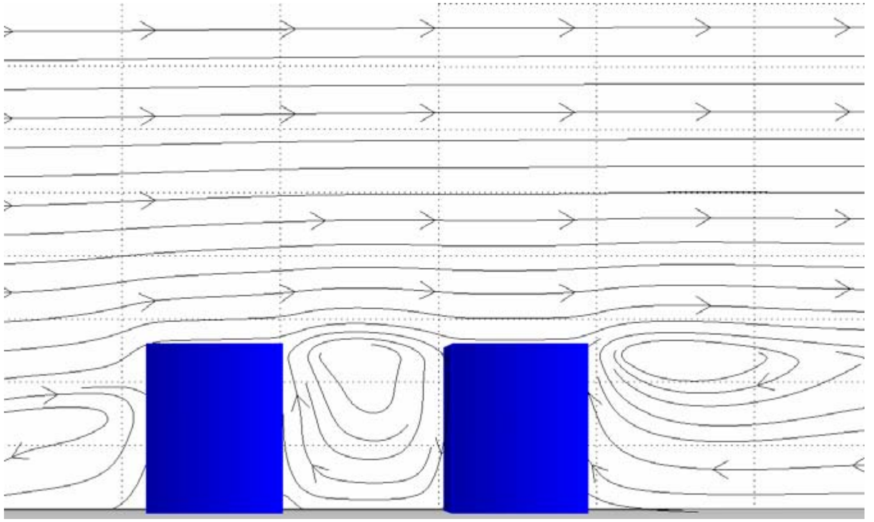


QUIC Pressure Solver (Gowardhan et al., 2006)

Momentum Equation:

$$\cancelto{0}{\frac{\partial \overline{U_i}}{\partial t}} = -\underbrace{\frac{\partial(\overline{U_i}\,\overline{U_j})}{\partial x_j}}_{\mathrm{I}} - \frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} - \underbrace{\frac{\partial(\overline{u'_i u'_j})}{\partial x_j}}_{\mathrm{II}} + \nu \underbrace{\frac{\partial^2 \overline{U_i}}{\partial x_j \partial x_j}}_{\mathrm{III}} \qquad (1)$$

where,

I - Advective terms

II -Reynolds stress terms

III -Diffusive terms

*Assuming **steady state** and taking **divergence** of Eqn. 1*

QUIC Pressure Solver

$$\frac{\partial}{\partial x_i}\left(\frac{\partial \overline{P}}{\partial x_i}\right) = \rho \frac{\partial}{\partial x_i}\left(\nu \frac{\partial^2 \overline{U_i}}{\partial x_j \partial x_j} - \frac{\partial(\overline{U_i}\,\overline{U_j})}{\partial x_j} - \cancelto{0}{\frac{\partial(\overline{u'_i u'_j})}{\partial x_j}} \right) \qquad (2)$$

- *The pressure Poisson equation is solved by iterative method with* $\partial p / \partial n = 0$

- *Reynolds Stresses are neglected due to lack of information*

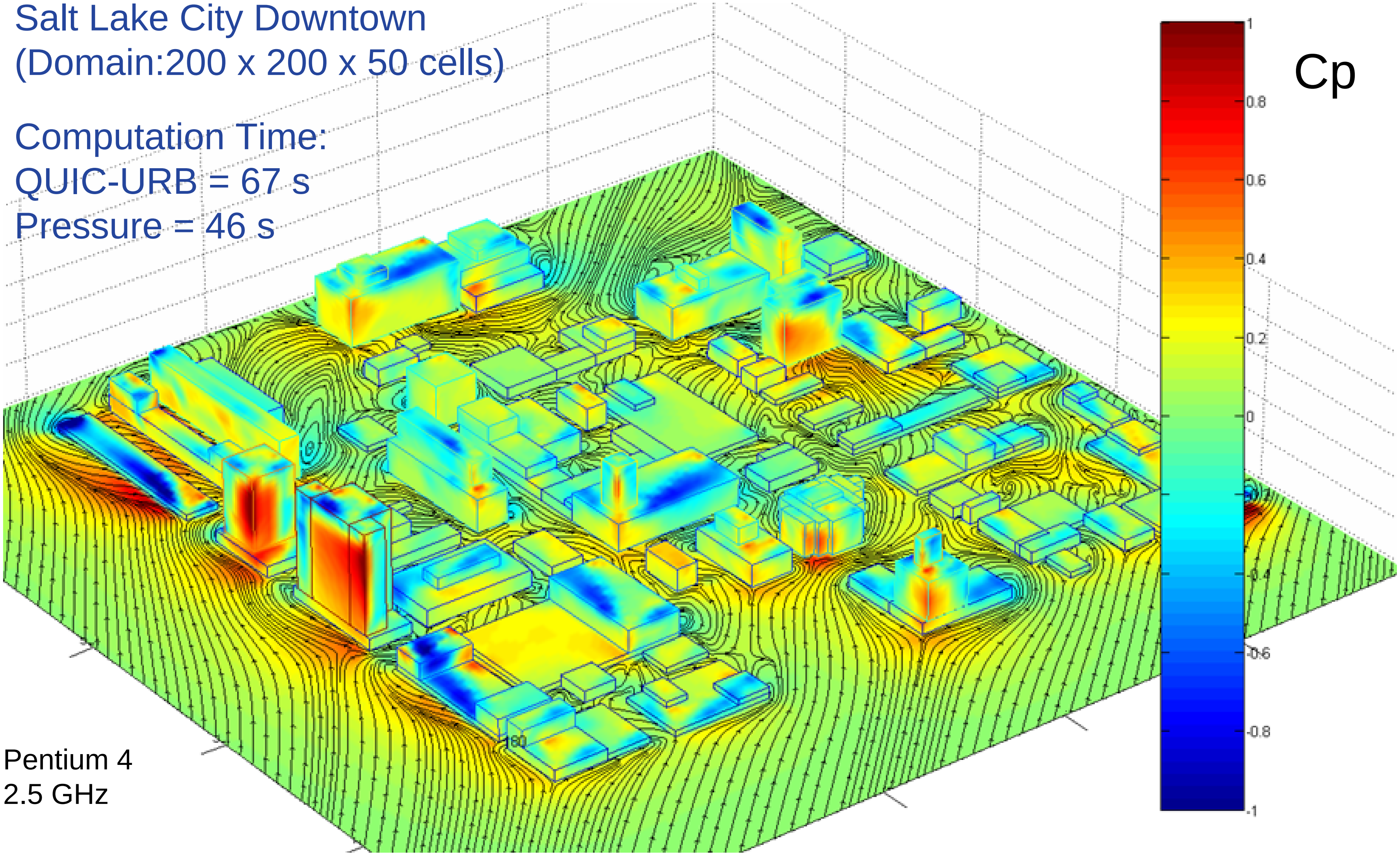
- *Coefficient of Pressure is calculated using the following formula:*

$$C_p = \frac{\overline{P} - \overline{P_o}}{\left(\frac{1}{2} \rho V_o^2\right)}$$

QUIC Wind & Pressure Solvers

Salt Lake City Downtown
(Domain:200 x 200 x 50 cells)

Computation Time:
QUIC-URB = 67 s
Pressure = 46 s



Pentium 4
2.5 GHz

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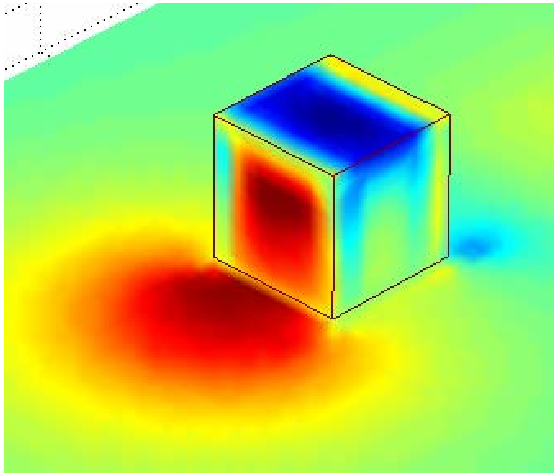
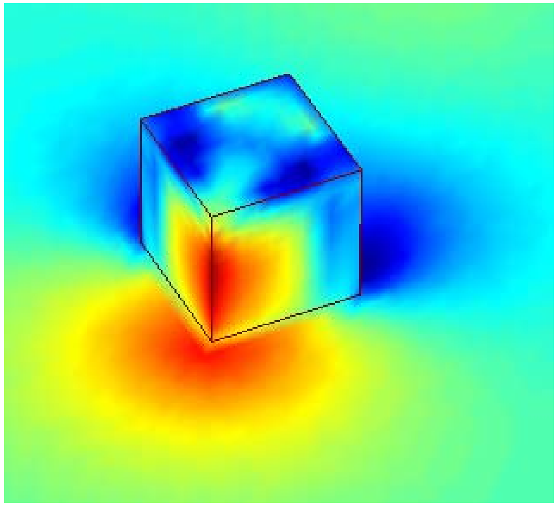
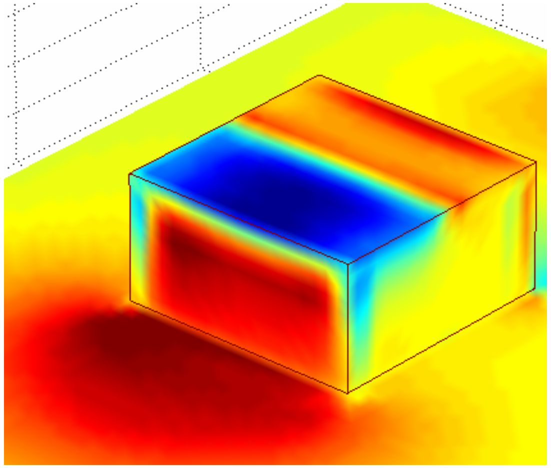
Model Evaluation Cases



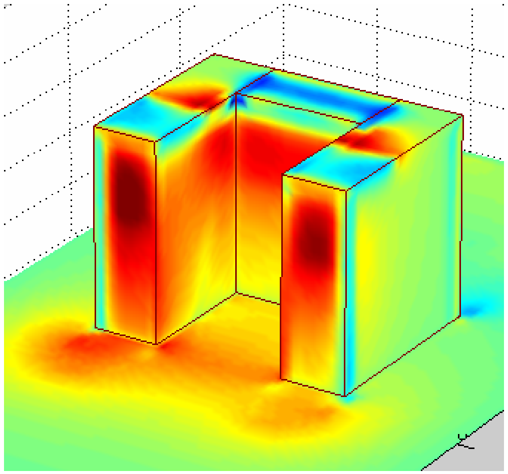
Cube (90 deg)



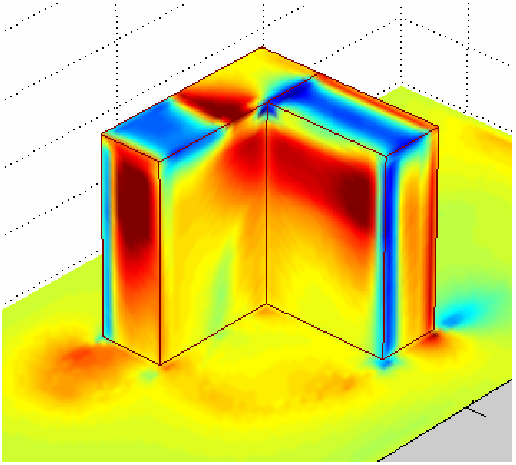
Cube (45 deg)



Squat

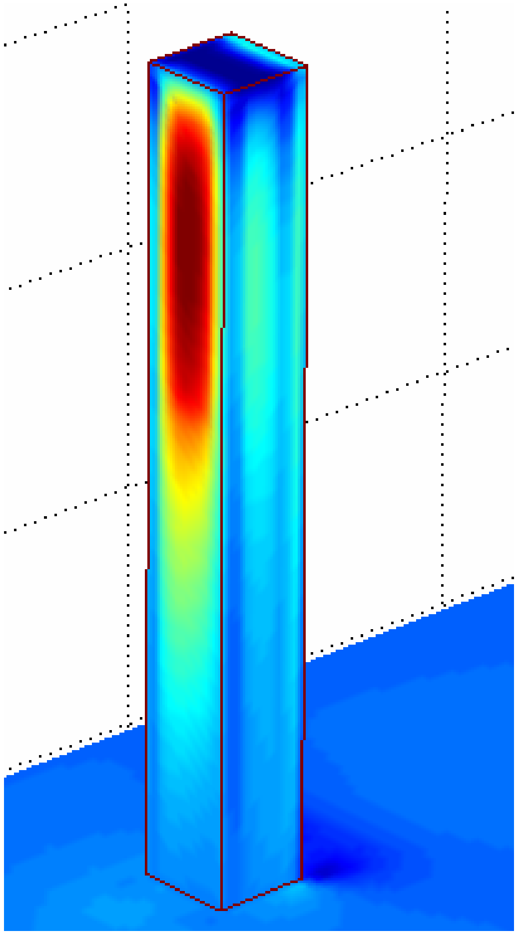


U-shaped

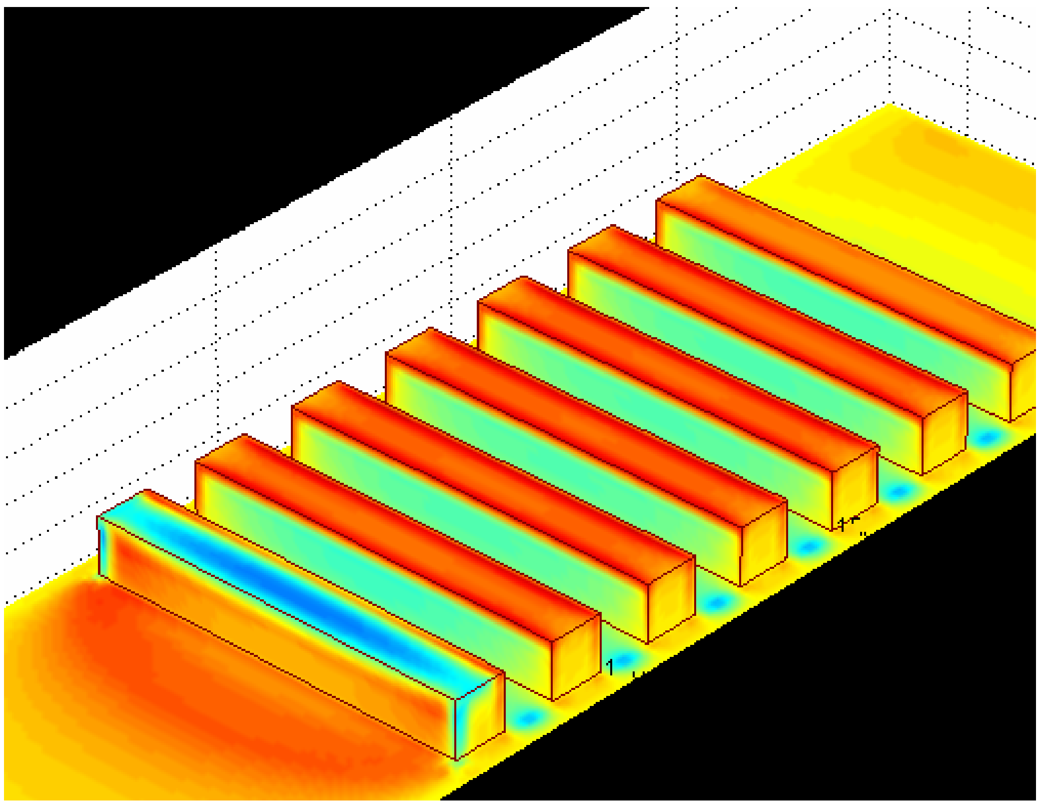


L-shaped

Model Evaluation Cases

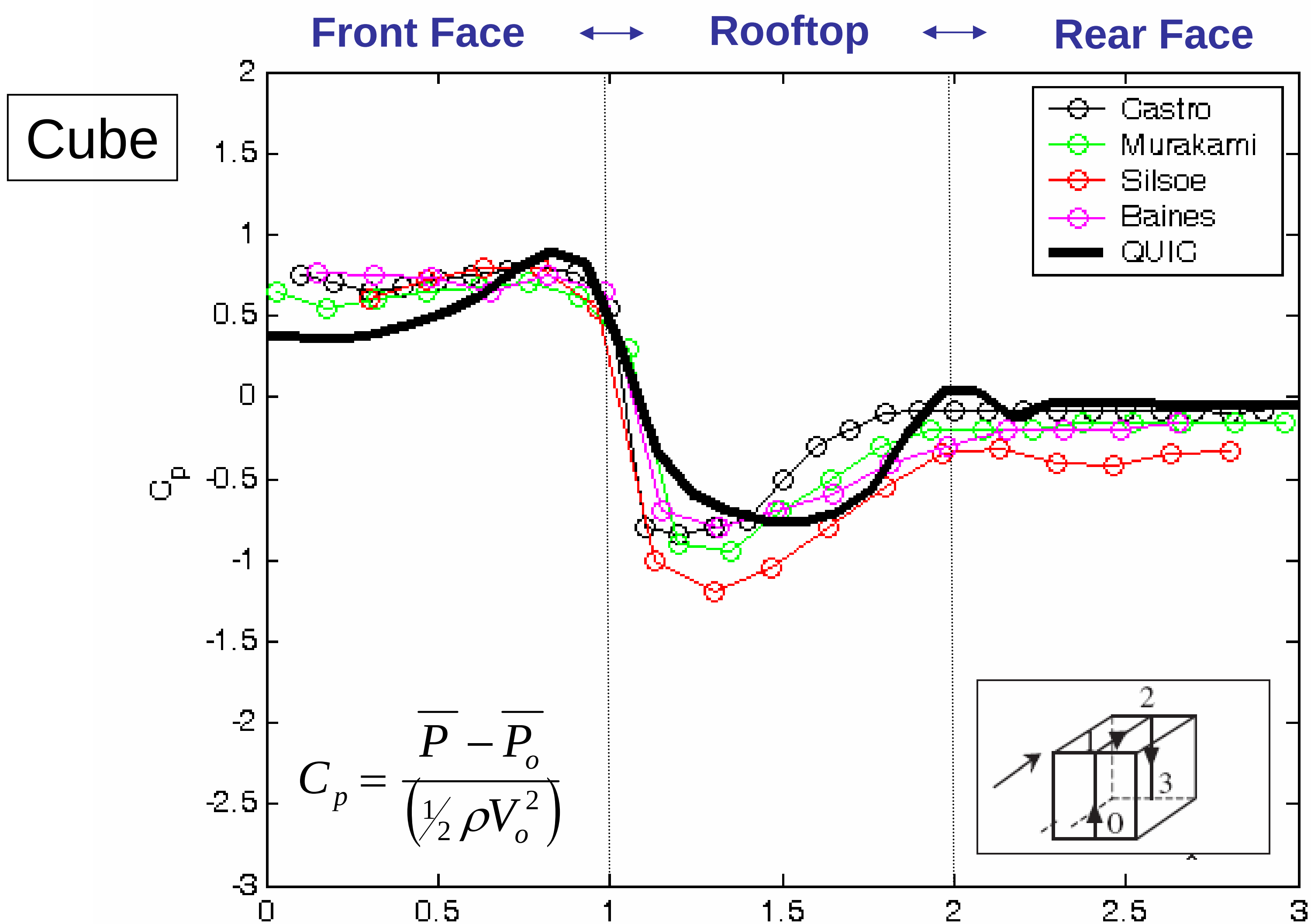


High-Rise



7x1 Wide Building Array

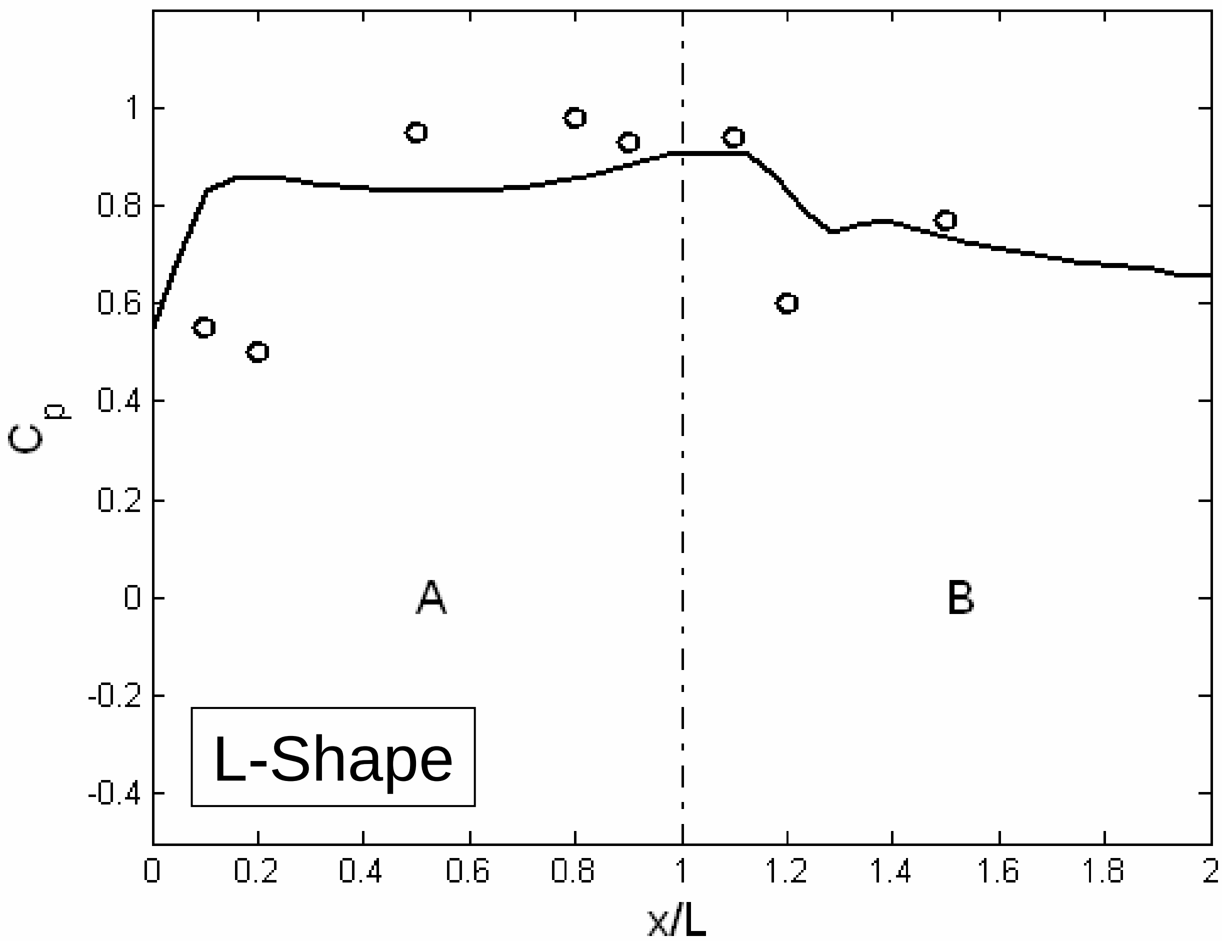
QUIC vs. Experimental Data: Cube (90 deg.)

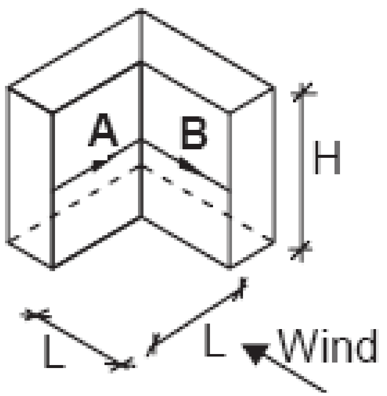


Adapted from Richards & Hoxey (2006)

QUIC vs. Experimental Data: L-Shaped Building

Front Face A ⟷ Side Face B





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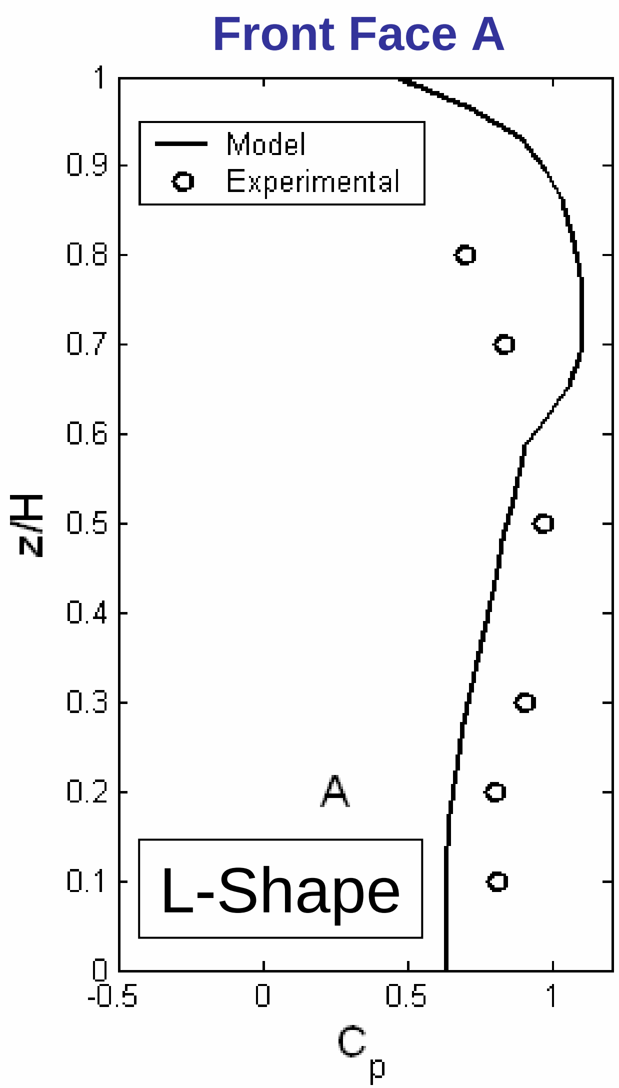

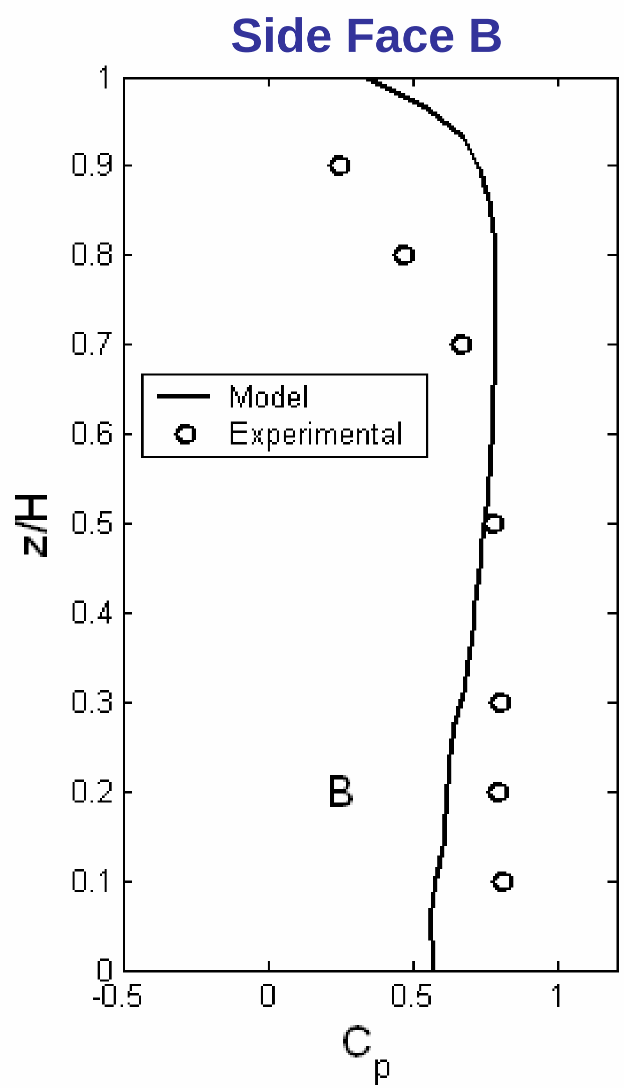

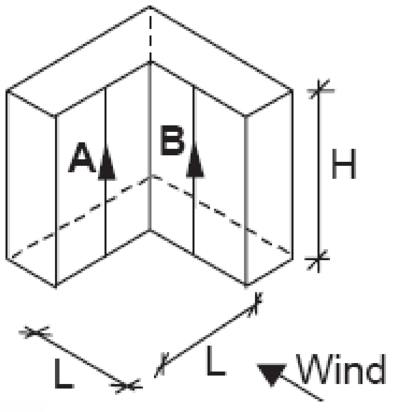

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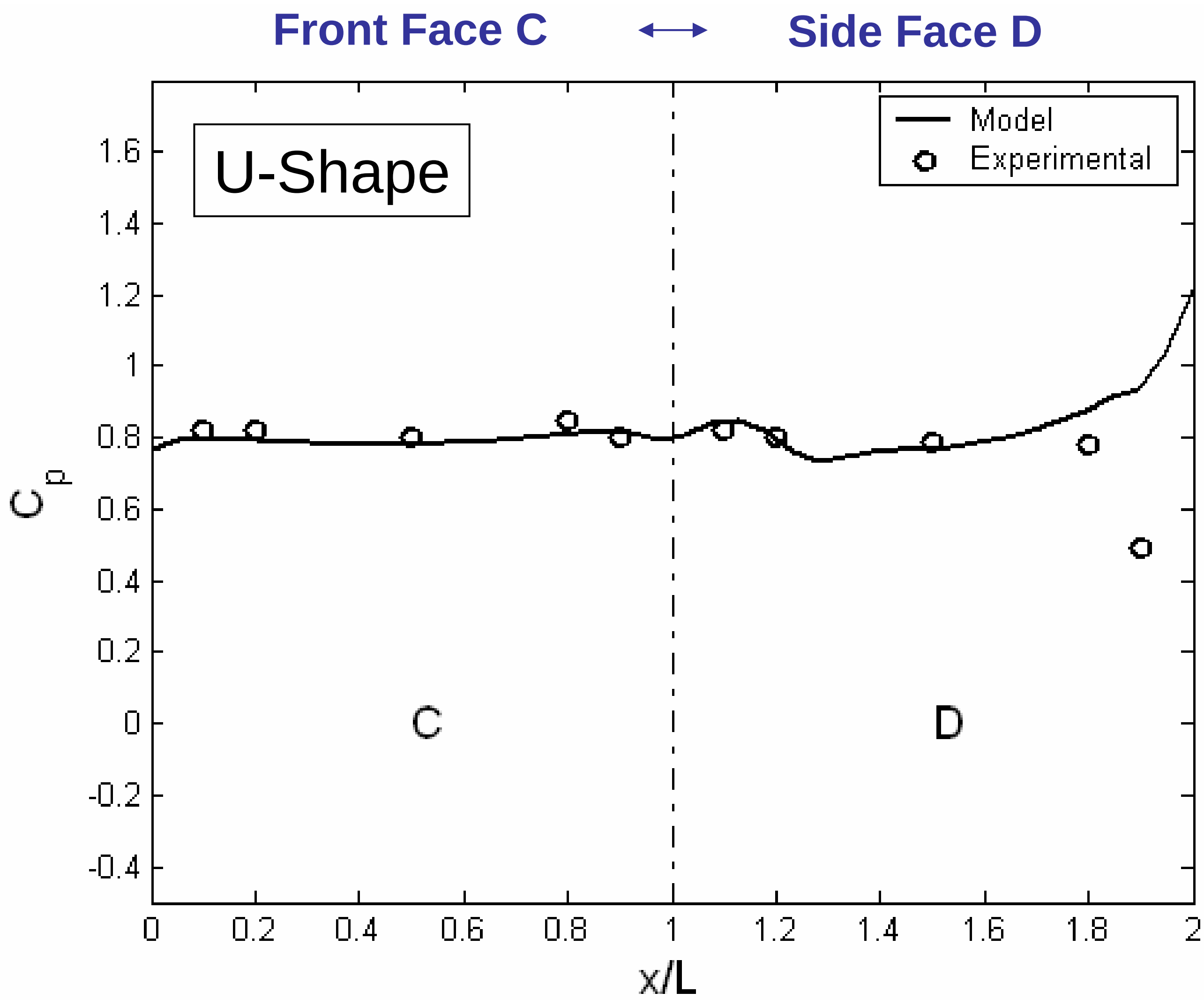
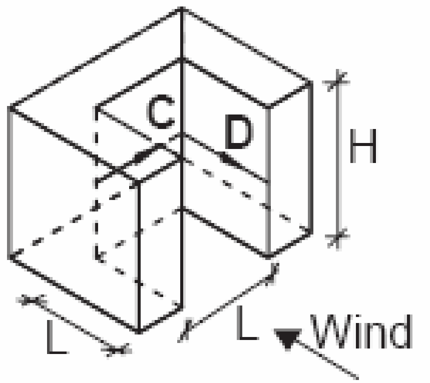
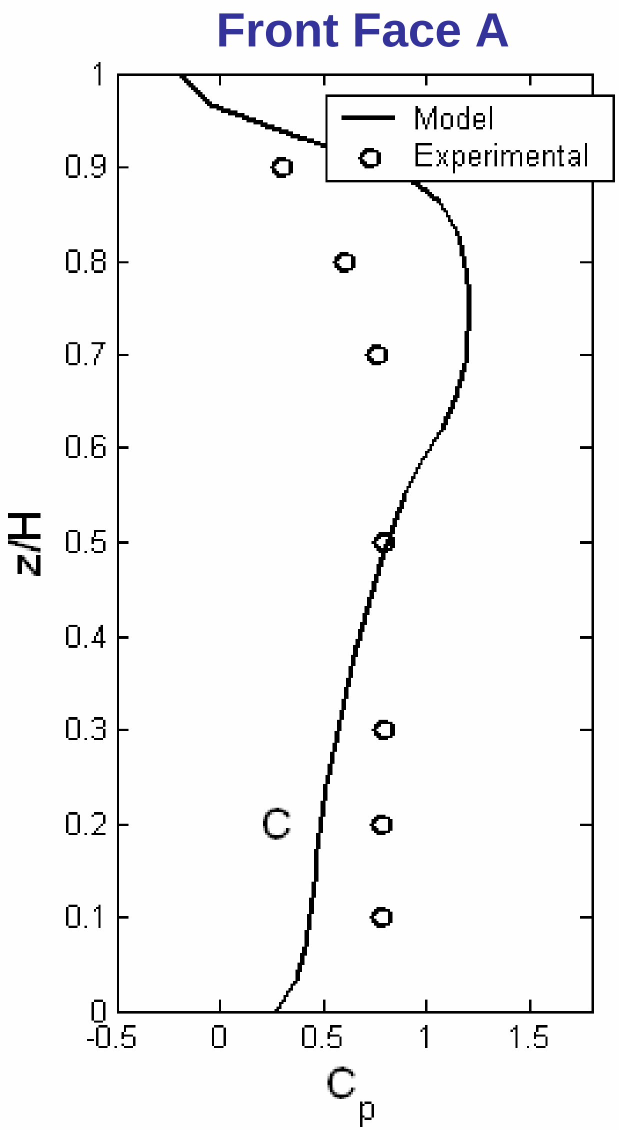
QUIC vs. Experimental Data: U-Shaped Building

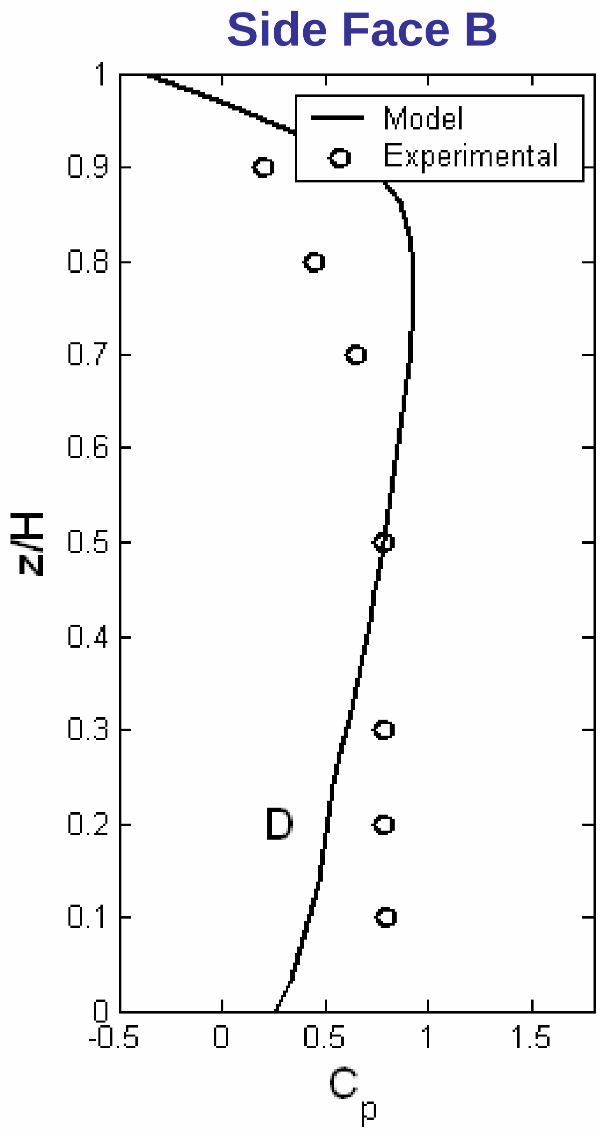


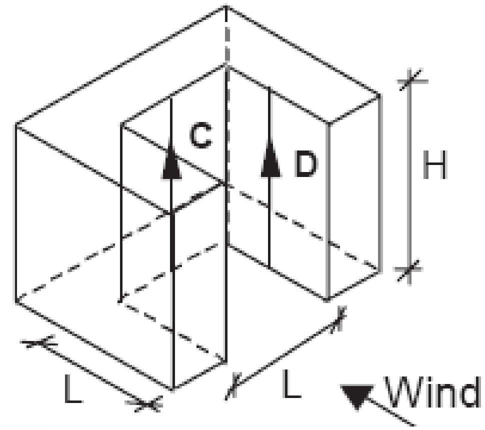


Adapted from Gomes et al (2005)

QUIC vs. Experimental Data: U-Shaped Building







U-Shape

Adapted from
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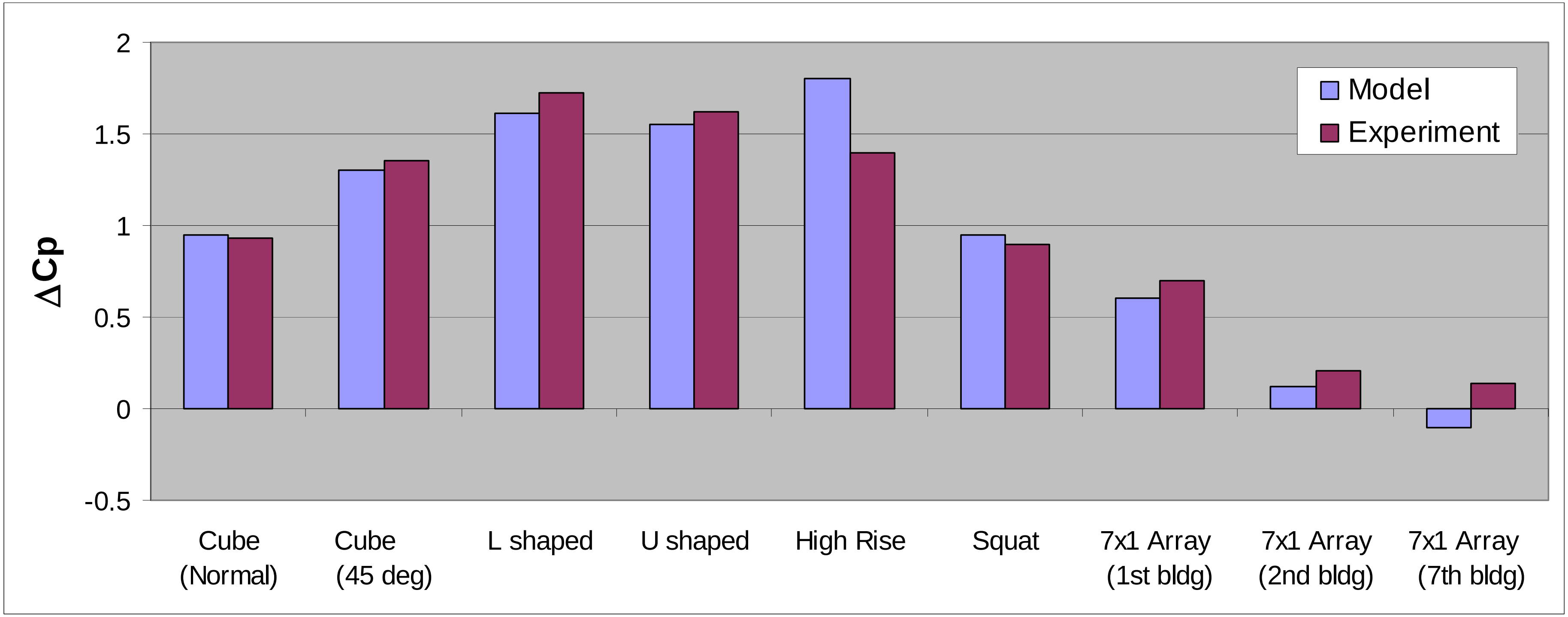
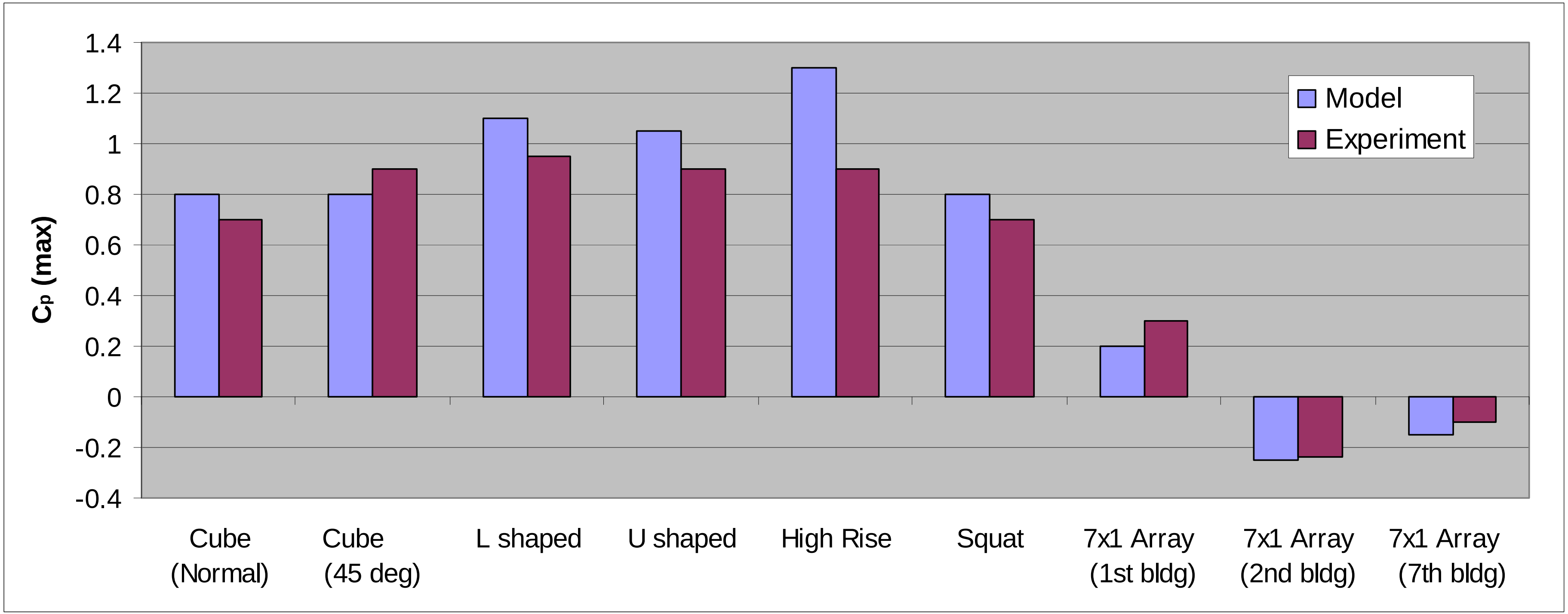
QUIC vs. Experimental Data



ΔC_p = Max C_p Front Face – Min C_p Back Face

$$C_p = \frac{\overline{P} - \overline{P_o}}{\left(\frac{1}{2}\rho V_o^2\right)}$$

QUIC vs. Experimental Data



The Maximum C_p on the Front Face

$$C_p = \frac{\overline{P} - \overline{P_o}}{\left(\frac{1}{2}\rho V_o^2\right)}$$

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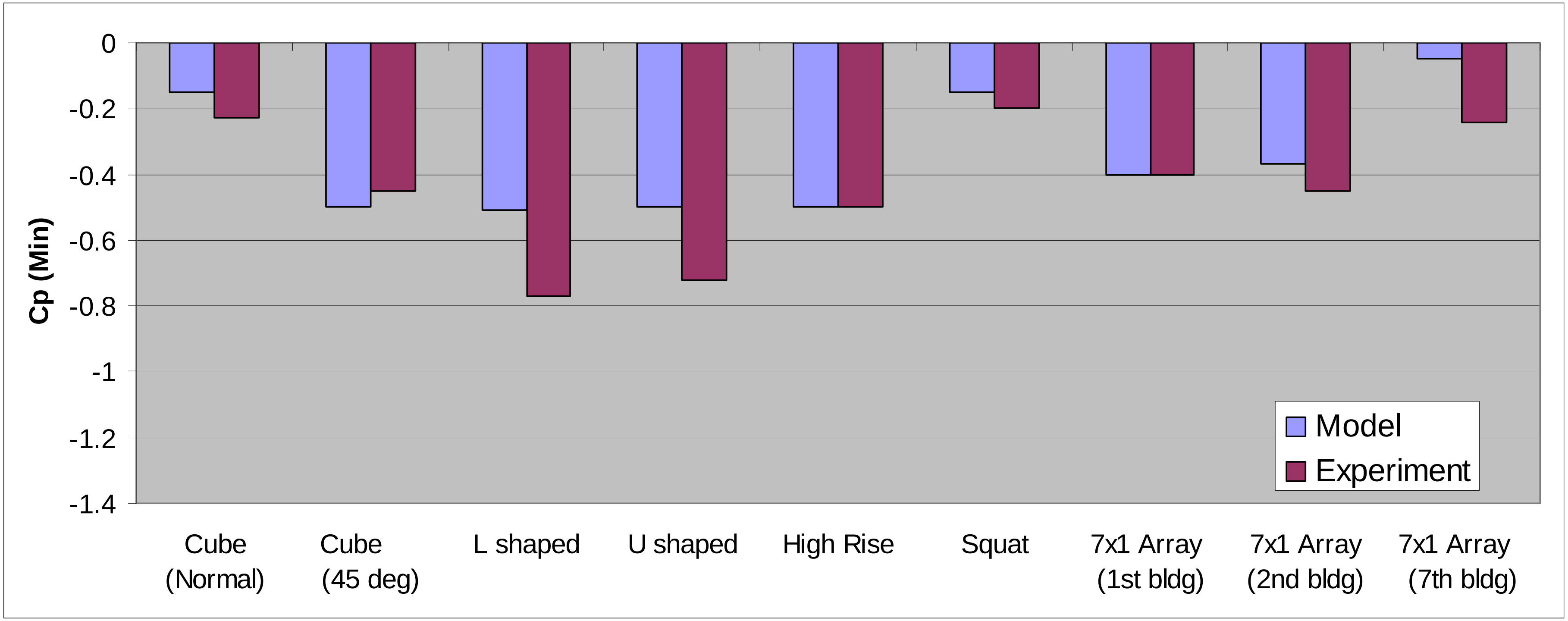


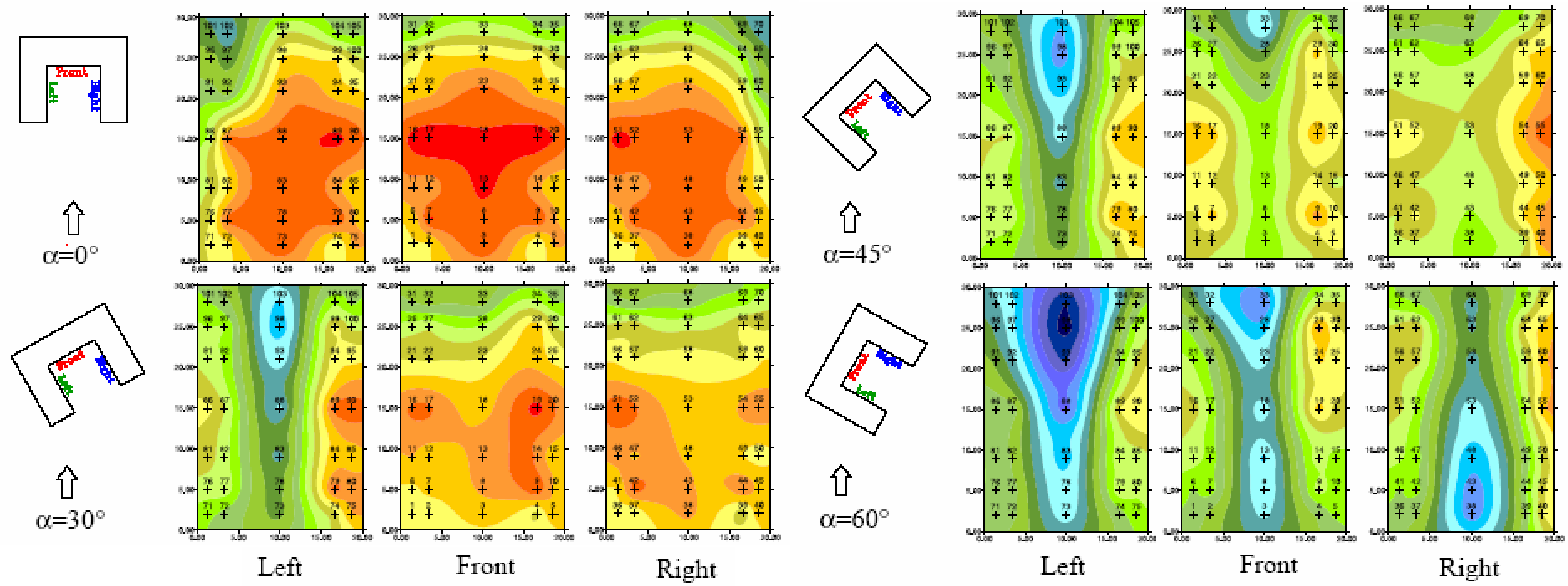
The Minimum C_p on the Back Face

$$C_p = \frac{\overline{P} - \overline{P_o}}{\left(\frac{1}{2}\rho V_o^2\right)}$$

Where the Combined Wind & Pressure Solvers Could Make a Difference

- Off-angle winds
- Dense Urban Areas - Sheltering effects of surrounding buildings
- Detailed analyses of building of interest (where locations of vents, windows, doors are known)

Off-Angle Winds

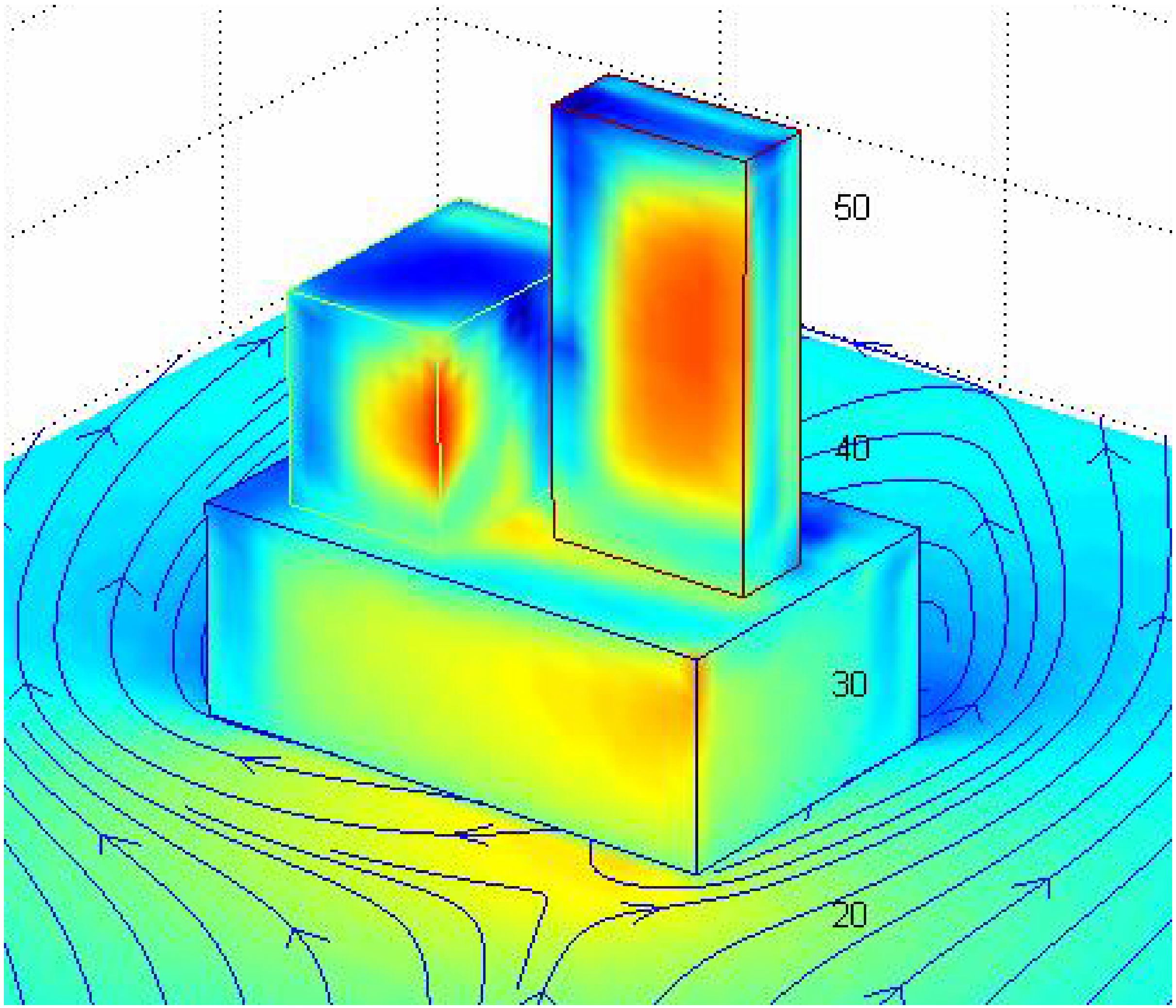


CFD simulations of Gomes et al. (2005)

Detailed Analyses of Buildings of Interest

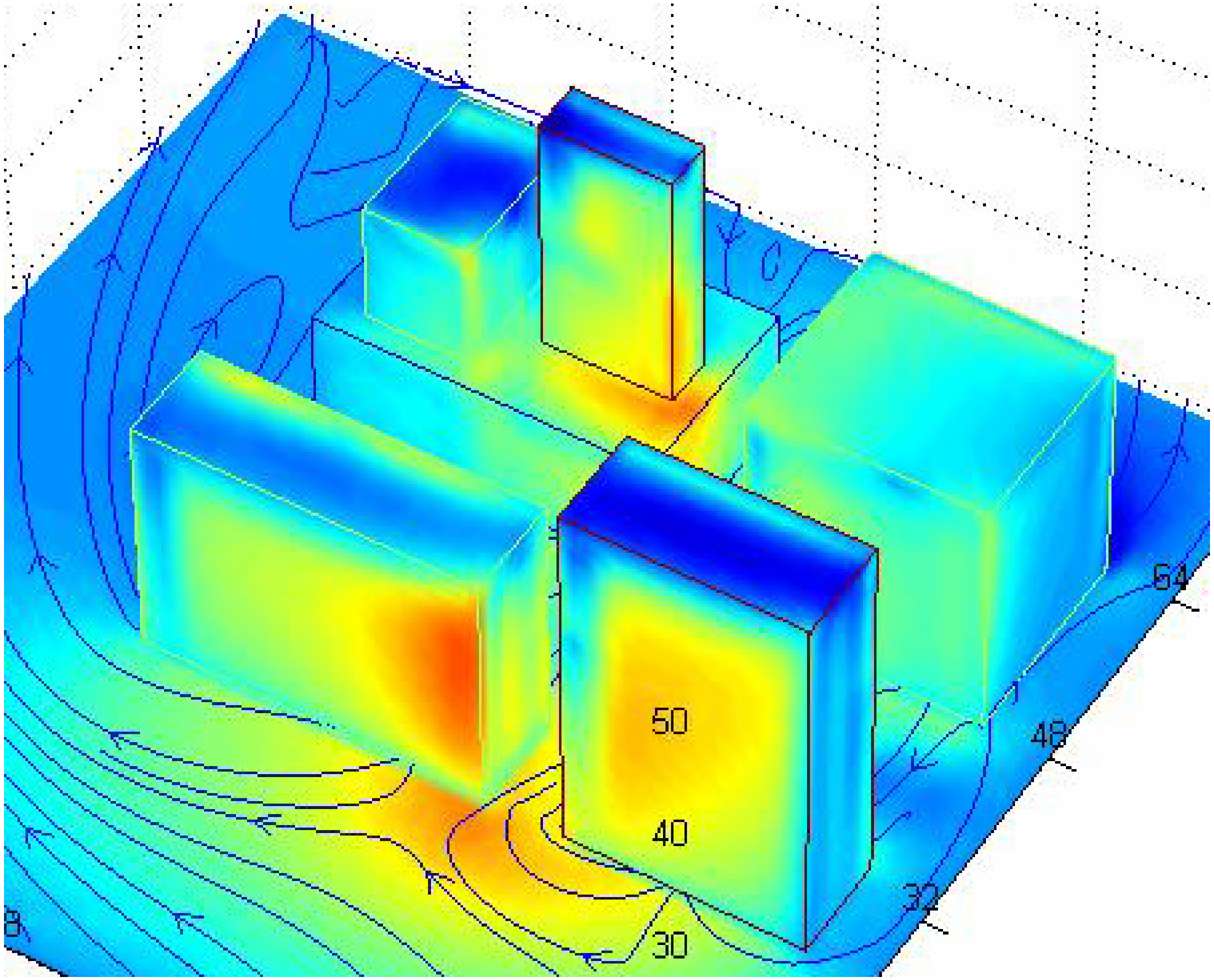
Specify pressure boundary conditions at inlets and outlets for control volume codes.

e.g., COMIS



Dense Urban Areas – Sheltering Effect

In city centers, buildings will have much lower natural ventilation rates due to obstruction of wind by surrounding buildings.



Dense Urban Areas – Sheltering Effect

In city centers, buildings will have much lower natural ventilation rates due to obstruction of wind by surrounding buildings.

Bauman et al (1988)

"Studies show wind pressure reductions of up to 90% resulting from wind blockage by upwind buildings. However, there is a variability of 80% depending on the configuration of the buildings."

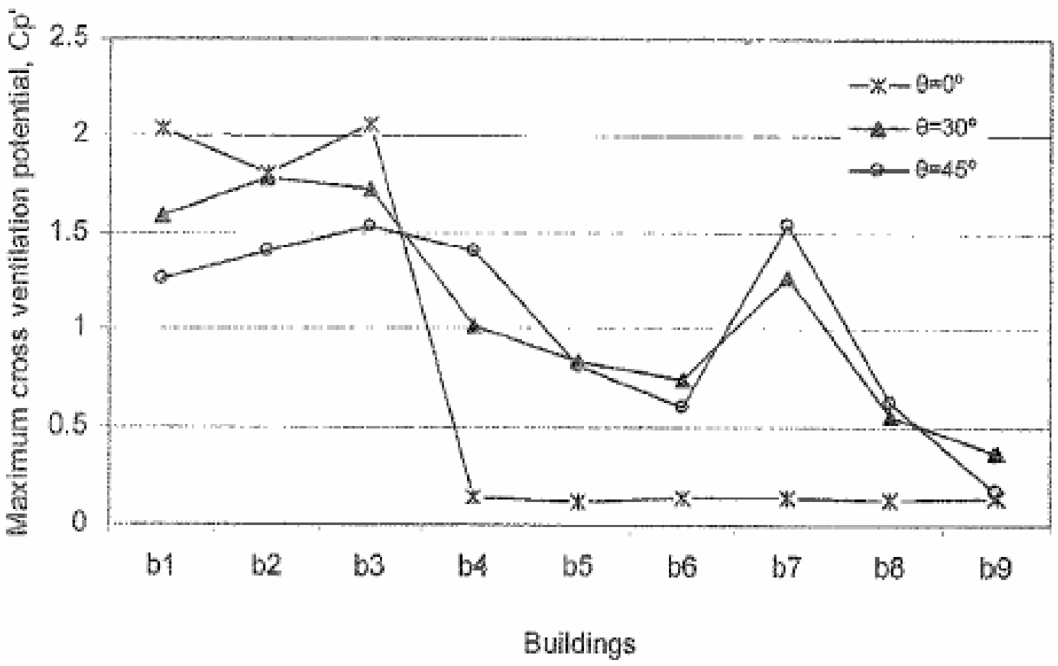


Figure 7. Cp' as a function of wind directions for the buildings in estate 1.

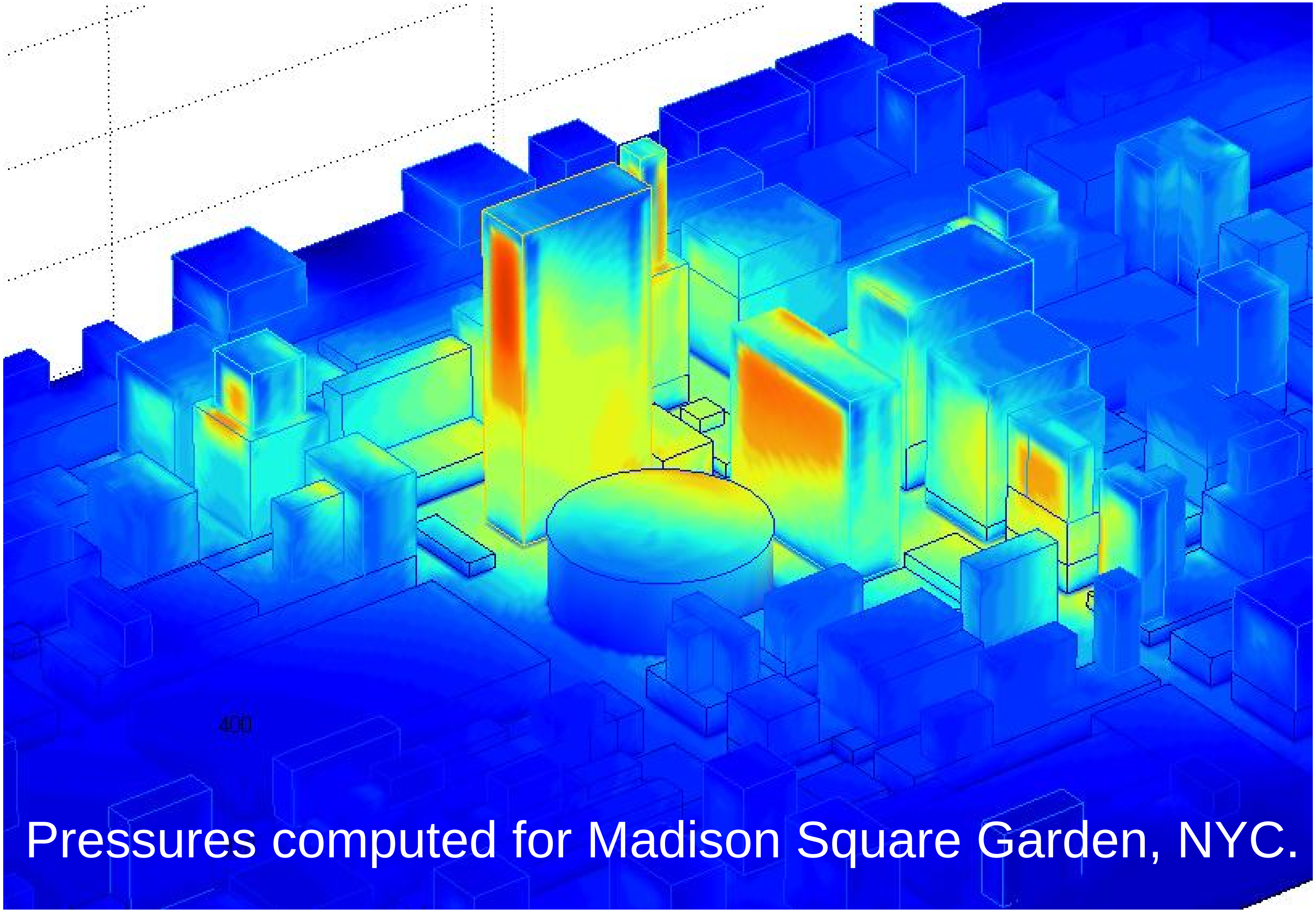
CFD simulations of Yang et al. (2005)

Dense Urban Areas – Sheltering Effect

Indoor models often have sheltering correction factors, e.g.,

UDM reduces the ΔP by a fixed amount if the building plan area density is above a specific threshold.

Dense Urban Areas – Sheltering Effect



Summary

- Wind-induced pressure information on buildings can be used to improve indoor dosage calculations (for outdoor and indoor releases)
- The QUIC wind and pressure solvers are relatively computationally inexpensive and would fit into a fast-response T&D modeling system
- Preliminary evaluation studies indicate that the QUIC wind and pressure solvers generally provide reasonable agreement with experimental studies

Technical Challenges

- Rooftop pressures on flat roofs difficult to match
- How about pitched roofs?
- Lack of experimental data in complex building environments
- Is turbulence important?

LA-UR-05-8025

Acknowledgements

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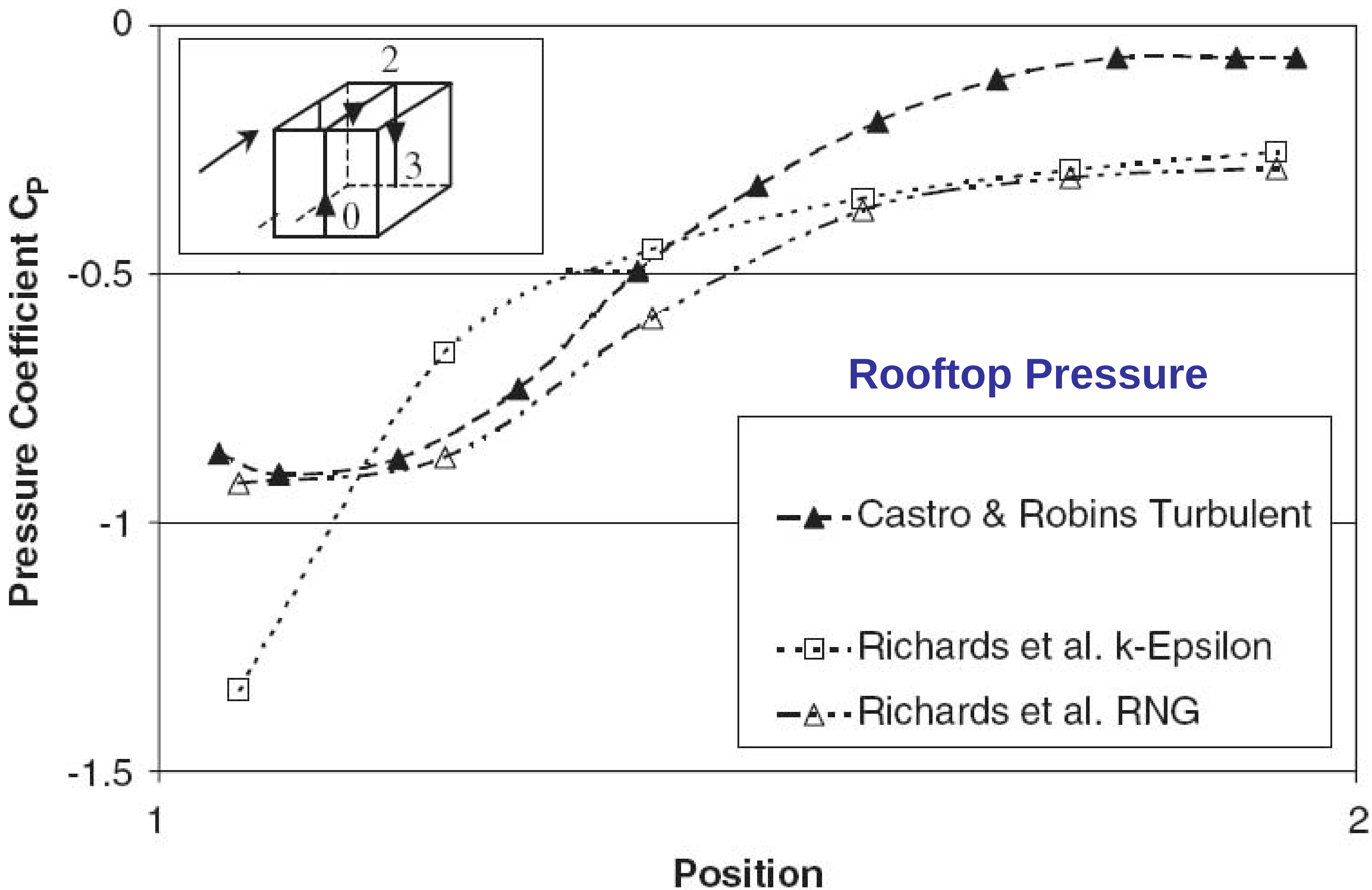
Special thanks to John Pace, John Hannan, and Rick Fry for the opportunity to perform this work.

CFD vs. Experimental Data



Adapted from Richards & Hoxey (2006)