Large-Scale Urban Aerodynamics Using Monotone Integrated Large-Eddy Simulations

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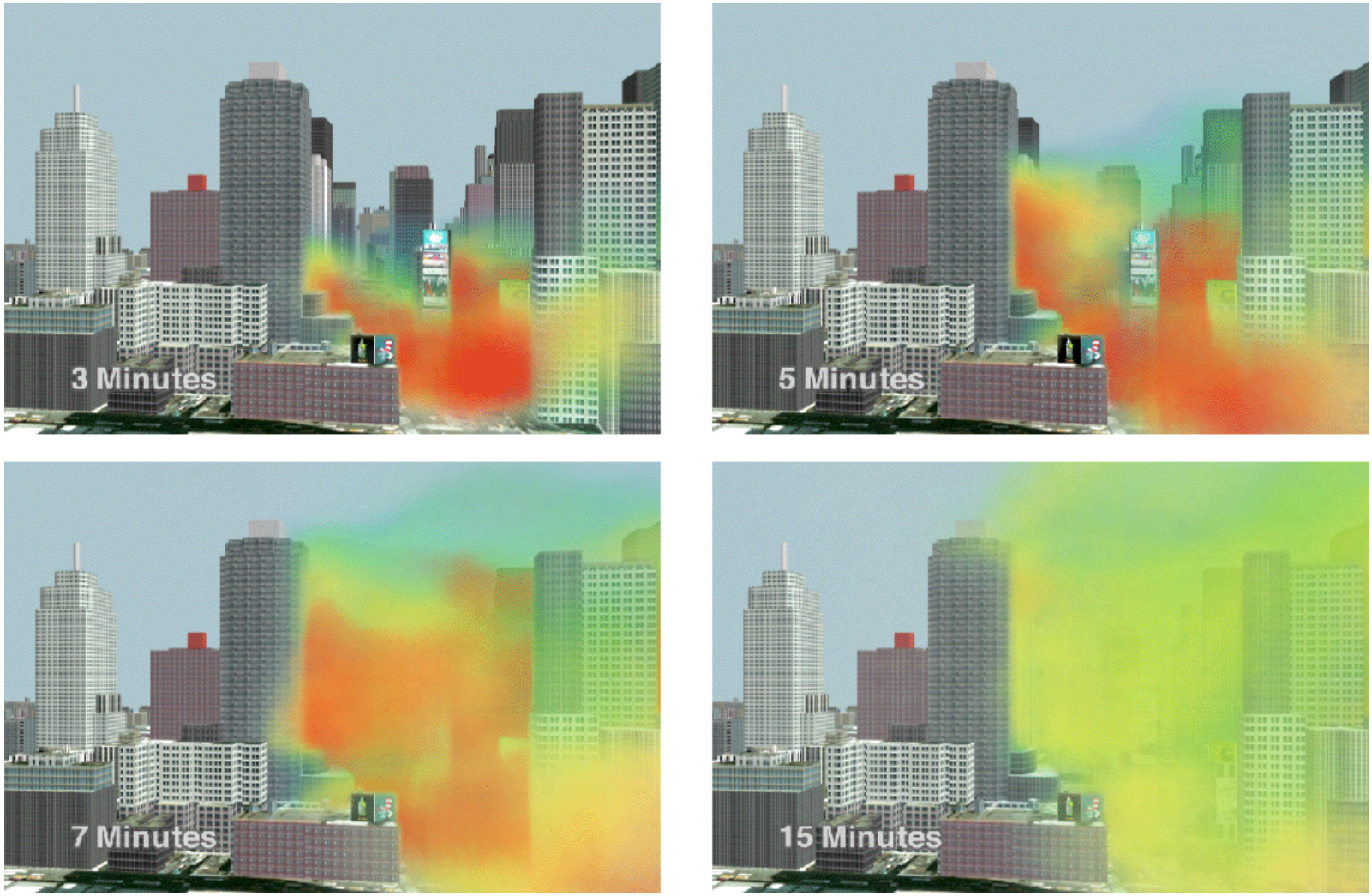
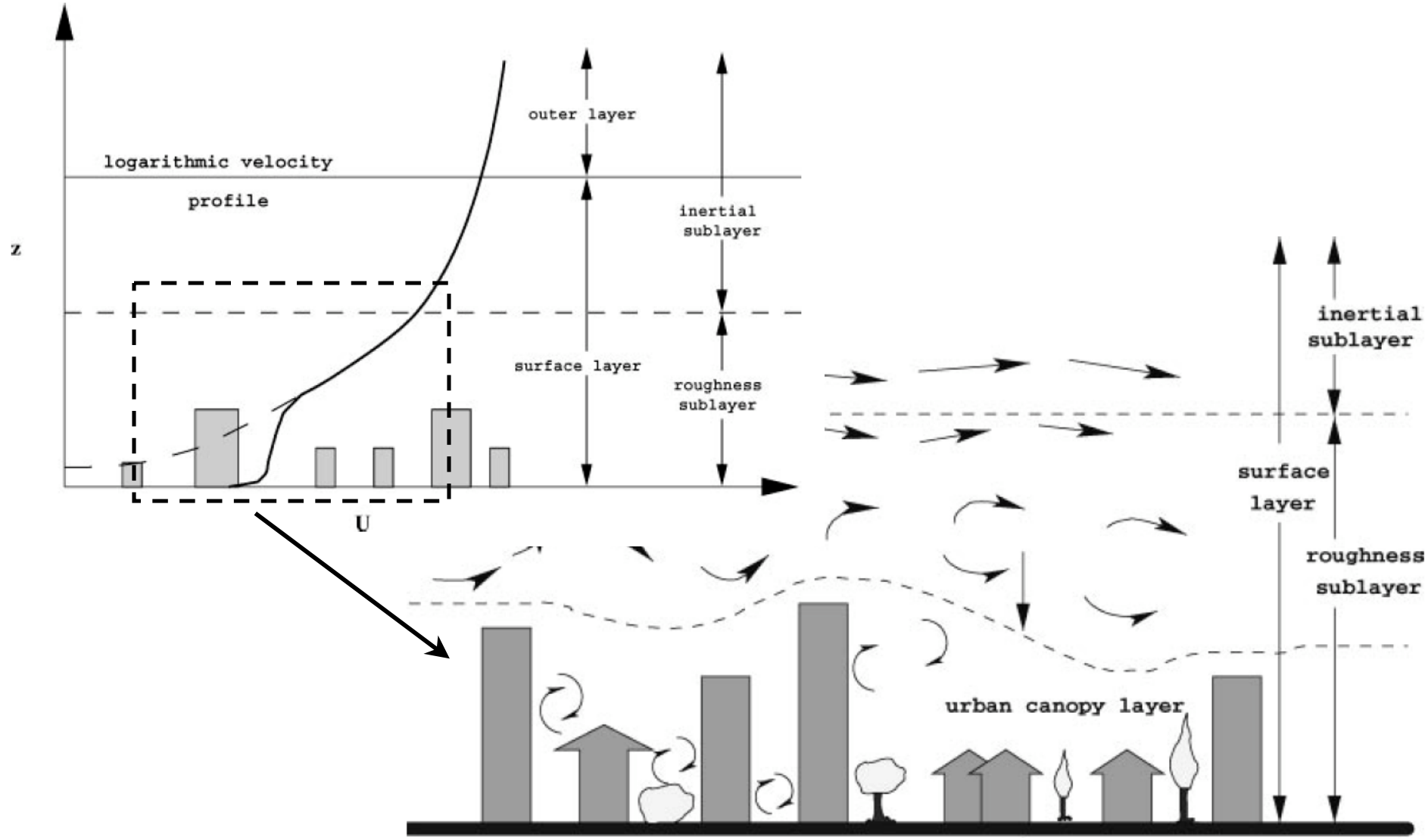
FAST3D-CT: NRL Times Square Simulation



Visualizations of a FAST3D-CT CFD simulation of an instantaneous release of a neutrally buoyant tracer gas at ground level in Times Square, New York City. The frames show relative tracer concentrations at 3, 5, 7, and 15 minutes after release. (Graphics: Robert Doyle)

How Does Urban Geometry Affect Contaminant Transport?



CFD Modeling

- Urban aerodynamics encompasses very complex geometries with unsteady buoyant flow physics, and vortex shedding.
- Simulations of dispersion of airborne pollutants in urban scale scenarios must predict both the detailed airflow conditions as well as the associated behavior of the gaseous and multiphase pollutants.
- Crucial technical issues include transport model specifics, boundary condition modeling, uncertainty and post-processing of the simulation database so that it can be used in *response to real-time emergencies*.

Development of Flux-Corrected Transport

1971. Basic nonlinear monotone algorithm (Boris)

1973. FCT for general finite difference algorithms (Boris & Book)

1976. Optimization for vector & parallel processing (Boris & Winsor)

1979. Fully multidimensional FCT and generalization to use with arbitrary high- and low-order algorithms (Zalesak)

1985. Finite-Element FCT on unstructured grids (Lohner & Baum)

1986. Barely Implicit Flux-Corrected Transport (Patnaik)

1989. Massively Parallel Implementations of complex physics with geometry and FCT (Boris, Young, Whaley, Oran, Fyfe)

1992. Complex geometry VCE algorithms (Boris, Landsberg, Young)

1993. Third Edition of LCPFCT Report (Boris, Landsberg, Oran, Gardner)

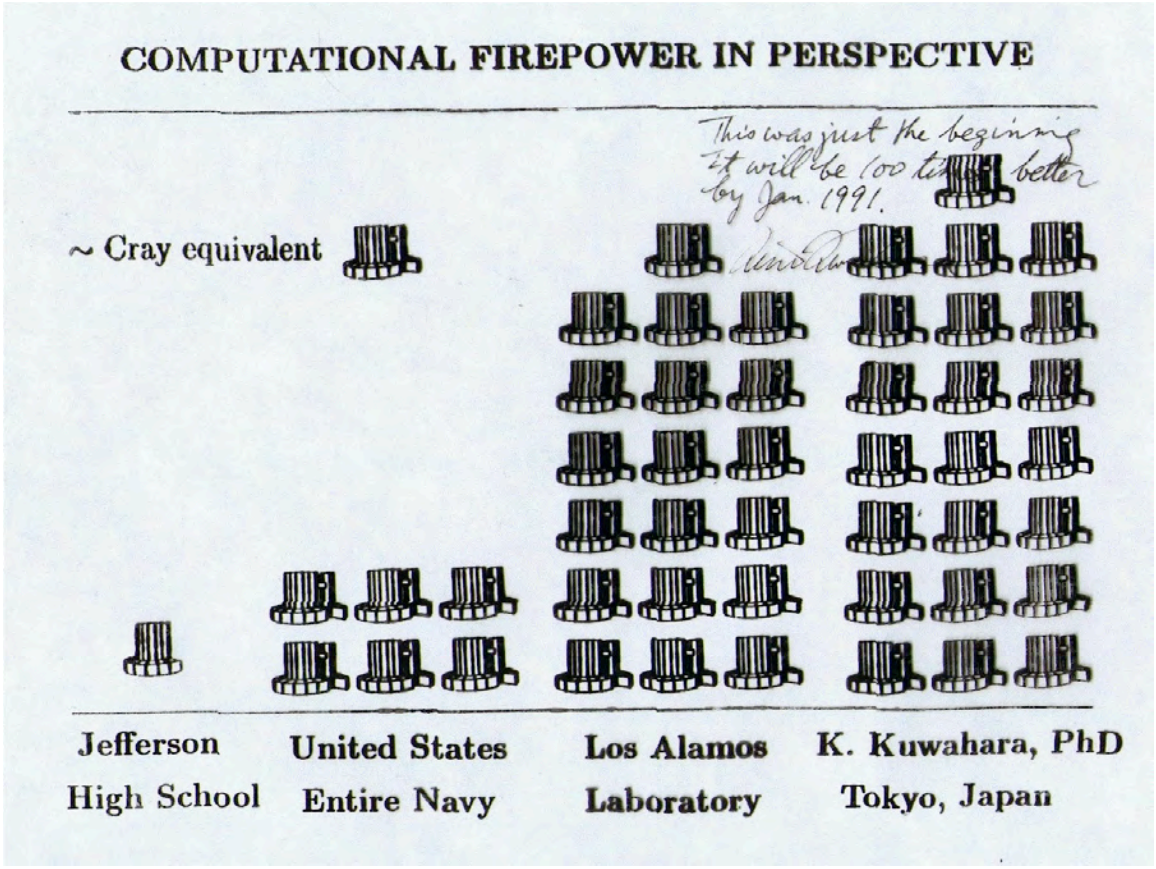
http://www.lcp.nrl.navy.mil/lcpfct/

Numerous Other Contributions at Other Laboratories

NRL

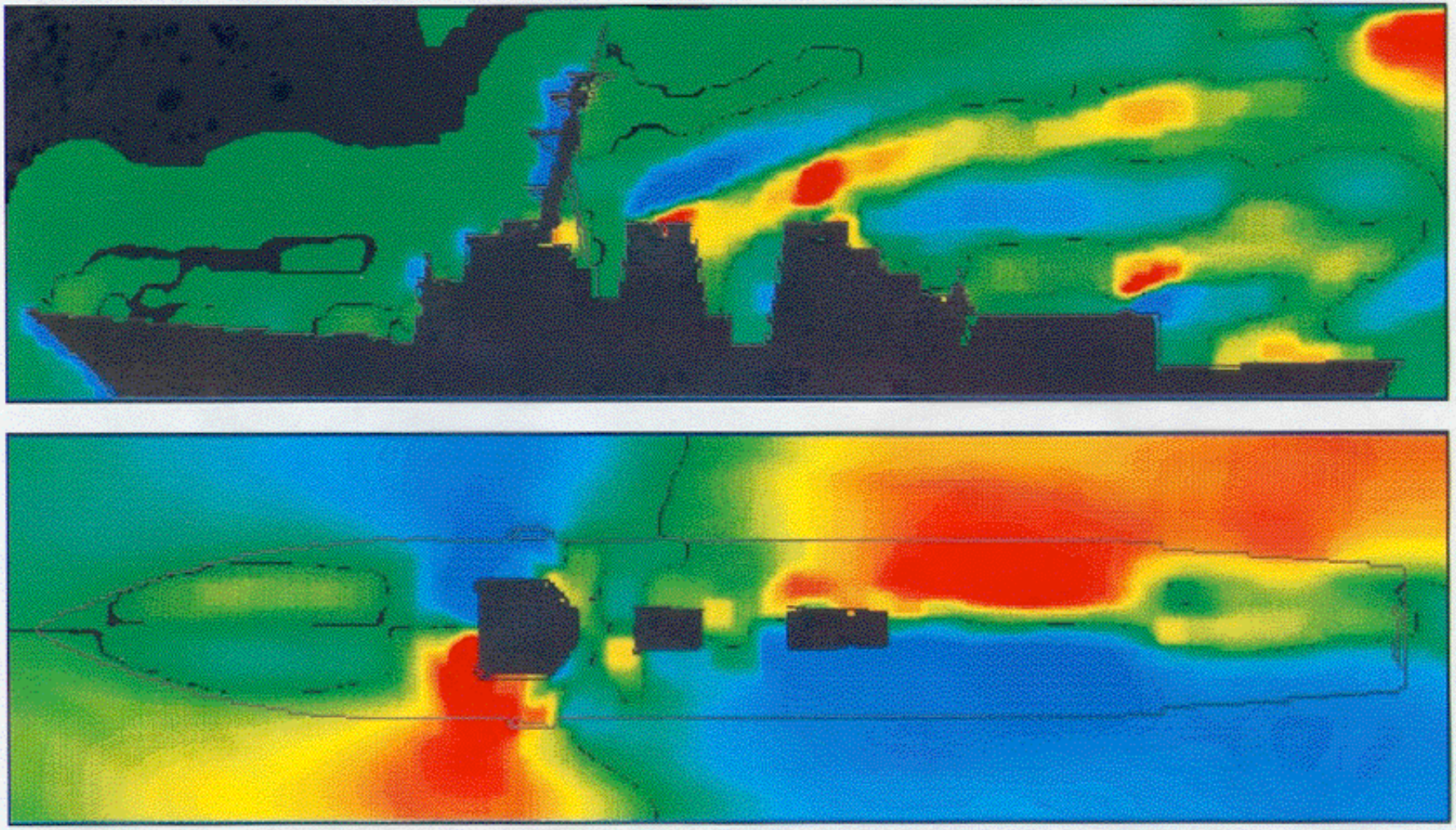
1990

1942 - 2008



Top Challenges for Urban Aerodynamics CFD

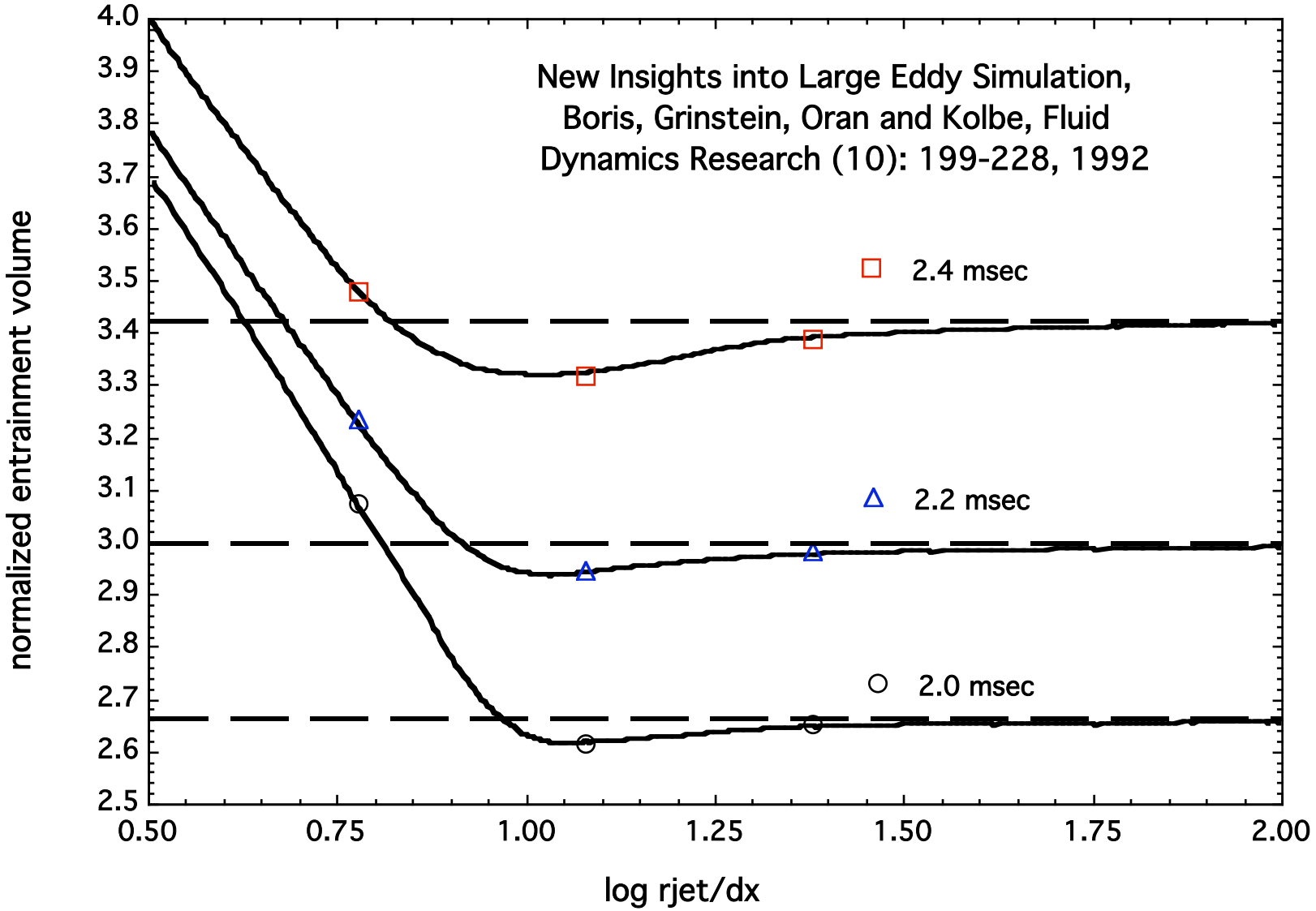
Hardware – Many processors in parallel
Validation – There is no truth (large variability)
Operations – Dilemma - speed or accuracy



Contours of transverse velocity over the DDG51 destroyer in a headwind. Red indicates positive high values of transverse velocity, blue indicates negative high values of transverse velocity. The unsteady flow solution was computed on an Intel iPSC/860 parallel computer.

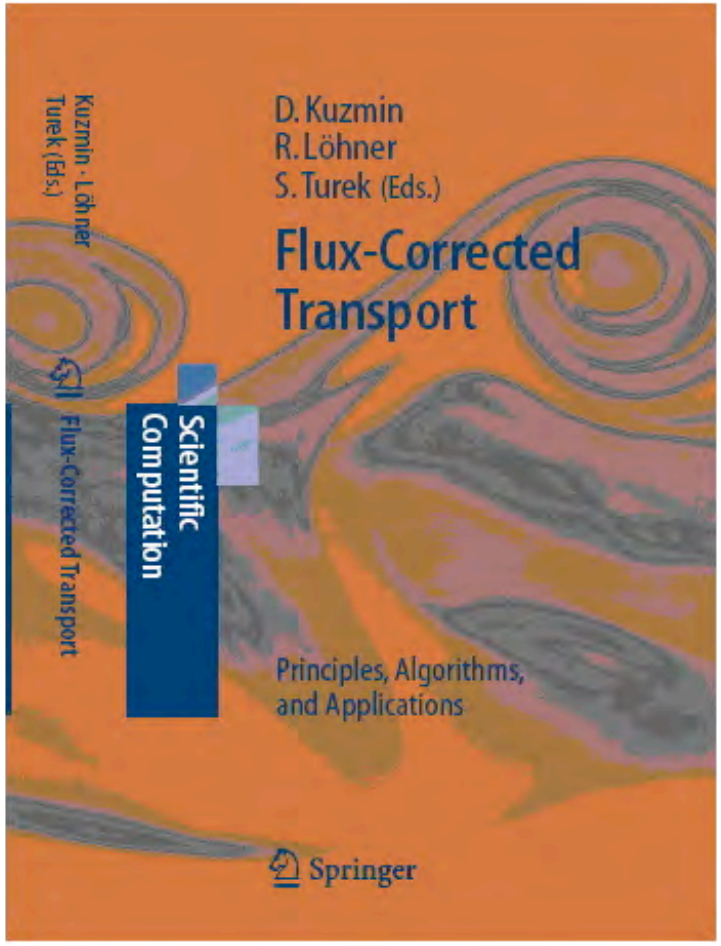
1994

Convergence of FCT MILES with Increasing Resolution

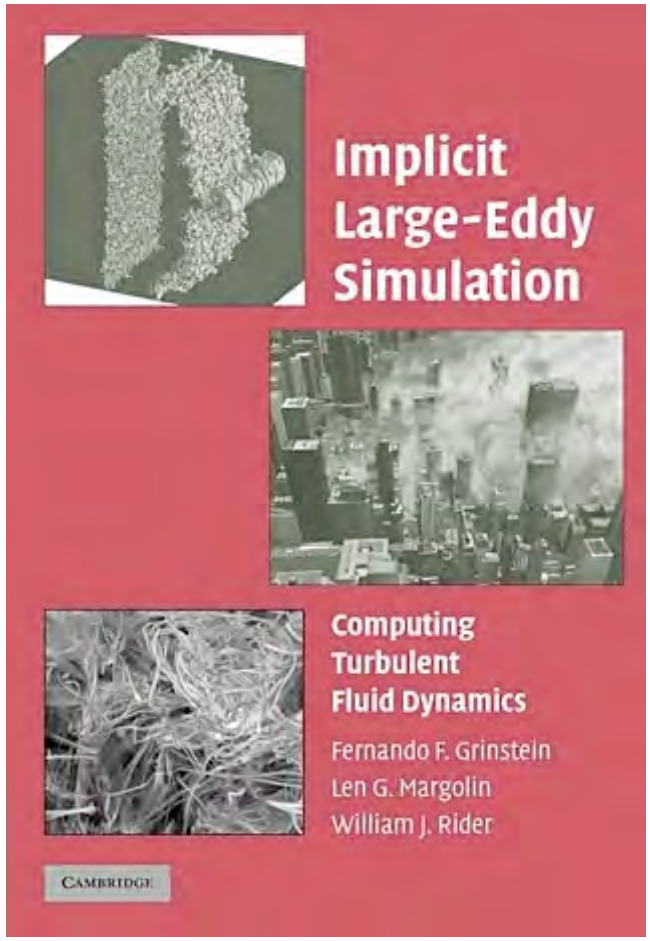


1990

NRL Techniques for Solving Urban Flows



Flux-Corrected Transport
Springer, 2005



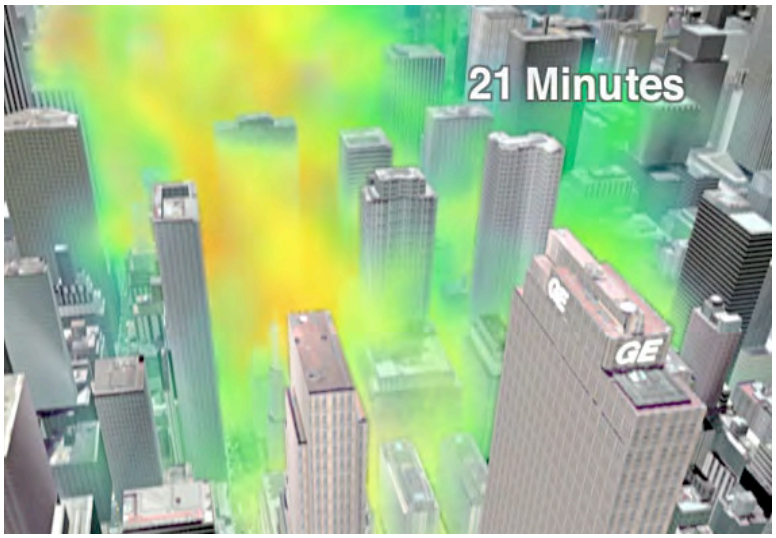
Implicit Large Eddy Simulation
Cambridge U.P., 2007

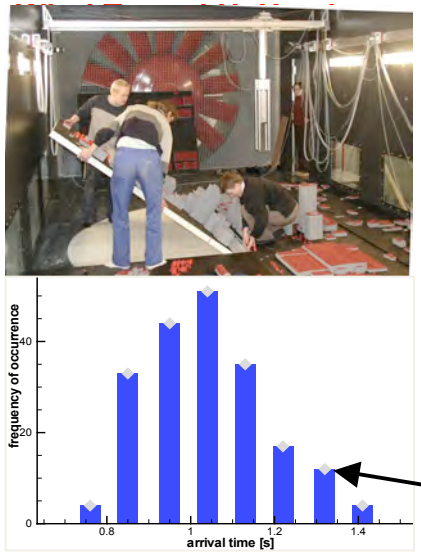
also: Numerical Simulation of Reactive Flow (2001, Oran and Boris)

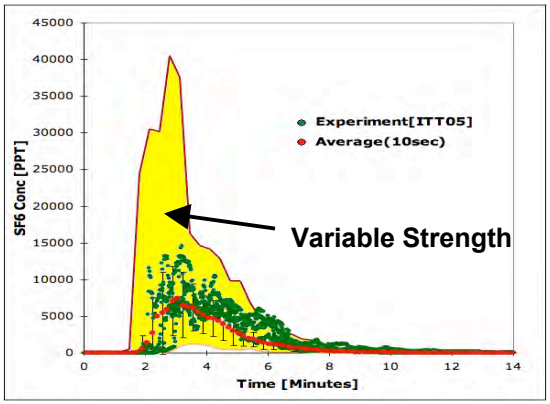
Validating Urban Aerodynamics Is Hard

- Urban transport and dispersion is more complex than incumbent models can represent and presents questions that they cannot answer because the phenomena are time dependent and dominated by building-scale vortex shedding. Large-Eddy Simulation (CFD) solves these problems.
- Operational planners and users deserve better information on uncertainty and variability than possible with steady-state and stochastic methods.
- Uncertainty and variability are unavoidable due to wind fluctuations, unknown source characteristics, geometry details, etc. Thus the impacts of variability must be quantified and prediction errors made smaller.
- High Fidelity, Time Dependent CFD and wind tunnel experiments are the only way to quantify the physical variability – field data are insufficient.
- The added cost to perform multi-realization CFD and wind tunnel studies is comparable to the cost of using slow incumbent models and small compared to comprehensive field trials.

Dynamic Variability in Urban Airflow

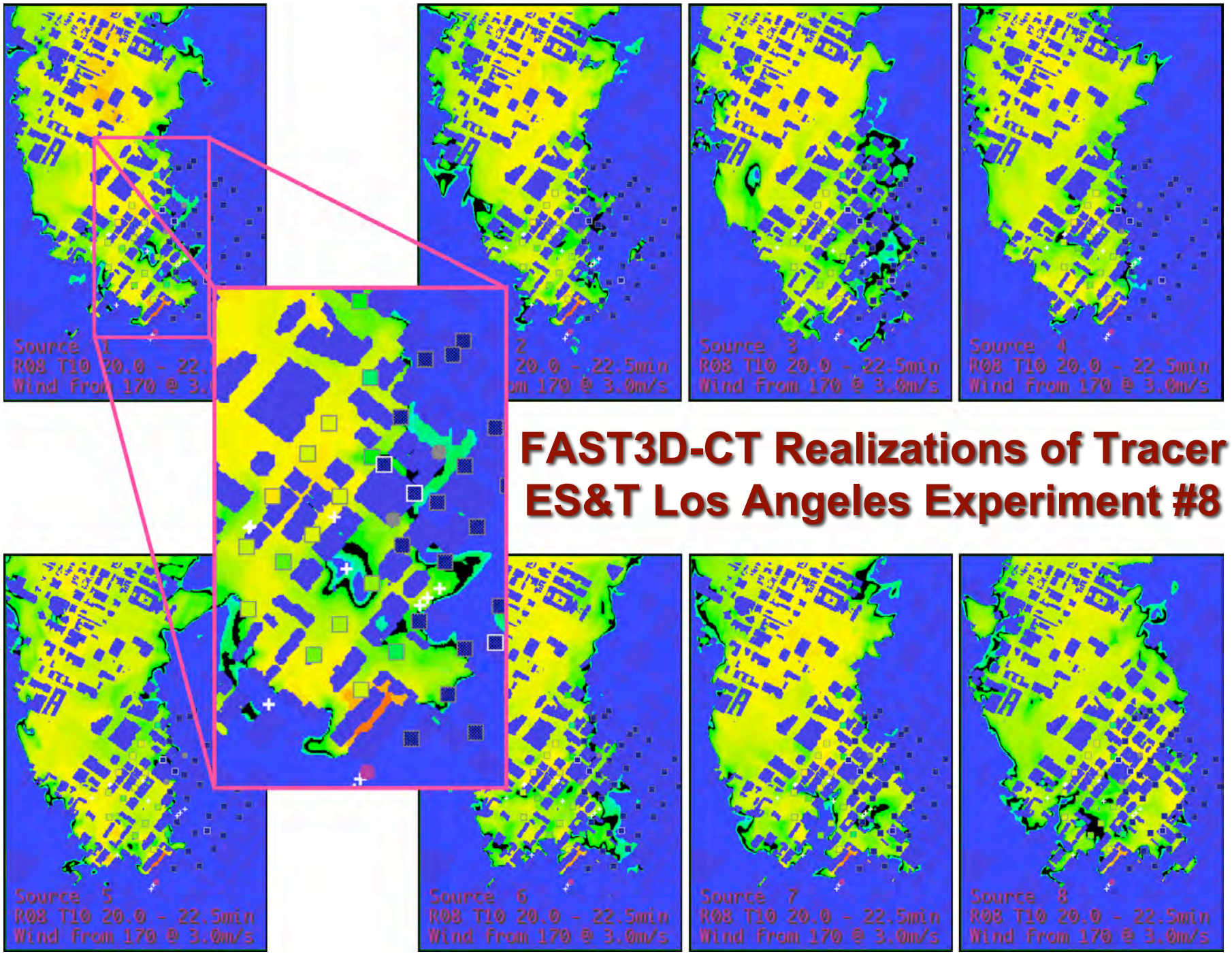






- The wind has dynamic flow structures that are also generated by building vortex shedding.
- Determine: contaminant dispersion, wind loads on structures, and response of UAVs in urban terrain.
- Experiments and numerical simulations for Oklahoma City show that the distribution of contaminant is far from Gaussian for acute releases. Pockets of high concentrations are interspersed with areas with little or no contaminant (severe intermittency).
- NRL-LCP&FD's unsteady large-eddy simulation model FAST3D-CT provides high spatial and temporal resolution to study this variability from first principles.

Research Need: Use numerical simulations and wind-tunnel experiments to characterize concentration variability and intermittency as they affect WMD contaminant transport and UAV design and operations in urban environments.



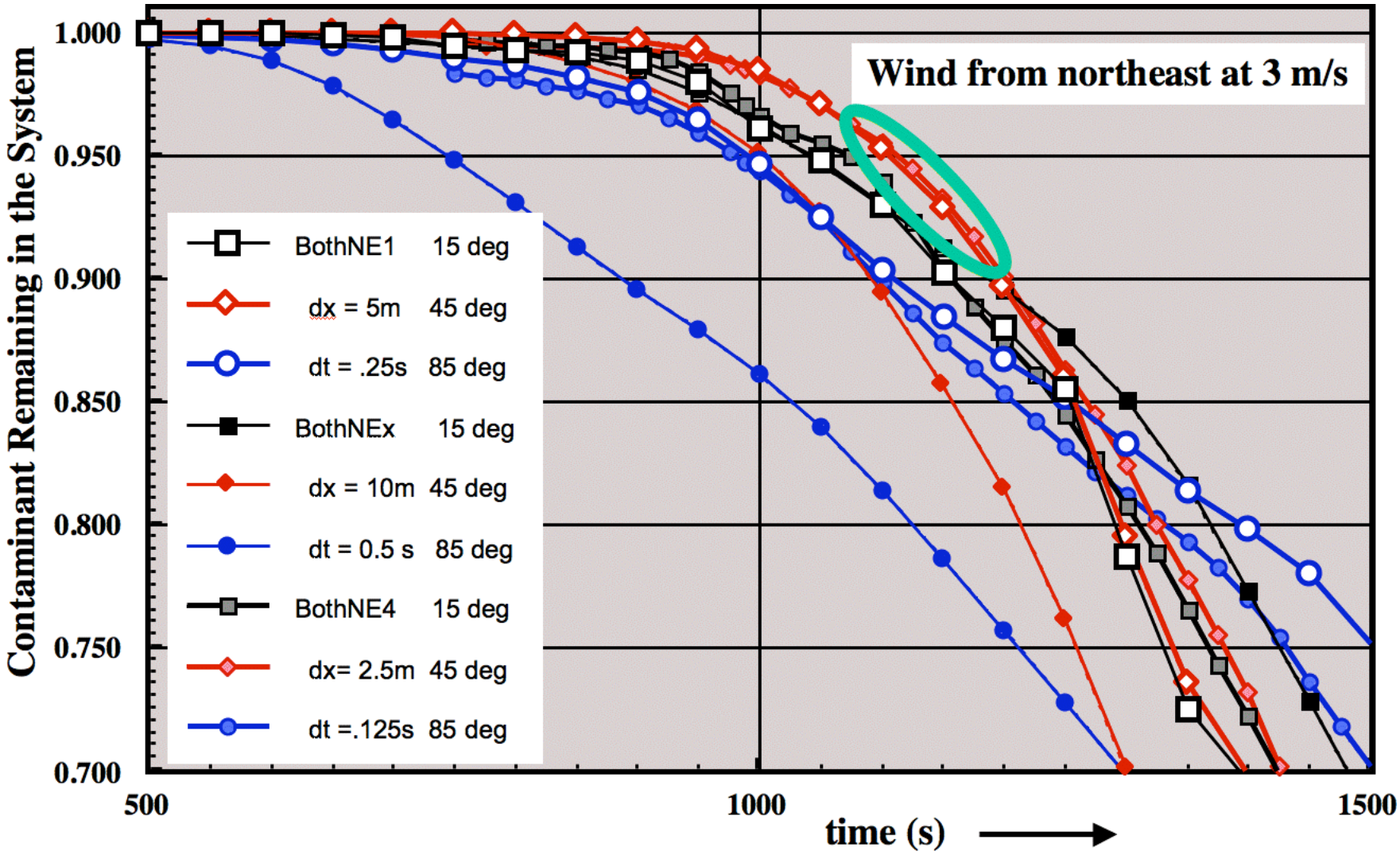
FAST3D-CT Realizations of Tracer ES&T Los Angeles Experiment #8

Showing Grid Convergence Is Very Difficult

- Two different-resolution LES (MILES) solutions will begin to deviate exponentially even when initialized identically because more short wavelength structure is allowed at higher resolution.
- Because there is “no true solution,” three different resolutions must be computed, not two.
- To Double the Resolution: 16 times as much computing is needed to reach the same physical run time in 3D.
- Most important phenomena are time dependent but non-periodic. Therefore convergence might be measured statistically on macroscopic quantities to hopefully average over fluctuations.
- To Double the Resolution and Demonstrate 2^{nd}-Order Convergence requires 16 times as long in physical running time so the accuracy of the statistical measures will be a factor of four higher. FACTOR = 256.

NRL

Grid Convergence for Washington DC: 2000



Grid Convergence for Washington DC: 2008

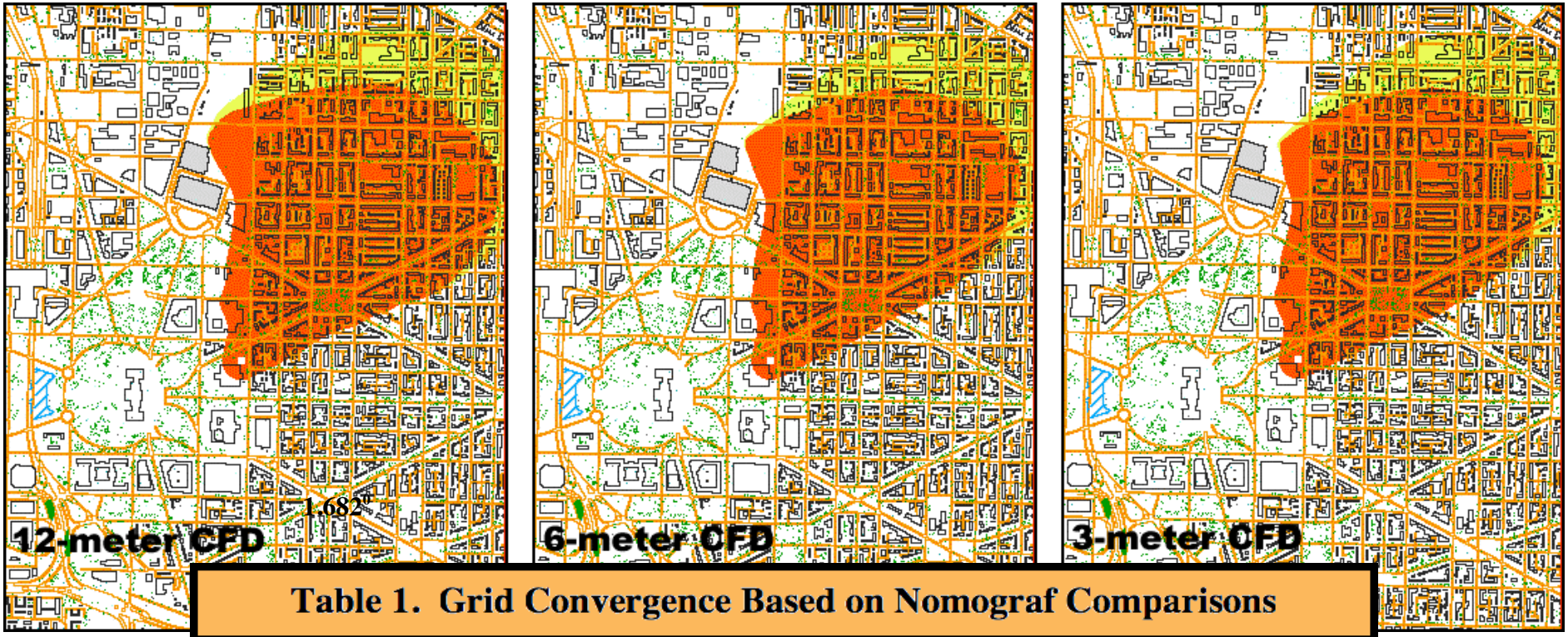


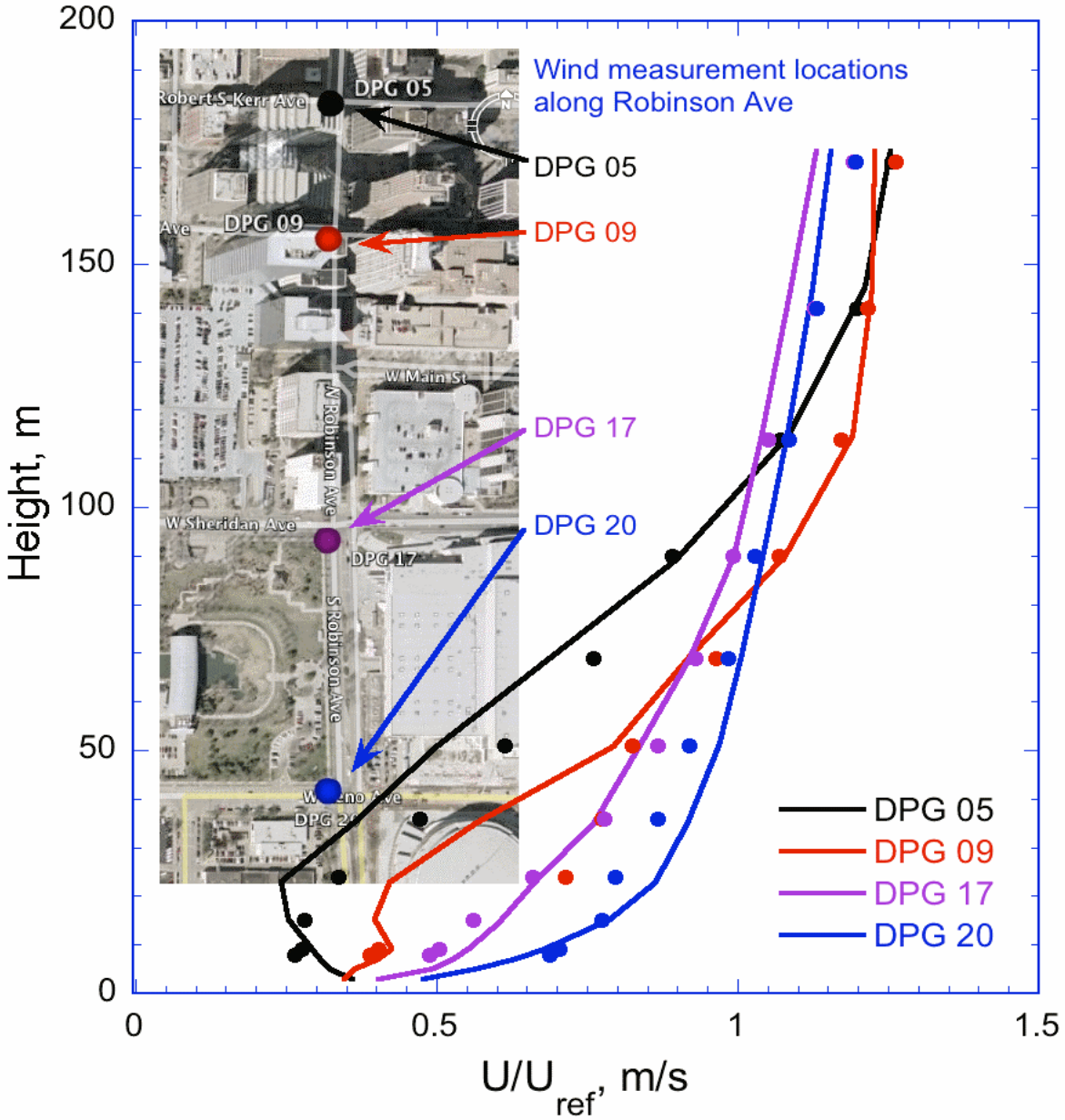
Table 1. Grid Convergence Based on Nomograf Comparisons

	6-m resolution compared to 3-m		12-m resolution compared to 6-m		Error Ratio 12m-6m/6m-3m	
wind	Δθ(⁰)	Δ%	Δθ(⁰)	Δ%	θ Ratio	% Ratio
0⁰	1.682⁰	1.820%	5.080	4.064%	3.02	2.23
60⁰	1.715⁰	1.386%	5.020⁰	4.075%	2.93	2.94
120⁰	1.675⁰	1.005%	4.857⁰	3.055%	2.90	3.04
180⁰	1.609⁰	2.061%	5.152⁰	3.449%	3.20	1.67
240⁰	1.673⁰	1.104%	5.167⁰	3.685%	3.09	3.34
300⁰	1.694⁰	1.158%	5.128⁰	3.083%	3.03	2.66
average	1.688⁰	1.470%	5.032⁰	3.326%	2.98	2.26

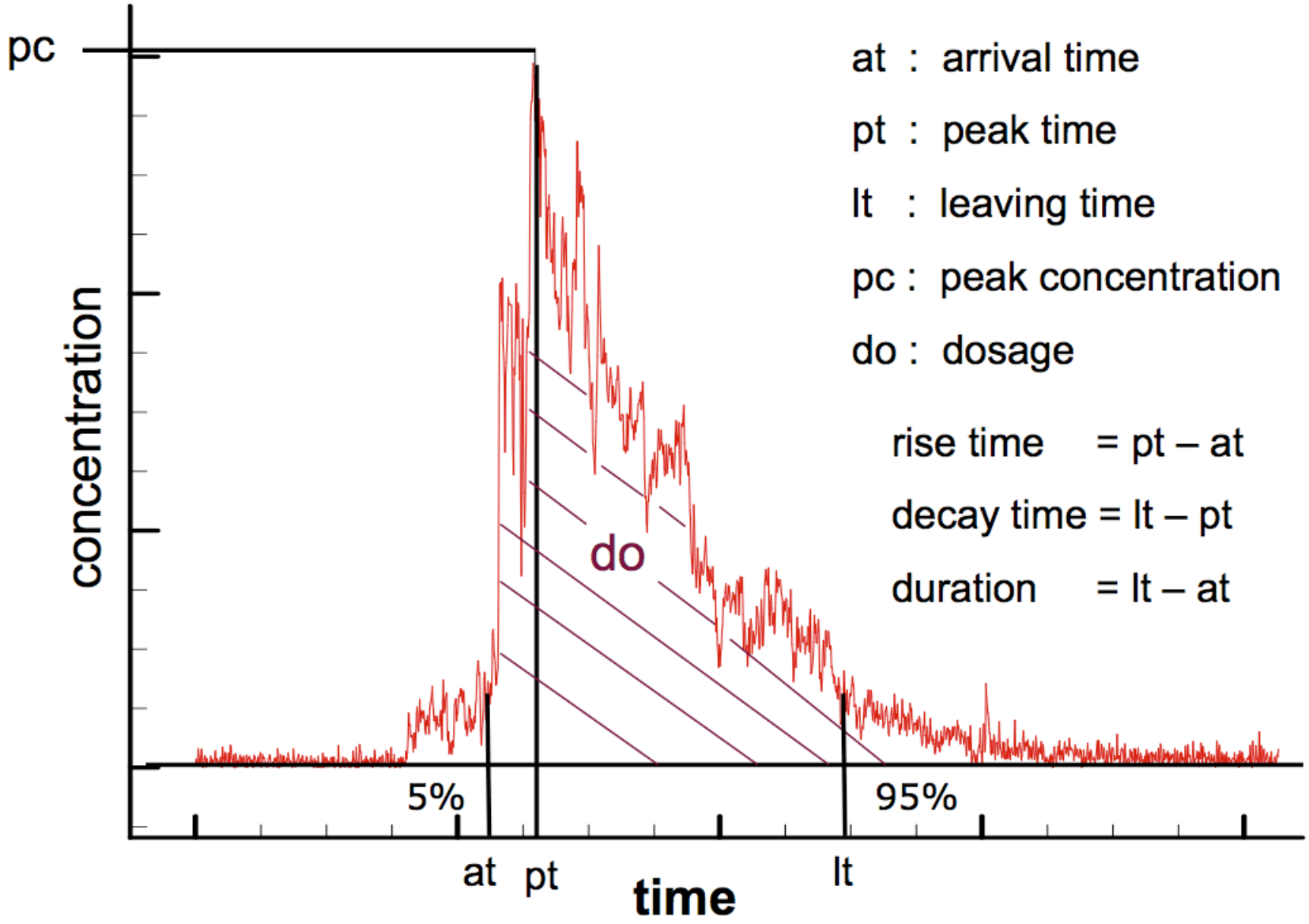
Not Enough Field Trial Data

- Field trials first considered plumes from long duration pollution sources. The models, metrics, and measurements have focused on long time averages at locations far downwind.
- Since variability is unavoidable, and most important phenomena are time dependent, the dynamic flow structures must be to captured. Long time average data and widely separated measurement locations do not do this.
- Field trial data are also generally insufficient to quantify variability because only one realization, or at most a very few, can be measured before the background conditions change.
- Field trials are important primarily because they are real. They are the most important way to avoid technological surprise.

Validating the Mean Flow Is Not Enough



Definition of Puff Parameters



at : arrival time

pt : peak time

lt : leaving time

pc : peak concentration

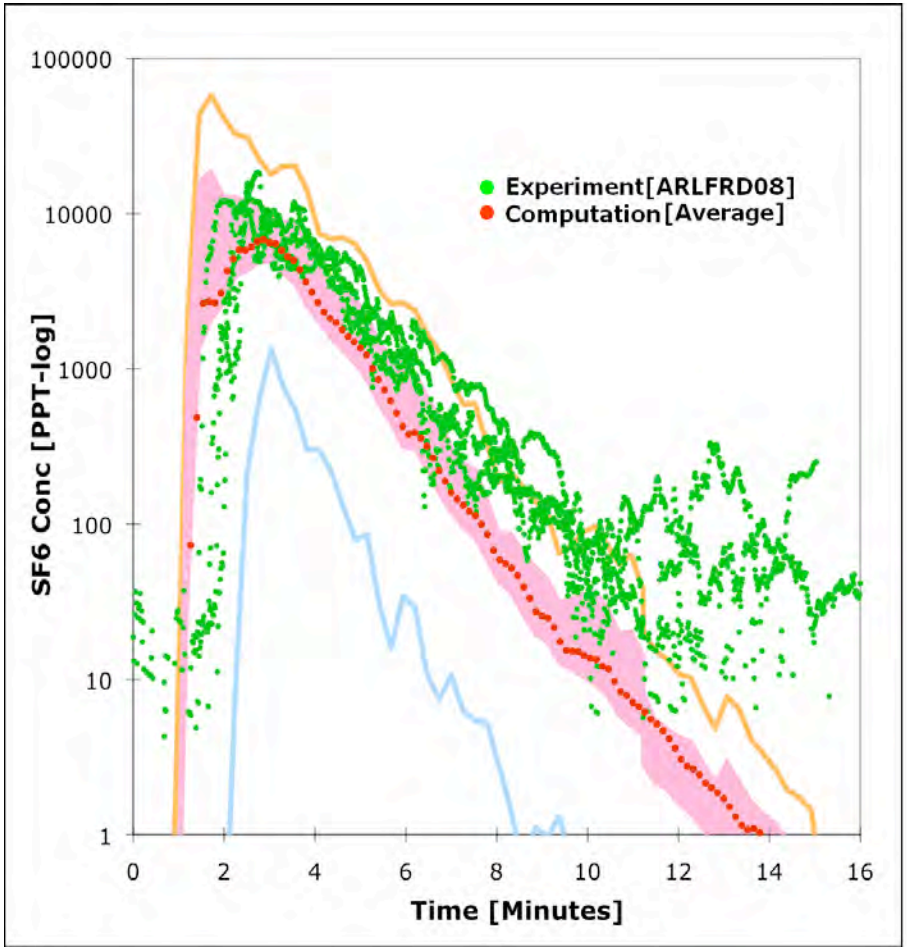
do : dosage

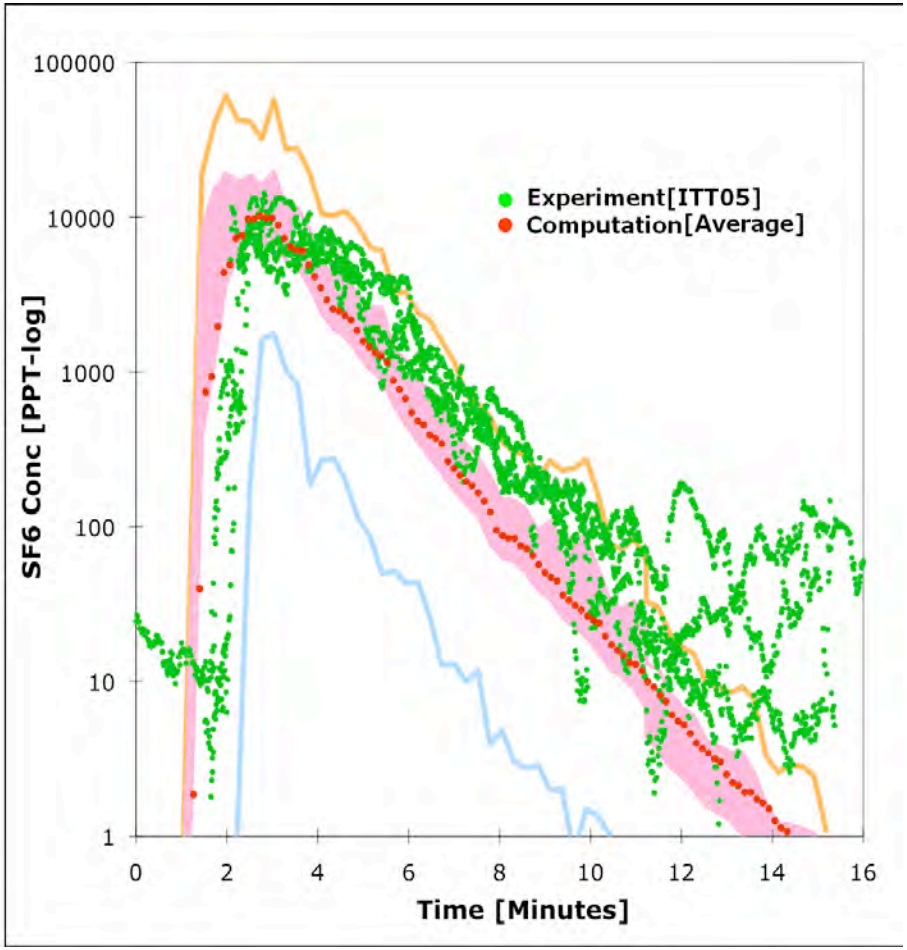
rise time = pt – at

decay time = lt – pt

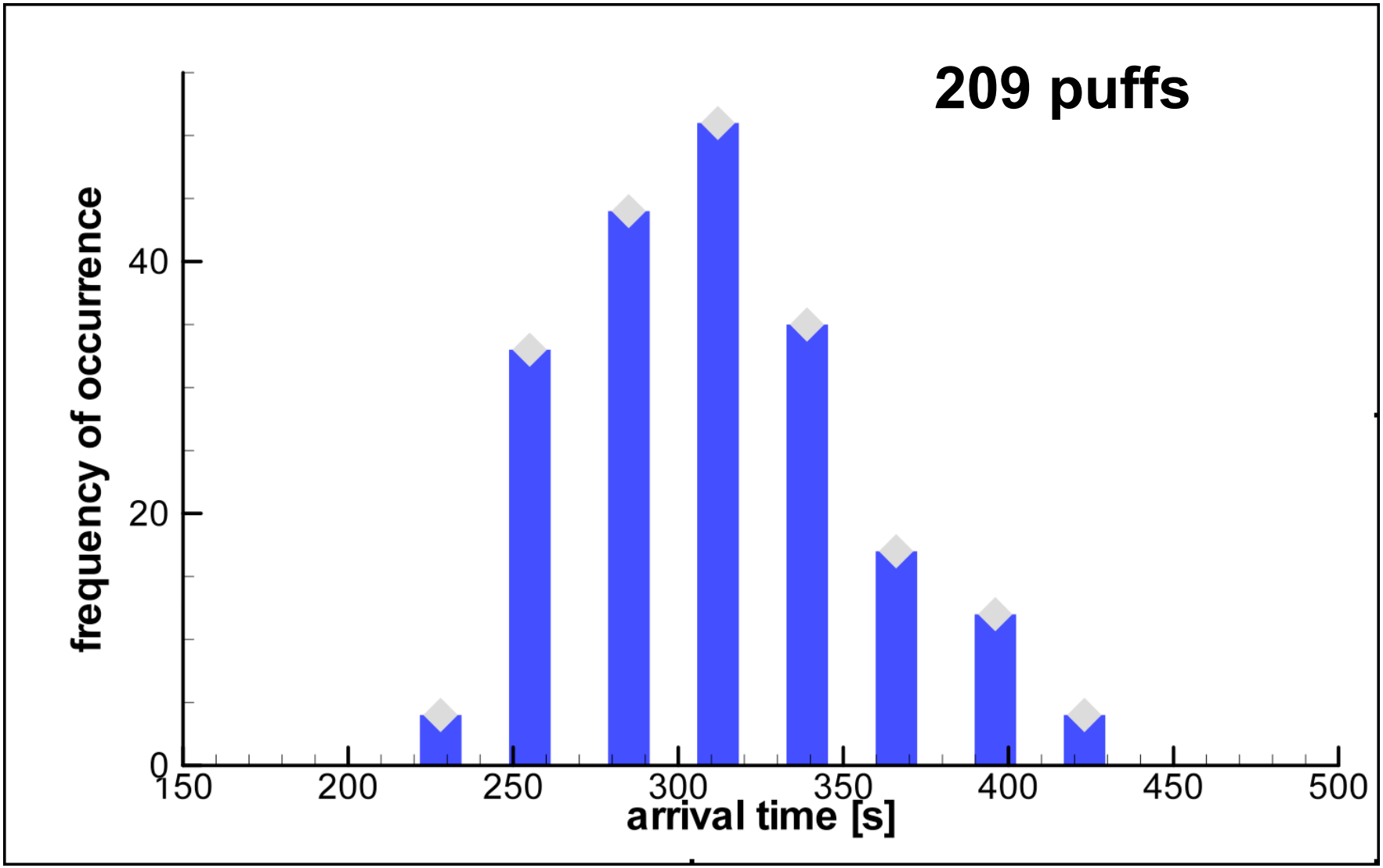
duration = lt – at

Oklahoma City
Multi-Puff Data Comparison





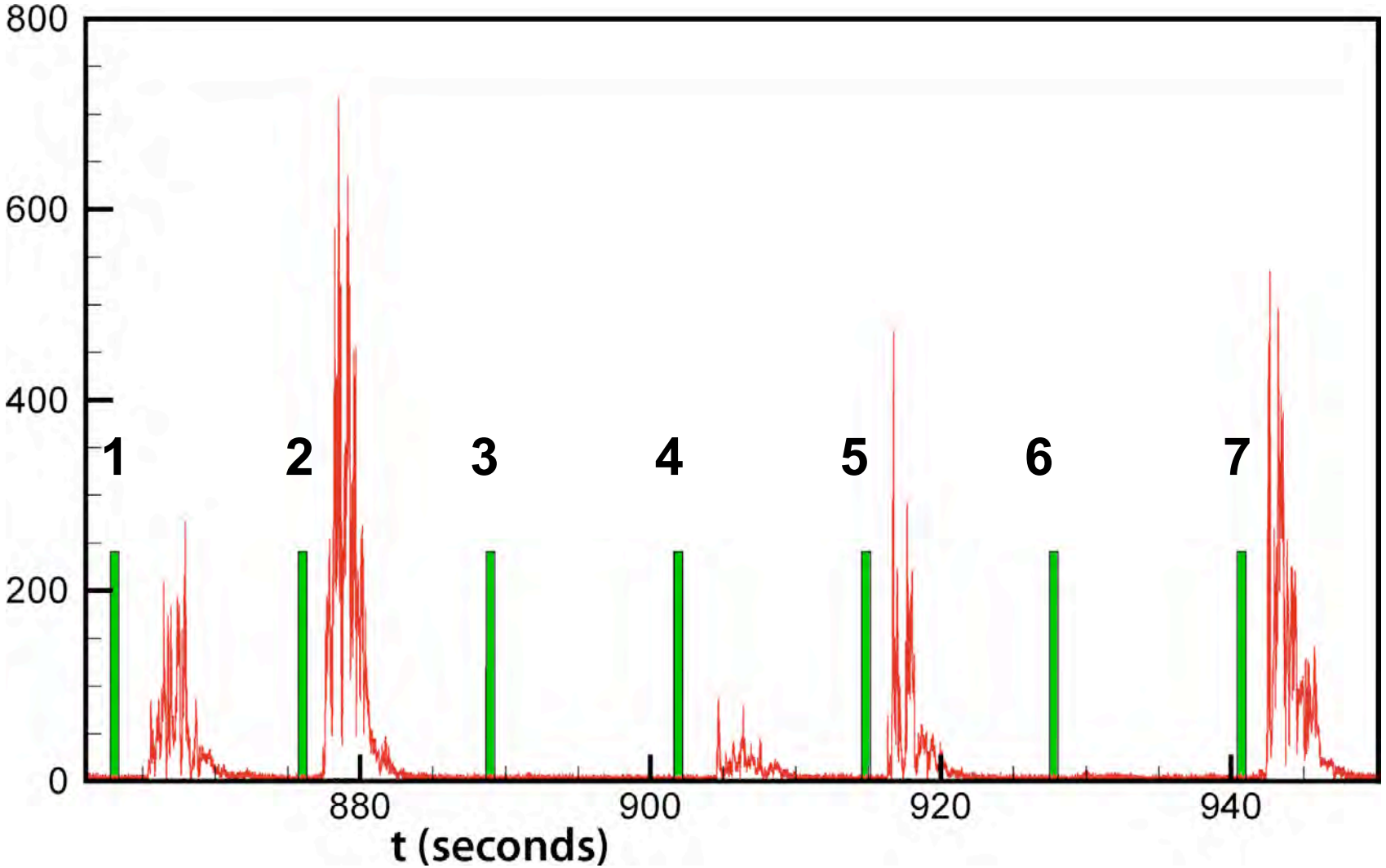
Wind Tunnels Measure Variability

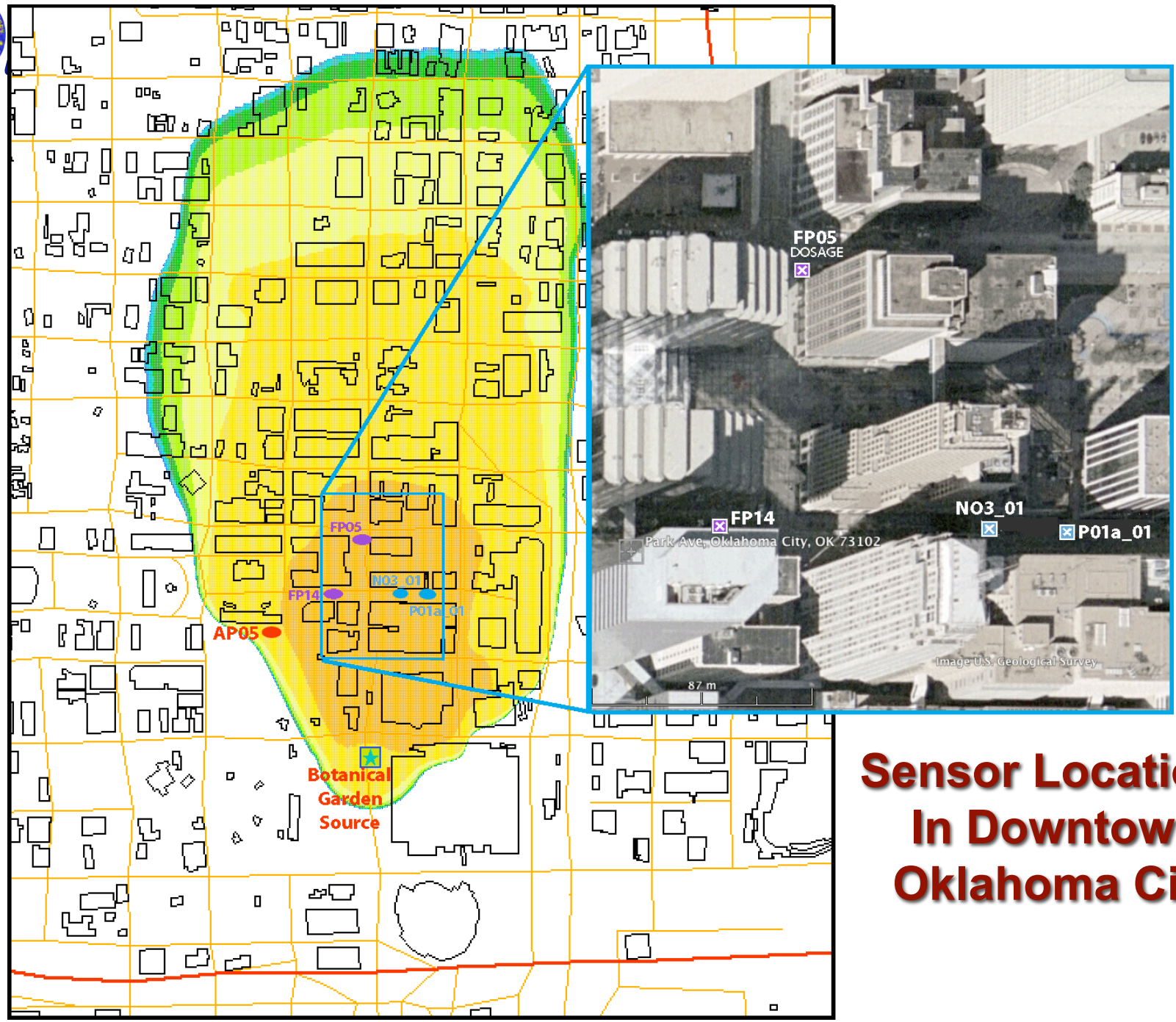


Validating with Wind Tunnels is Just Right

- High Fidelity, Time Dependent CFD and wind tunnel experiments are the only way to quantify the variability – field data are insufficient.
- Hundreds of independent realizations are needed to quantify most distribution functions and expensive to provide through CFD. Experiments are repeatable in a wind tunnel.
- The wind tunnel flow Reynolds Numbers are large enough that other source of error, such as simplified geometries and lack of traffic are as important.
- Wind tunnels have trouble scaling atmospheric buoyancy and therefore stability effects. Neutral buoyancy is usually assumed.
- The added cost to obtain multi-realization wind tunnel and CFD data sets is small compared to comprehensive field trials and comparable to the cost of using finite element, steady flow models.

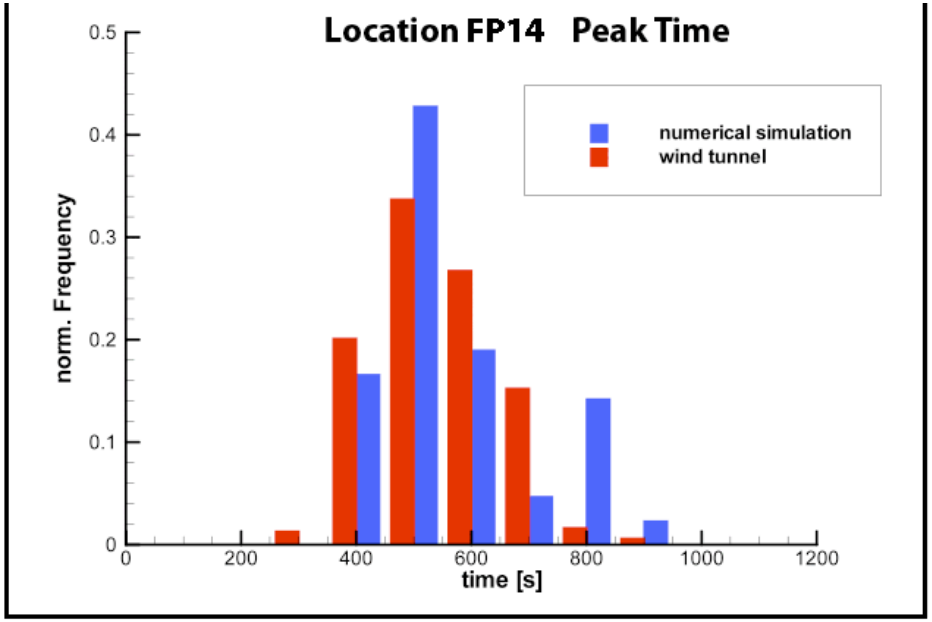
Concentration Variability Is Very Big

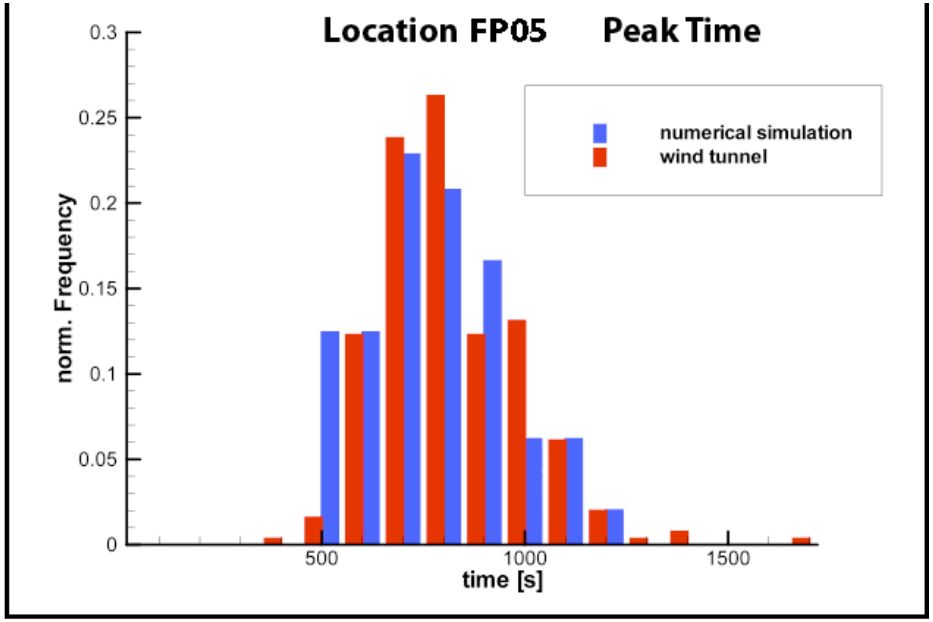




Sensor Locations In Downtown Oklahoma City

Distributions of 'Peak Time from the Wind Tunnel and from Numerical Simulations

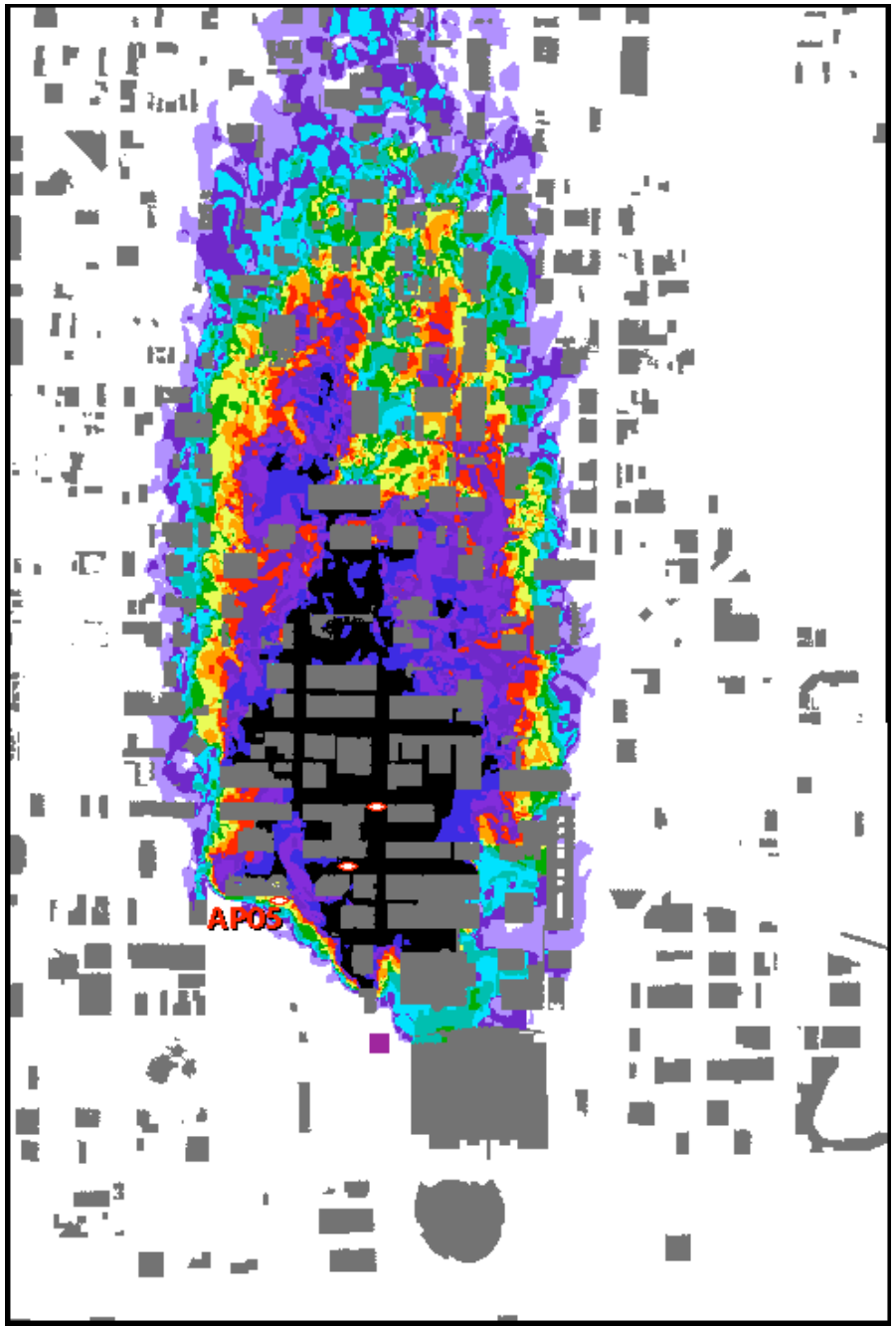


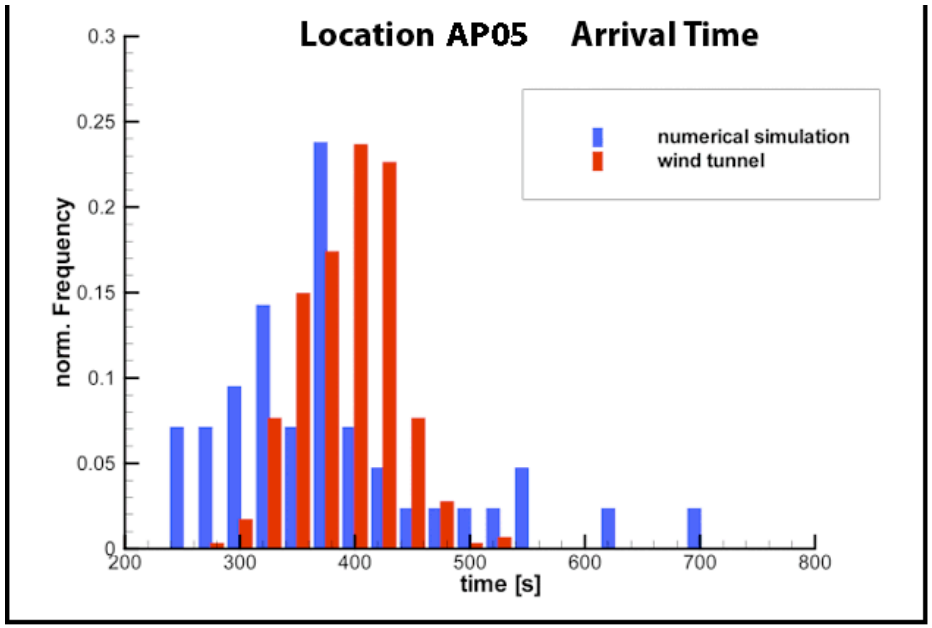


mean numerical peak time:	491 seconds
mean wind tunnel peak time:	514 seconds
difference:	4.2 %

mean numerical peak time:	727 seconds
mean wind tunnel peak time:	772 seconds
difference:	6.2 %

Contamination Probability Computed for a Tracer Released at the Botanical Garden in Oklahoma City

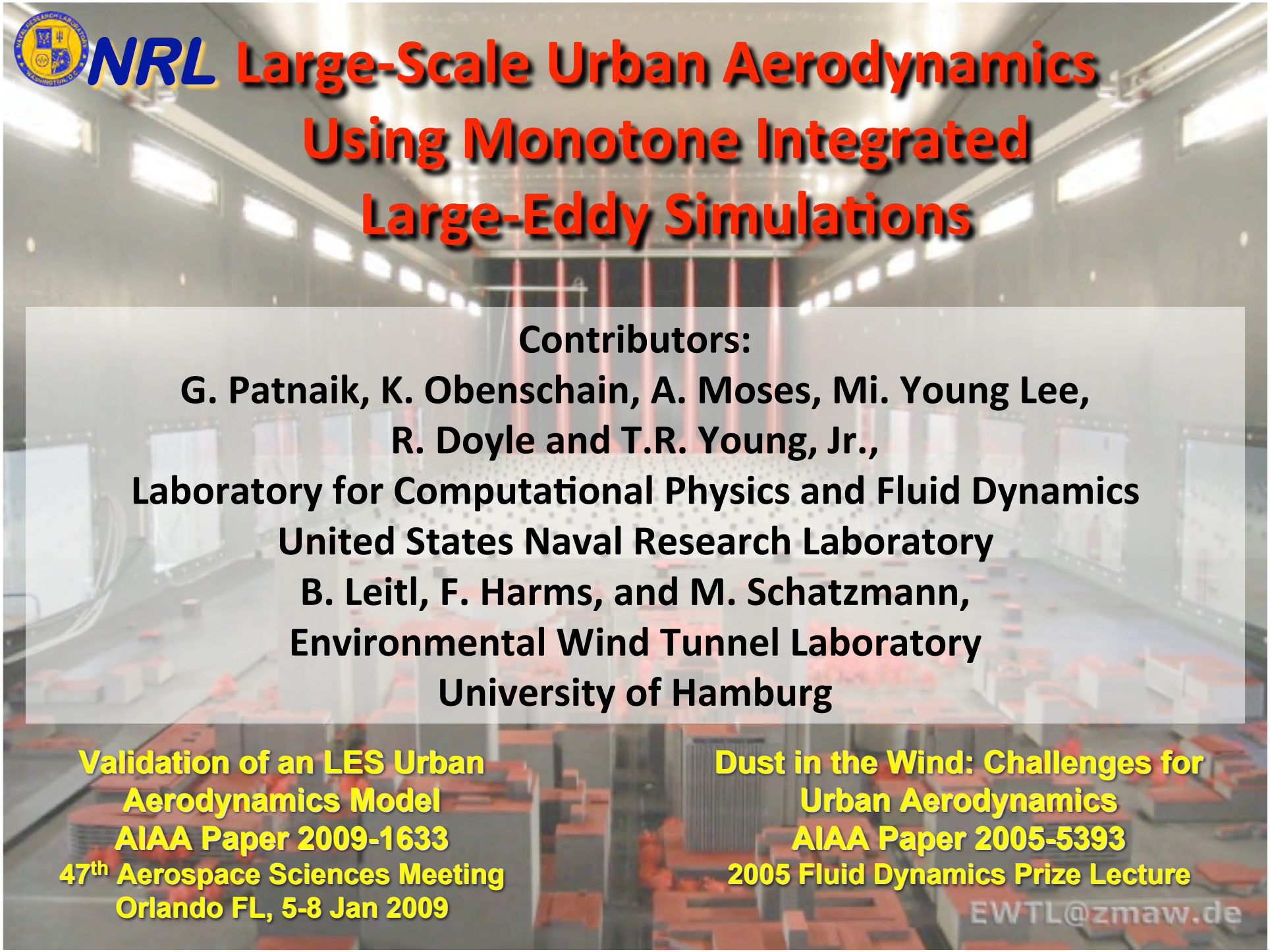




mean numerical arrival time:	376 seconds
mean wind tunnel arrival time:	393 seconds
difference:	4.4 %

Natural Variability Is Large So Why Work Hard?

- **Someone must simulate Urban Transport and Dispersion problems as accurately as possible.**
  - This requires time-dependent Large Eddy Simulation with building geometry, buoyancy and other physics.
- **Planners and operational users need information on uncertainty and natural variability.**
  - This is not available from incumbent models.
- **High Fidelity LES and wind tunnel experiments are the only way to quantify the physical variability.**
  - Field data is needed to avoid technological surprise, but not to quantify variability.
- **LES can end up costing less because users do not have to wait** (e.g. FAST3D-CT runs driving CT-Analyst).



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Environmental Wind Tunnel Laboratory
University of Hamburg

Validation of an LES Urban Aerodynamics Model
AIAA Paper 2009-1633
47th Aerospace Sciences Meeting
Orlando FL, 5-8 Jan 2009

Dust in the Wind: Challenges for Urban Aerodynamics
AIAA Paper 2005-5393
2005 Fluid Dynamics Prize Lecture

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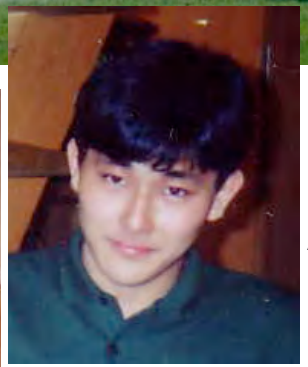

Thank You Kunio!

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2009