Coupled Urban Outdoor and Indoor Synthetic Dispersion Environments

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October 10, 2017

This research was funded in part by the Defense Threat Reduction Agency and performed under U.S. Department of Energy Contract number DE-AC02- 05CH11231. Aeris research funded as a subcontractor to Lawrence Berkeley National Laboratory (LBNL).

Atmospheric Science and Engineering Solutions

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WEATHER FINECASTING

Outline

- Background and enabling technology
  - Motivation for a coupled urban and interior virtual CBRN environment
  - Virtual environment system design
  - Graphics processing unit (GPU) based atmospheric dispersion modeling
- GPU-Large Eddy Simulation (LES) system validation effort
- GPU-LES system demonstration
- Looking forward

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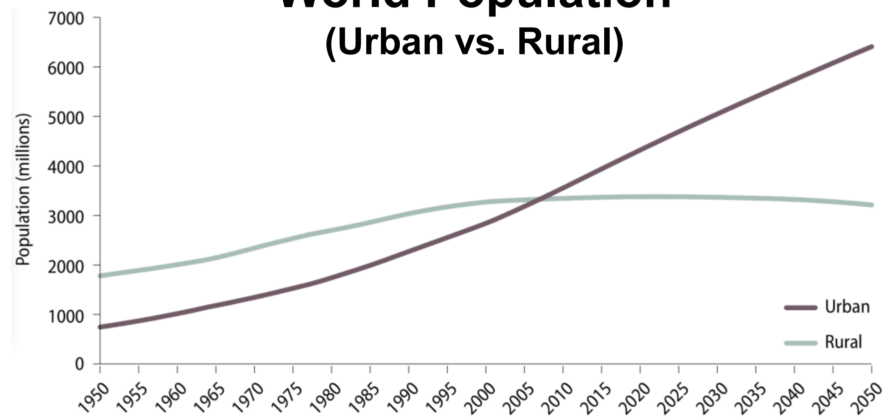
Indoor and Outdoor Air Quality
(Importance of Coupling Indoor/Outdoor Dispersion Models)

- **Most of the world's population lives in urban locations**
  - **In the US, > 80%**
  - **Urban populations are expected to continue to grow**
- **People spend the majority of their time indoors**
  - **In the US, > 86%**
- **Urban - indoor environments are some of the highest impact locations for health effects from pollution**

World Population
(Urban vs. Rural)



U.S. National Human Activity Pattern Survey (NHAPS)
(Nation – Percentage Time Spent)

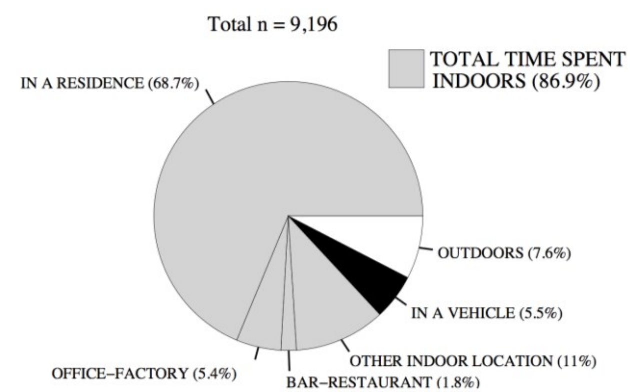


Image Sources:
- http://www.nhm.org/nature/sites/default/files/blog_images/urbanpop-edited.png
- Klepeis NE, Nelson WC, Ott WR et al., 2001: The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*. 11(3):231-252.

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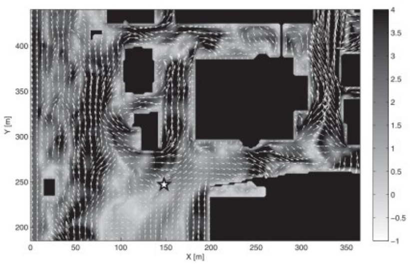
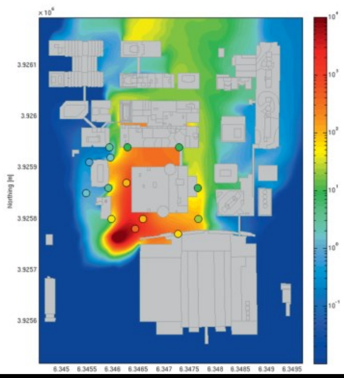
Urban and Outdoor Pollution Dispersion Models
(Virtual Environment System Design)

Urban Outdoor Virtual Environments

Winds and Turbulence

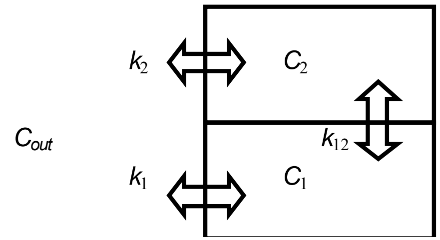


CB Concentrations

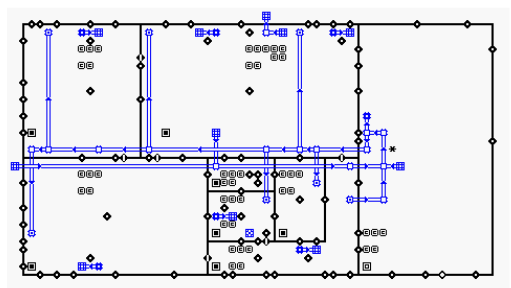


Indoor Virtual Environments

Analytical Models

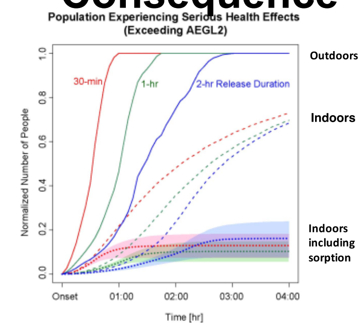


Multi-zone Models

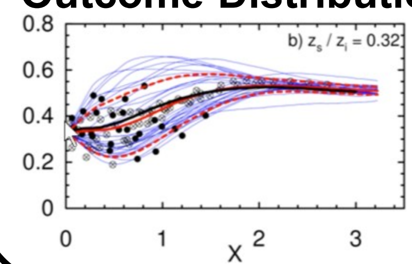


Air Quality Analysis Outcomes

Individual Scenario Consequence



Outcome Distribution

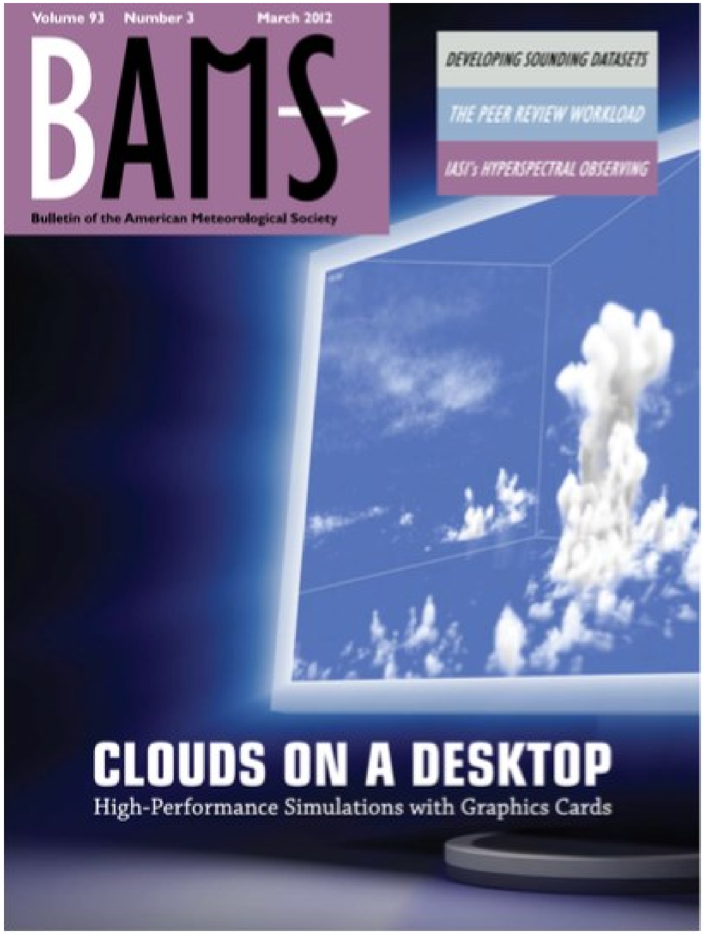


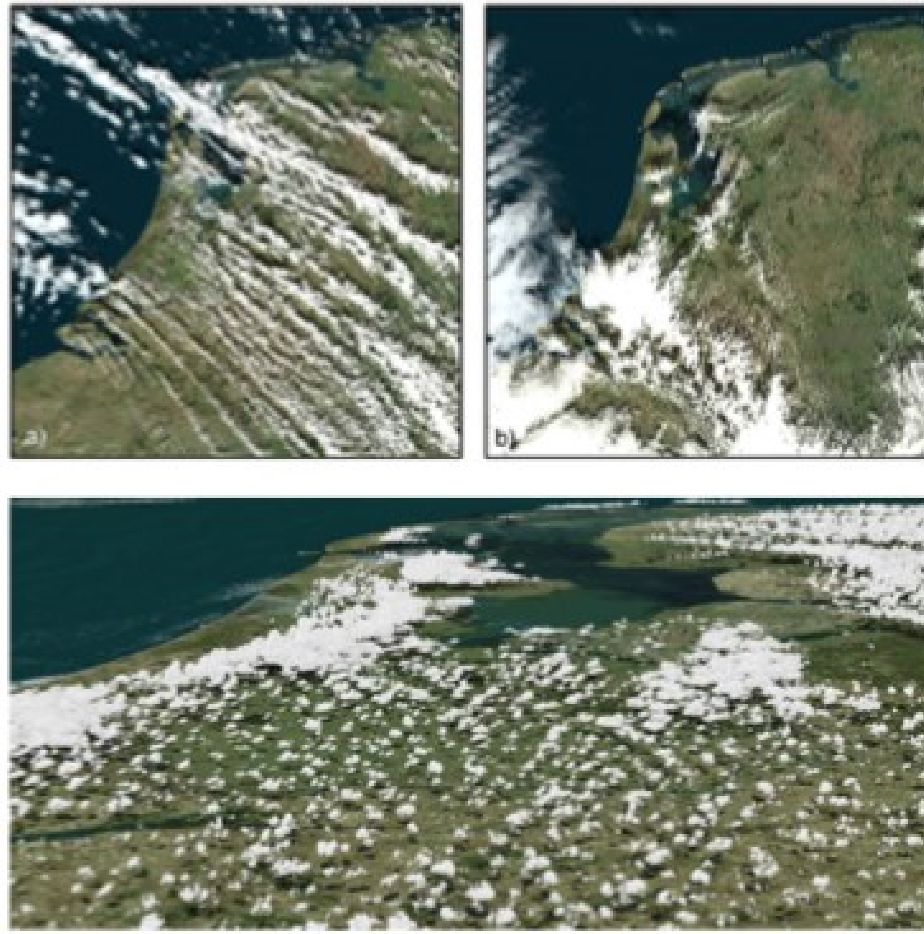
Use Improve Our Understanding of Indoor-Outdoor Contaminant Exchanges

Image sources: - Lundquist, K.A., F.K. Chow, and J.K. Lundquist, 2012: An immersed boundary method enabling large-eddy simulations of flow over complex terrain in the wrf model. *Mon. Wea. Rev.*, **140**, 3936–3955

- Jeff Weil, "Evaluation of a GPU-Based Large-Eddy Simulation for Dispersion in the Atmospheric Boundary Layer", Presented at the AMS - 19th Conference on Applications of Air Pollution Meteorology, 10-14 January, 2016

Enabling Technology
(GPU Resident Atmospheric Simulation Program (GRASP))





Publications:	**Schalkwijk et al. *BAMS 2012***
	Schalkwijk et al. *MWR 2015*
	Schalkwijk et al. *BAMS 2015*
	Schalkwijk et al. *BLM 2016*

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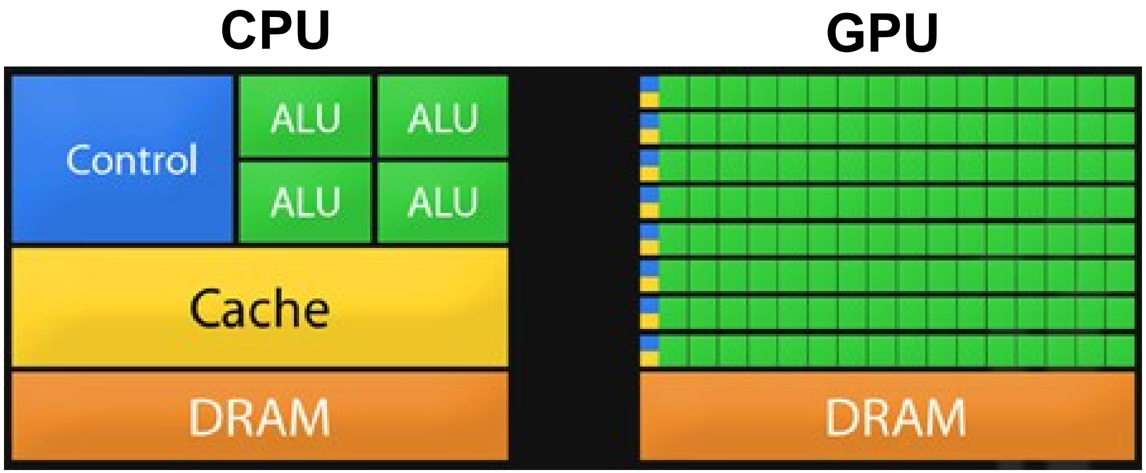
Enabling Technologies
(Background on GPU and CPU Hardware Designs)



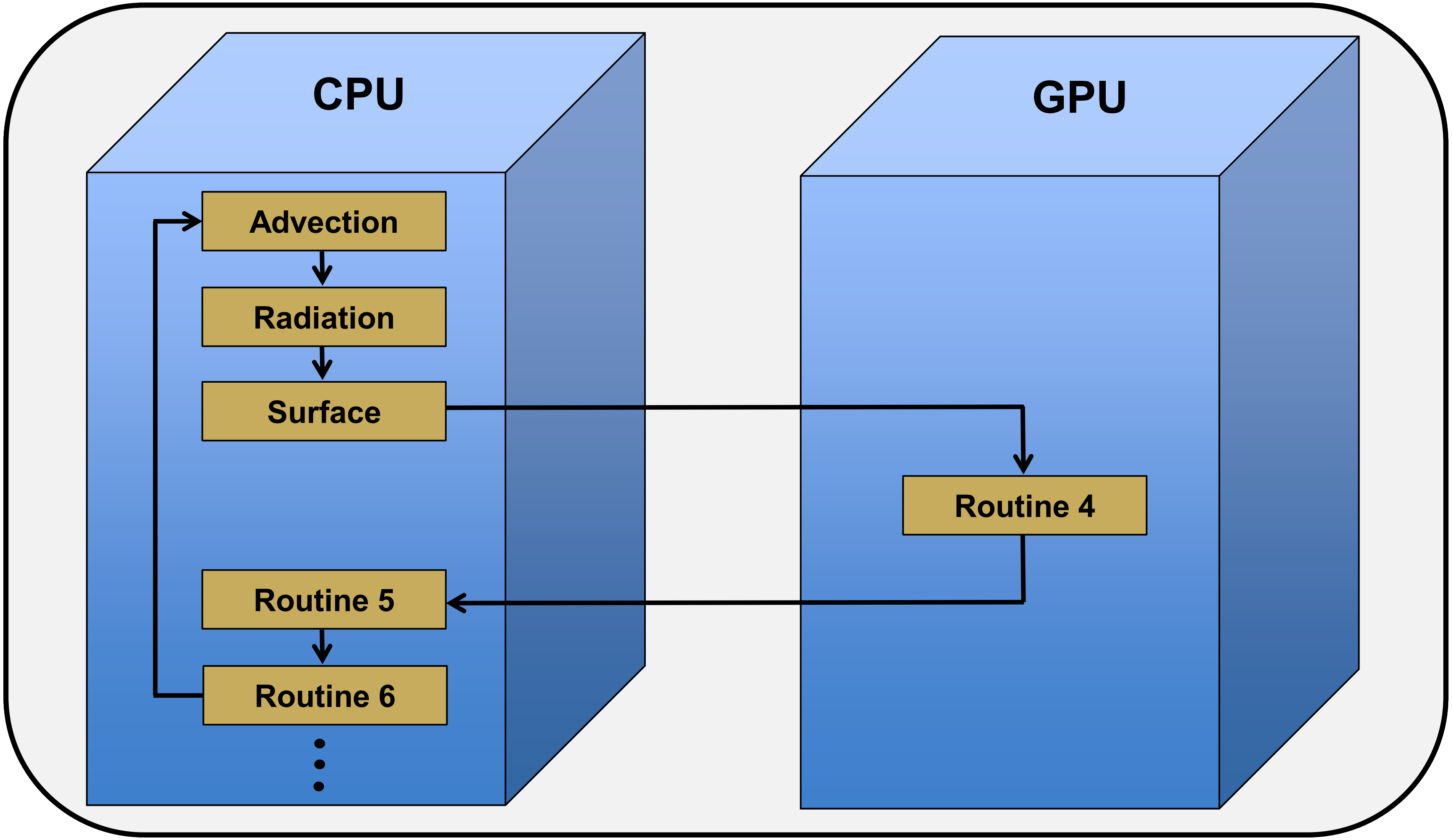
ALU:	**Arithmetic and logic unit**
Control:	**Directs the operation of the processor**
Cache:	**Static memory (fast access)**
DRAM:	**Dynamic random access memory (slow access)**

- **CPU is optimized to perform sequential operations**
  - **Multiple ALU's (cores) enable some parallel performance**
  - **Typically has a large cache memory availability compared to GPU**
- **GPU is optimized to perform highly parallel operations**
  - **Numerous ALU's (1000's on a single GPU card)**
  - **Faster and more advanced memory interfaces**
  - **Currently in a phase of rapid hardware technology advancements**

Image Source: - http://www.frontiersin.org/files/Articles/70265/fgene-04-00266-HTML/image_m/fgene-04-00266-g001.jpg

Atmospheric Modeling
(Past Practices for “GPU-Accelerated” HPC Computing)

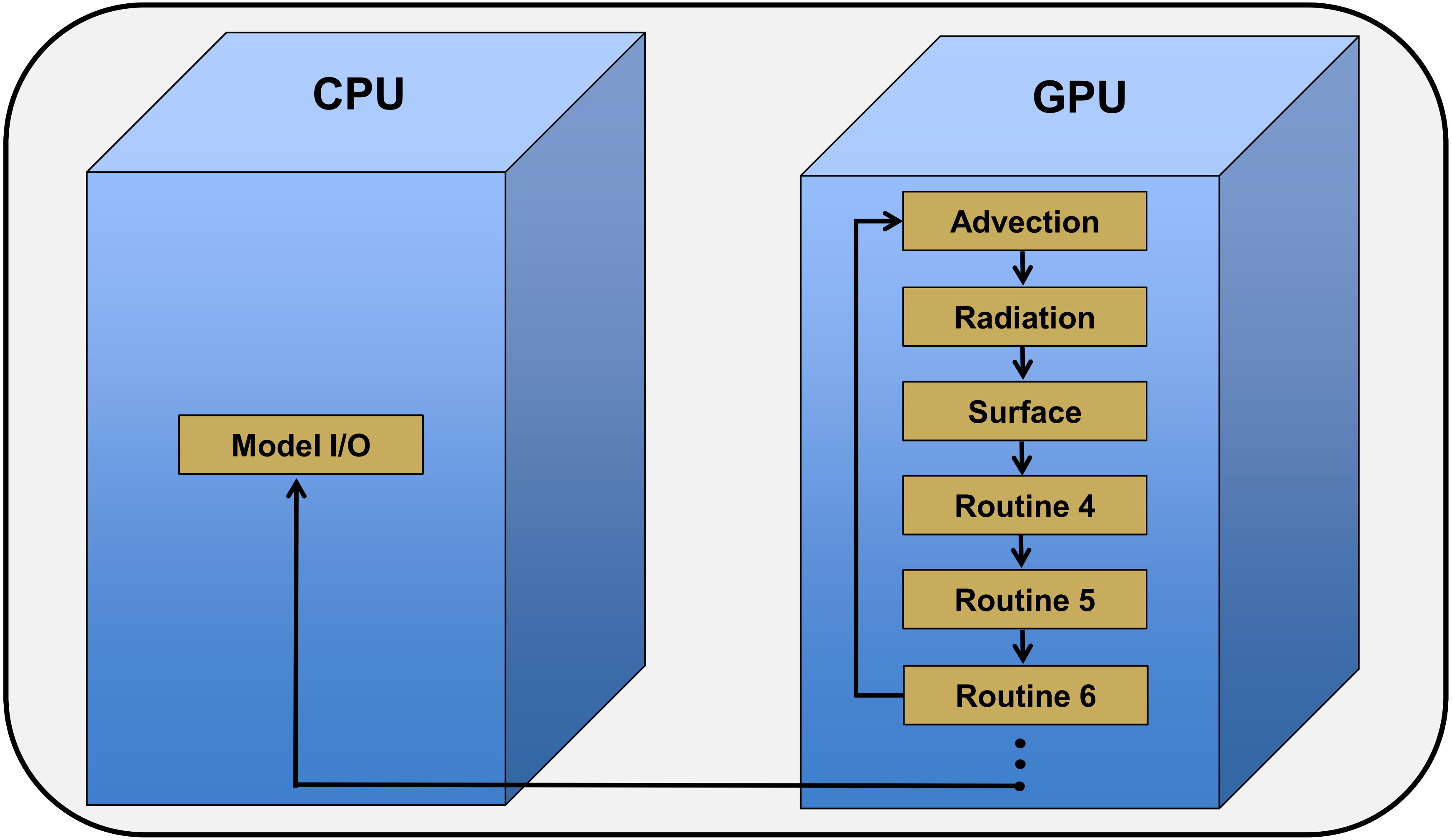
Atmospheric Modeling on a CPU/GPU Computer



Atmospheric Modeling

(Next Generation of GPU HPC Computing)

GPU Resident Modeling

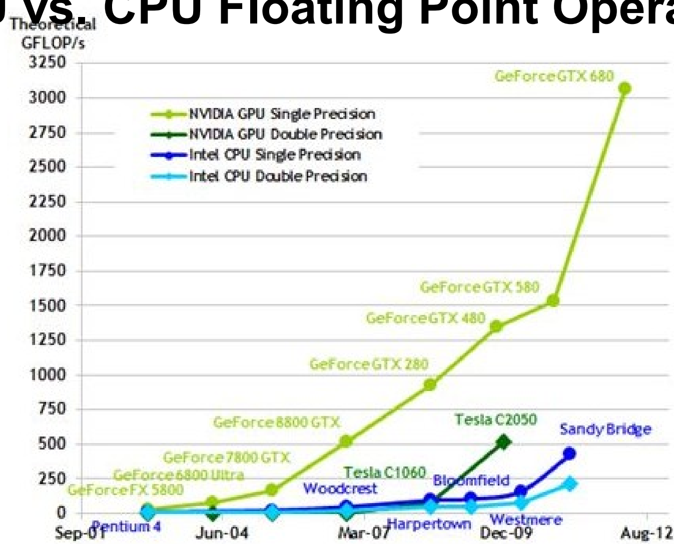


Returning us to a "Shared-Memory" Computing Paradigm

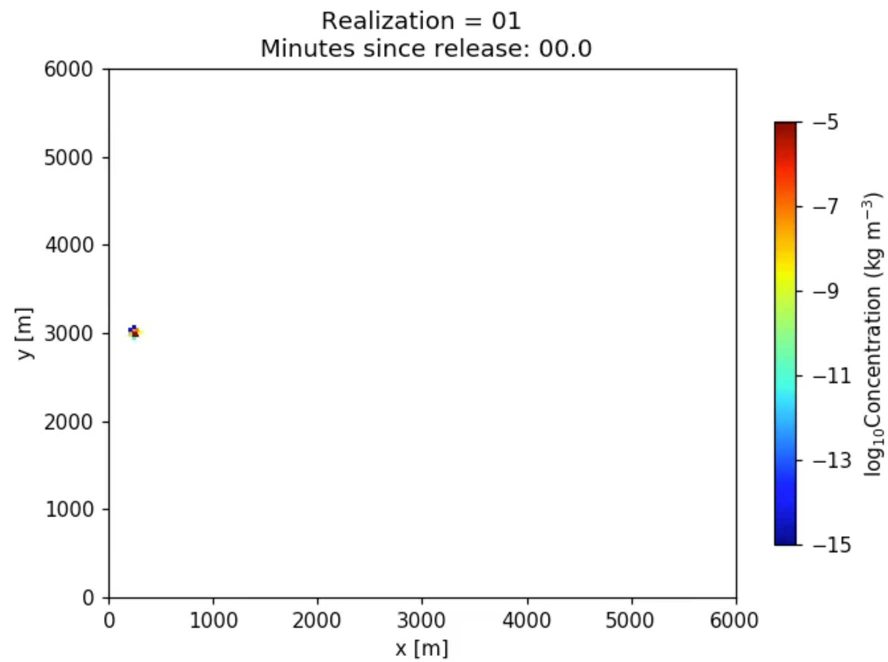
This Technology Enables
(Ensembles of Single Realization Dispersion Solutions)

- **GPU provides substantial computational advantage over comparable CPU-based solution**
- **Example: 1-hr simulation**
  - **8 core Intel Xenon: 1hr 32 mins**
  - **Nvidia K40: 36 seconds**
- **Rapid technology advances**

GPU vs. CPU Floating Point Operations



Puffs Released Into Unstable Outdoor Conditions



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GPU-LES Dispersion Model System Validation

(Incremental Approach From More Simple to More Complex)

- **Meteorological validation: *Completed***
- **Open terrain atmospheric transport and dispersion (AT&D): *In process***
  - Completed for unstable boundary layer
  - Neutral and stable boundary layer are in process
- **"Building aware" meteorology and AT&D: Collecting data sets and developing simulations**
  - Mock urban setting test (MUST)
  - 2015 Jack Rabbit II urban container testing (JRII-2015)
  - Joint Urban 2003 (JU2003)
- **Indoor-outdoor contaminant transport: No activity yet**

GPU-LES Dispersion Model System Validation

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Open Terrain Validation
(Model Simulation Design)

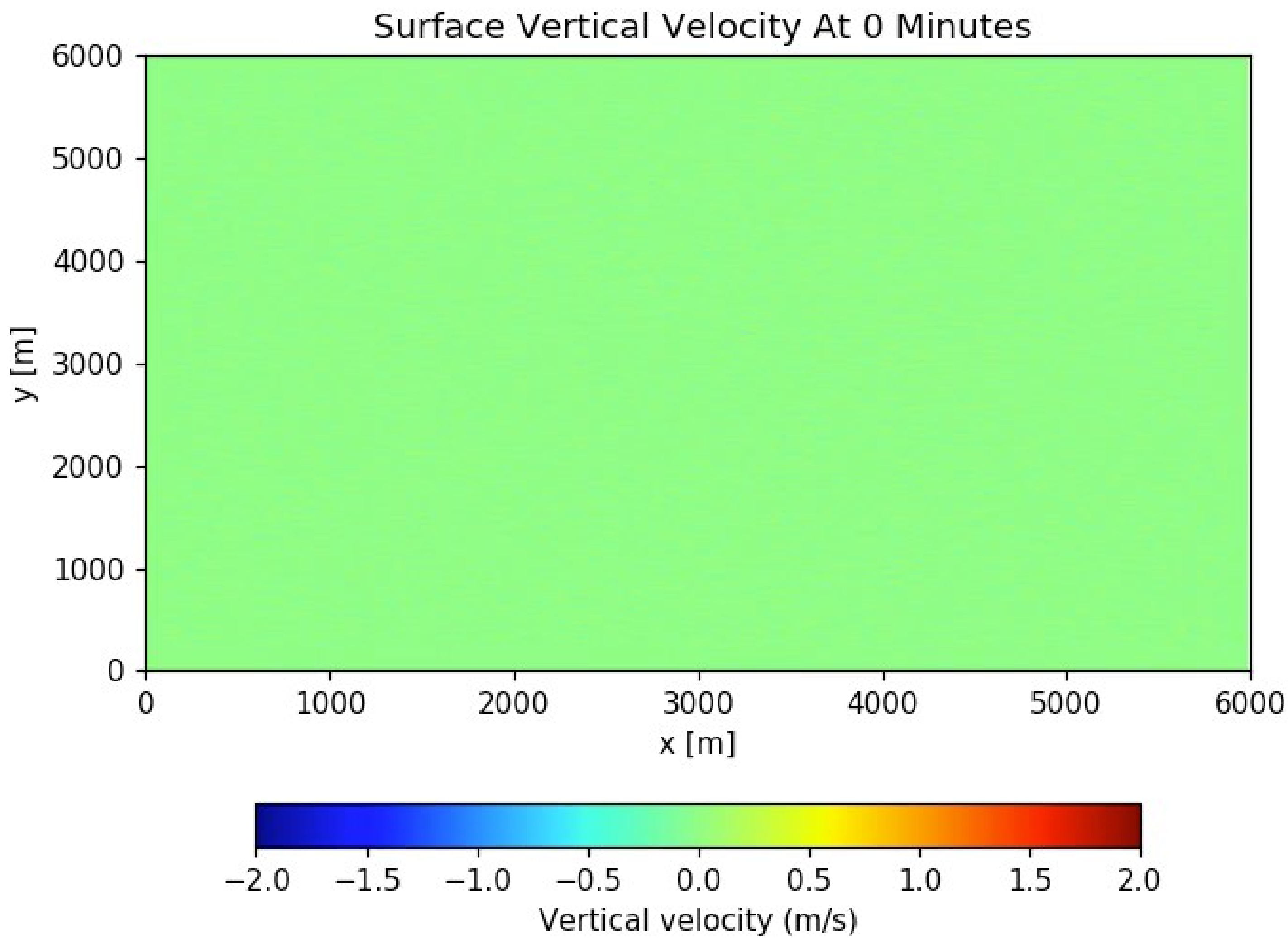
- GPU-LES configuration patterned after Weil et al. 2004 & 2012
  - Horizontal resolution: ~50 m vertical resolution: ~20 m
  - Domain: ~13 x ~13 km x ~2 km *(Larger than Weil et al. 2004)*
  - CBL depth: 1 km and heat flux = 0.24 m s^{-1} K
  - Wind Speed: ~3 ms^{-1} in convective boundary layer

- Release characteristics
  - Continuous near surface point release
  - 130 uncorrelated realizations produced
  - Time and space differences used to create the realizations

- Dispersion characteristics examined
  - Plume height normalized by the boundary layer height
  - Surface crosswind integrated concentration (CWIC)
  - Vertical profiles of CWIC
  - Surface crosswind dispersion
  - Vertical dispersion

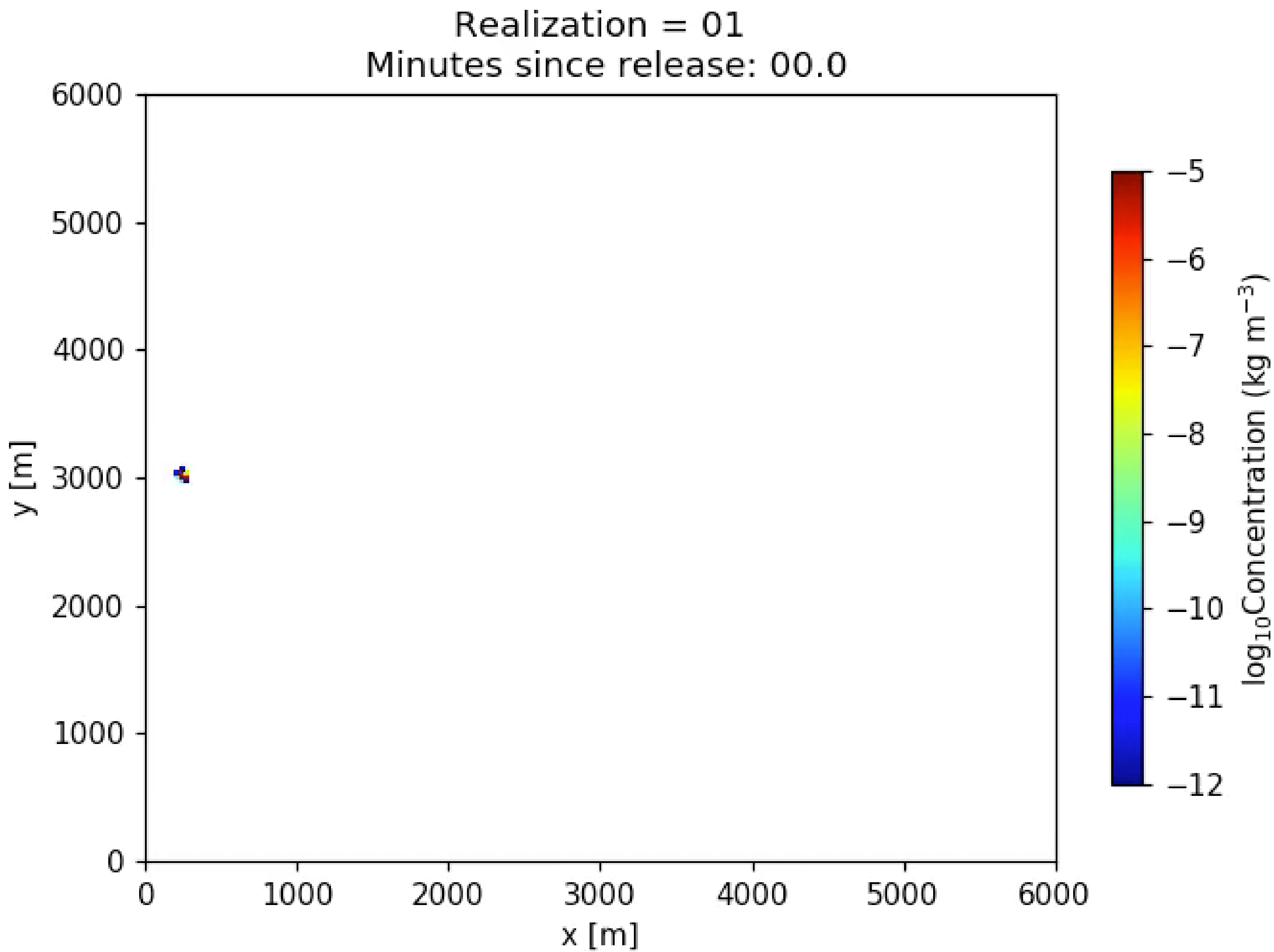
Open Terrain Validation
(Model Simulation Design)

Allow the Turbulence to Spin Up in the Model



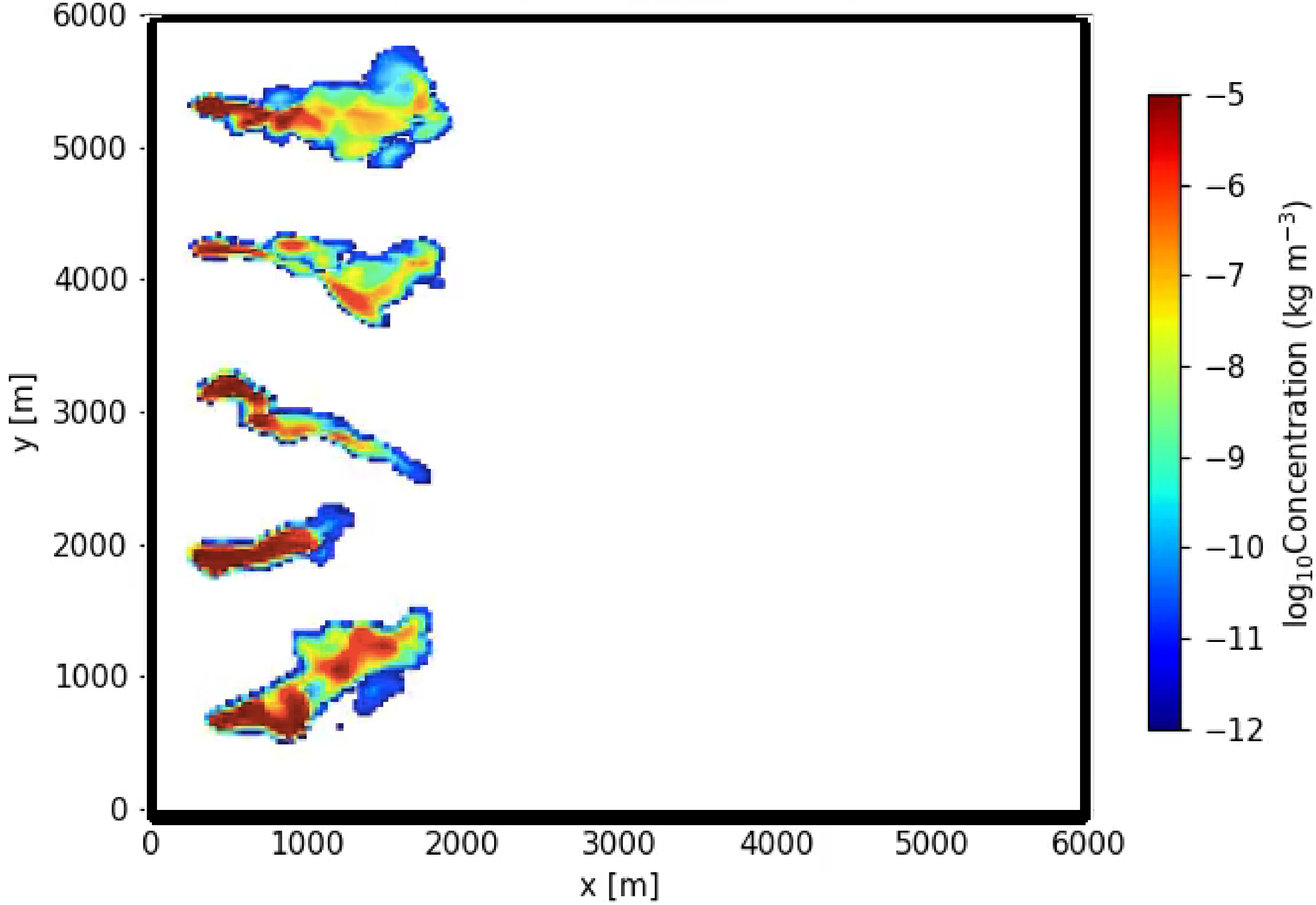
Open Terrain Validation
(Model Simulation Design)

Create Uncorrelated Dispersion Realizations

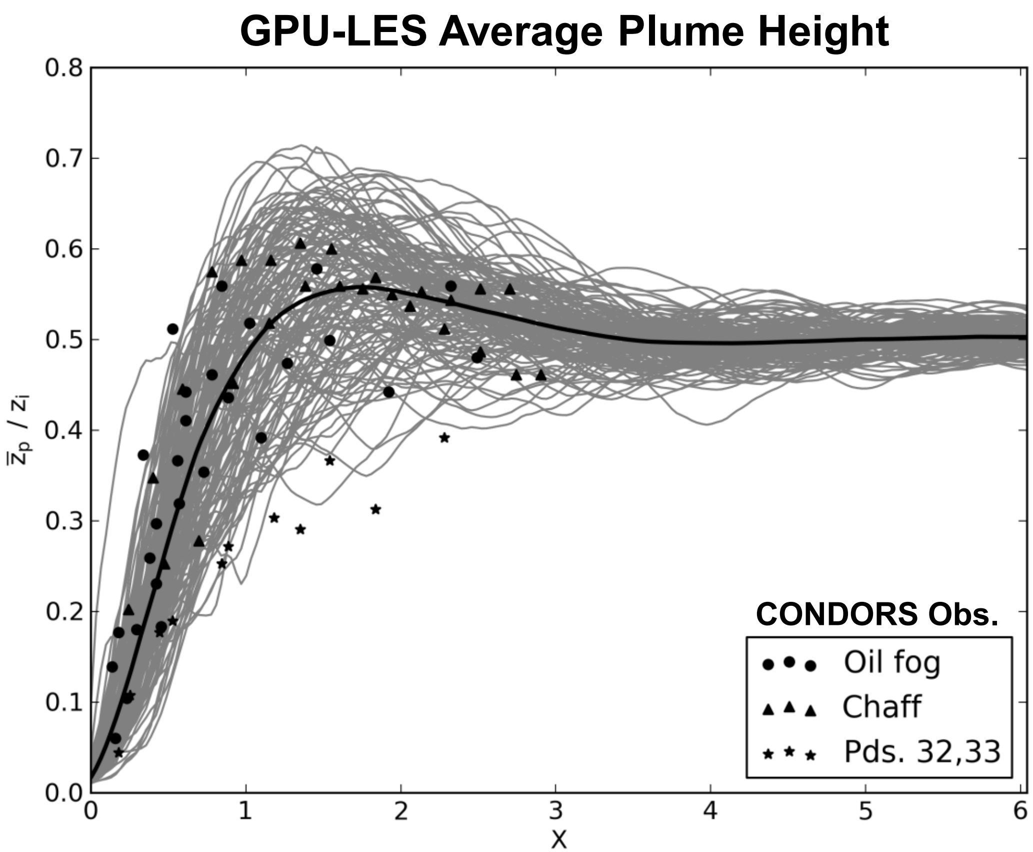


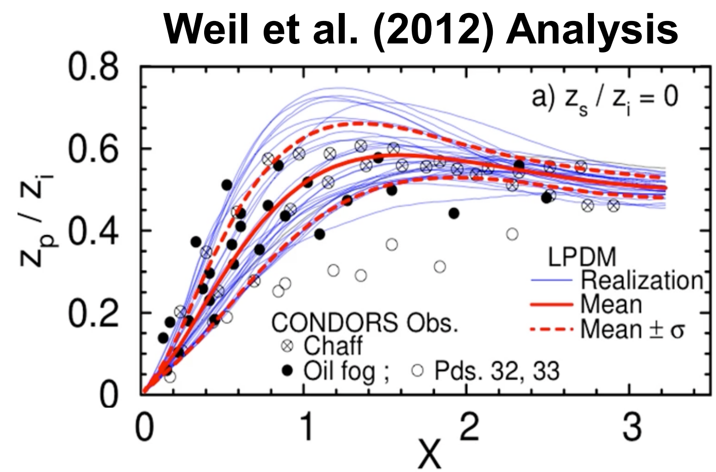
Open Terrain Validation
(Model Simulation Design)

Create Uncorrelated Dispersion Realizations
(Example – 6 Minutes After Start of Release)



Open Terrain Validation
(Plume Height Calculations)





Dimensionless Downwind Distance

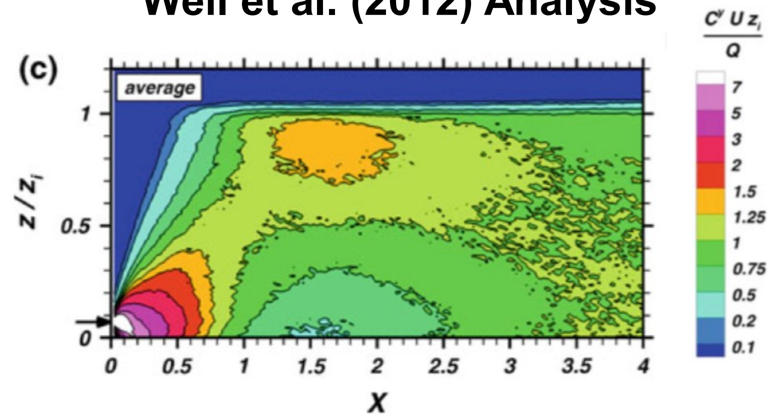
$$X = \frac{w_* x}{U z_i}$$

Image Source: Weil, J.C., P.P. Sullivan, E.G. Patton, C. Moeng, 2012: Statistical Variability of Dispersion in the Convective Boundary Layer: Ensembles of Simulations and Observations. *BLM*, **145,** 185–210

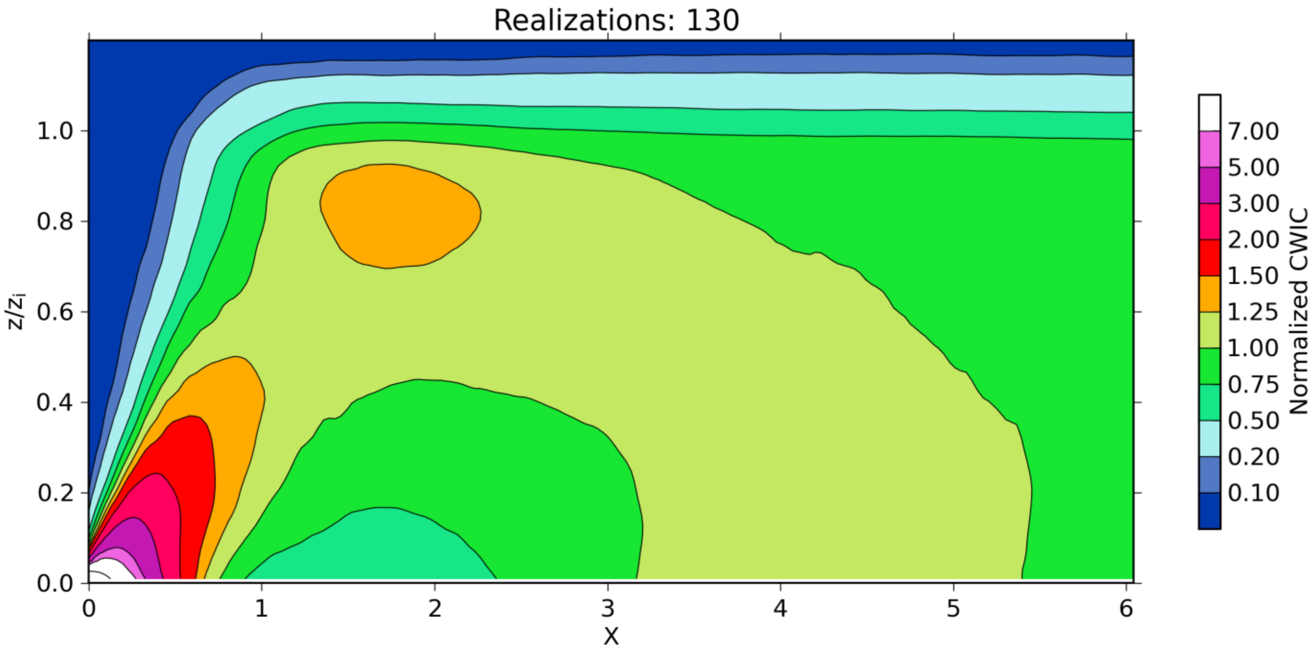
Open Terrain Validation

(Cross Wind Integrated Concentration (CWIC) Calculations)

Weil et al. (2012) Analysis



GPU-LES Average CWIC



Dimensionless Downwind Distance

$$X = \frac{w_* x}{U z_i}$$

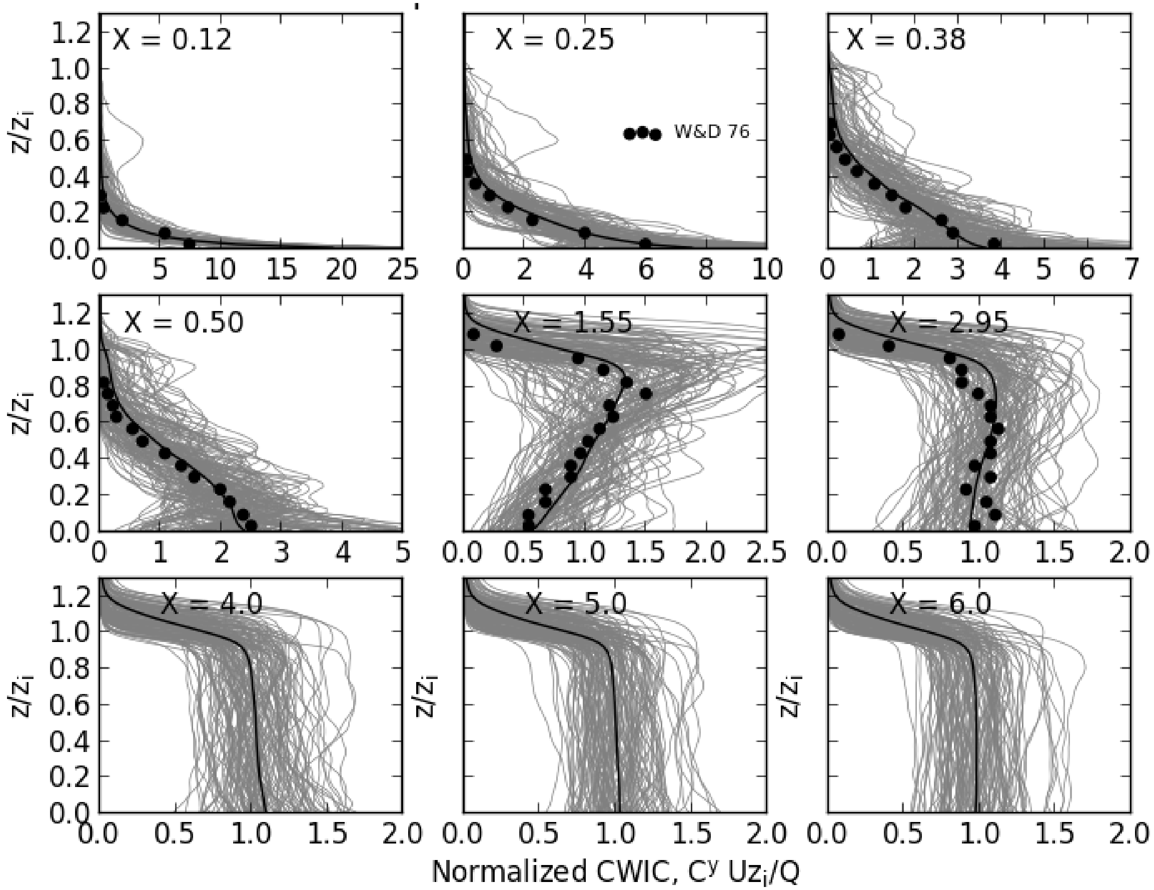
Concentration

$$CWIC = \frac{C^y U z_i}{Q}$$

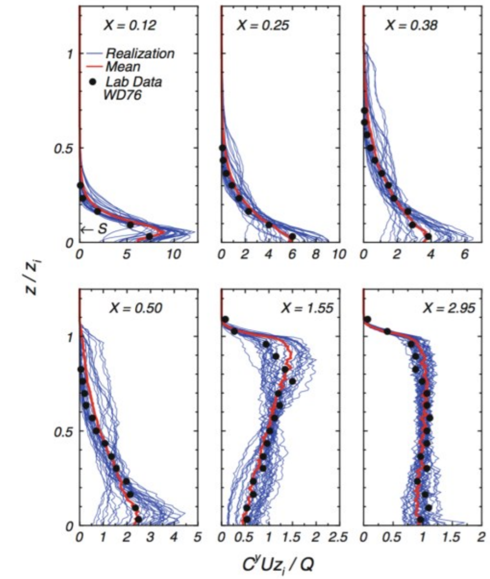
Image Source: Weil, J.C., P.P. Sullivan, E.G. Patton, C. Moeng, 2012: Statistical Variability of Dispersion in the Convective Boundary Layer: Ensembles of Simulations and Observations. *BLM*, **145,** 185–210

Open Terrain Validation
(CWIC Vertical Profile Calculations)

GPU-LES Vertical Profiles of CWIC



Weil et al. (2012) Analysis



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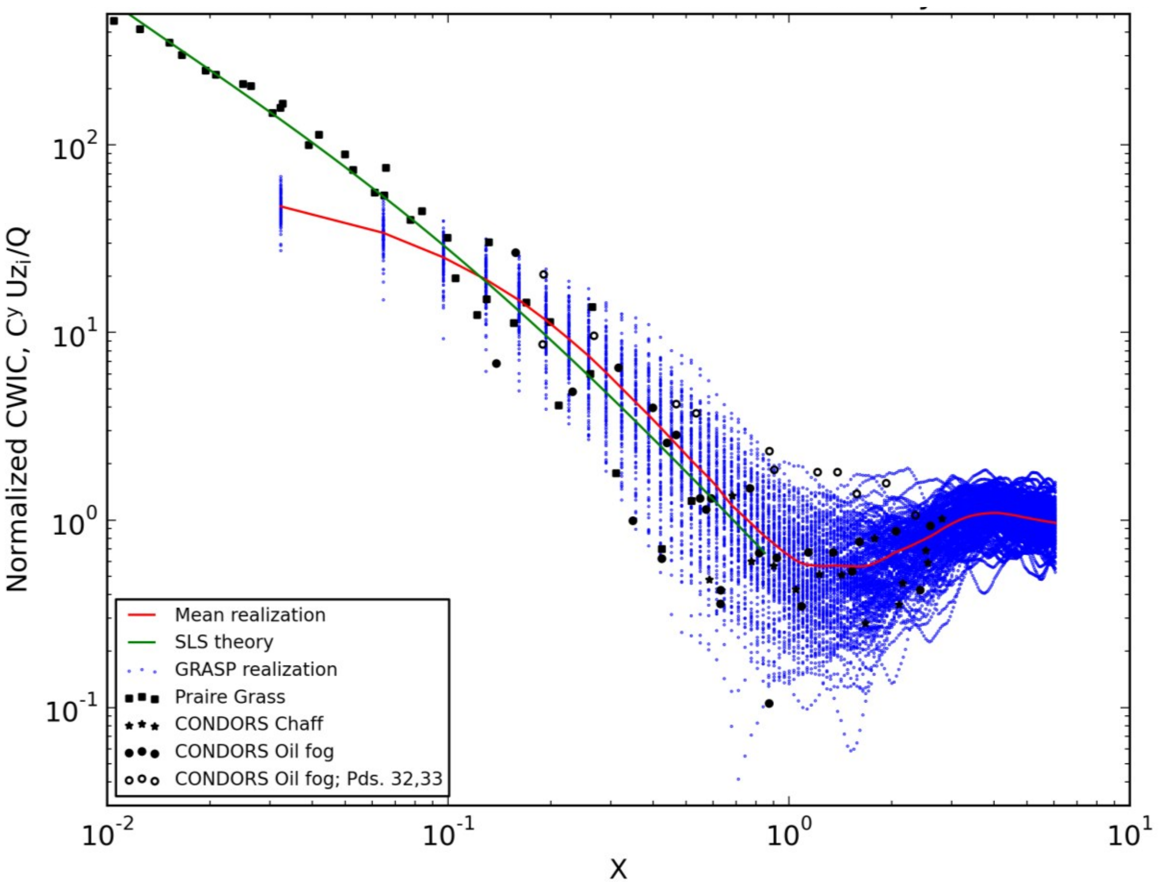
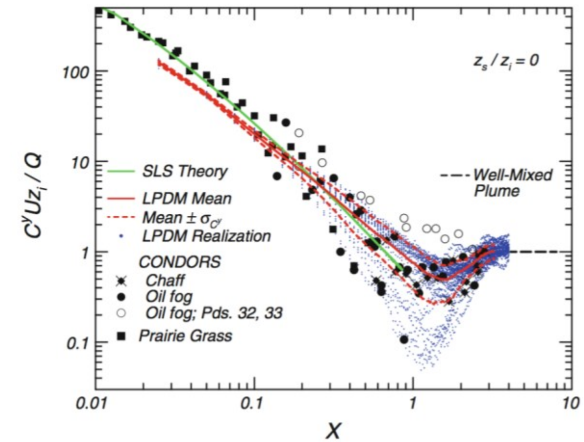
Open Terrain Validation

(Surface Cross Wind Integrated Concentration (CWIC) Calculations)

GPU-LES Surface CWIC



Weil et al. (2012) Analysis



Dimensionless Downwind Distance

$$X = \frac{w_* x}{U z_i}$$

Concentration

$$CWIC = \frac{C^y U z_i}{Q}$$

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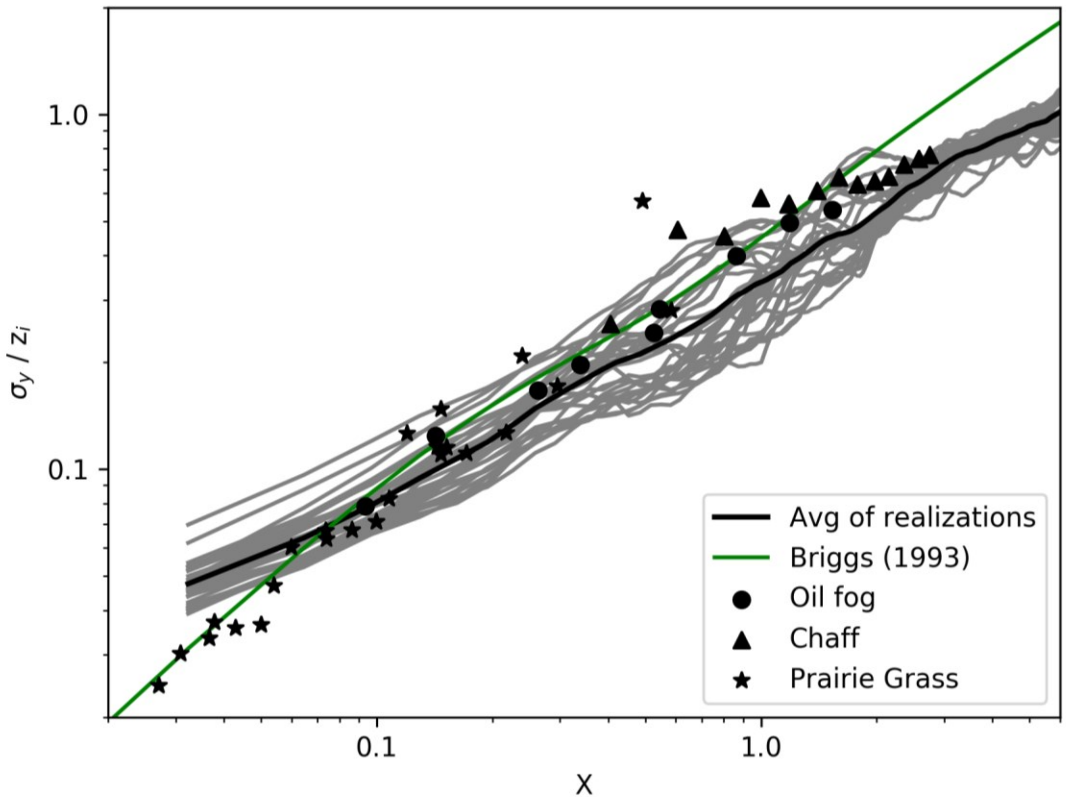
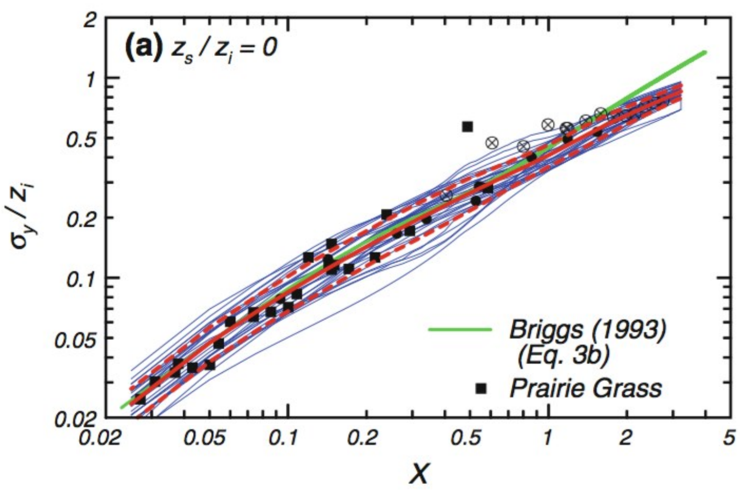
Open Terrain Validation
(Surface Cross Wind Dispersion Calculations)

GPU-LES Surface Cross Wind Dispersion



Weil et al. (2012) Analysis



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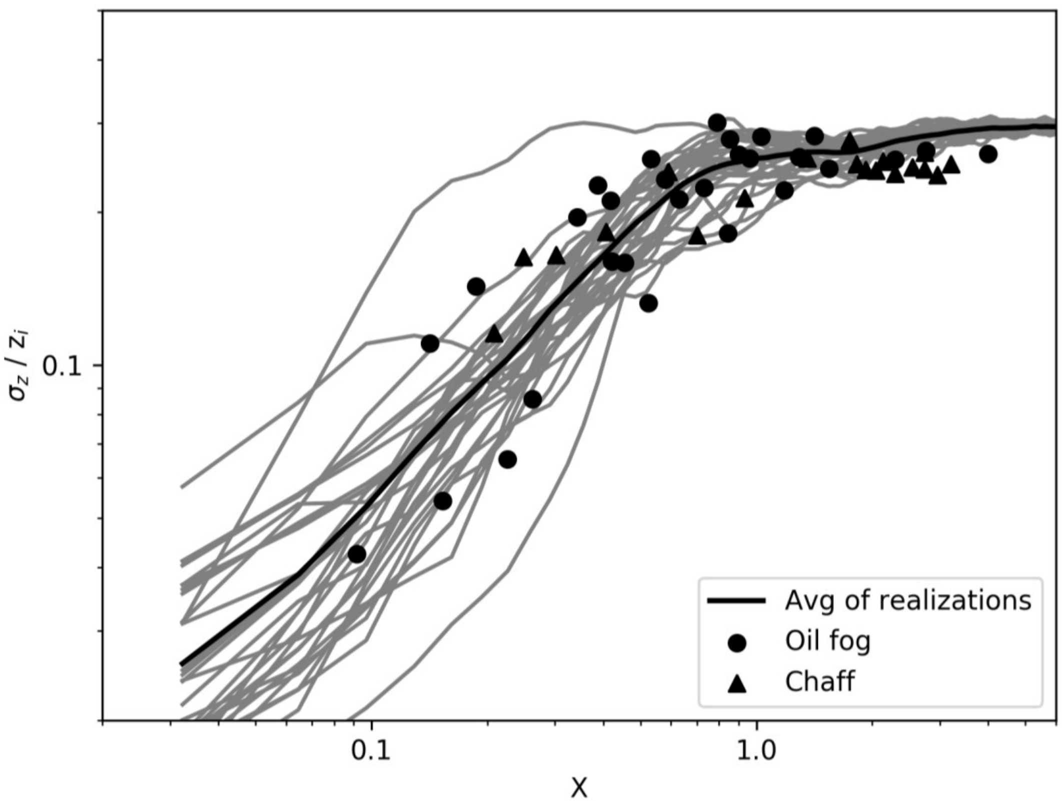
Open Terrain Validation
(Surface Vertical Dispersion Calculations)

GPU-LES Vertical Dispersion



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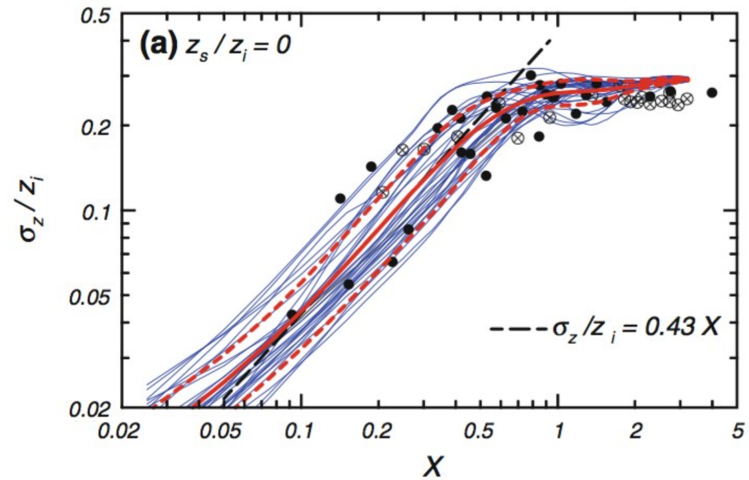

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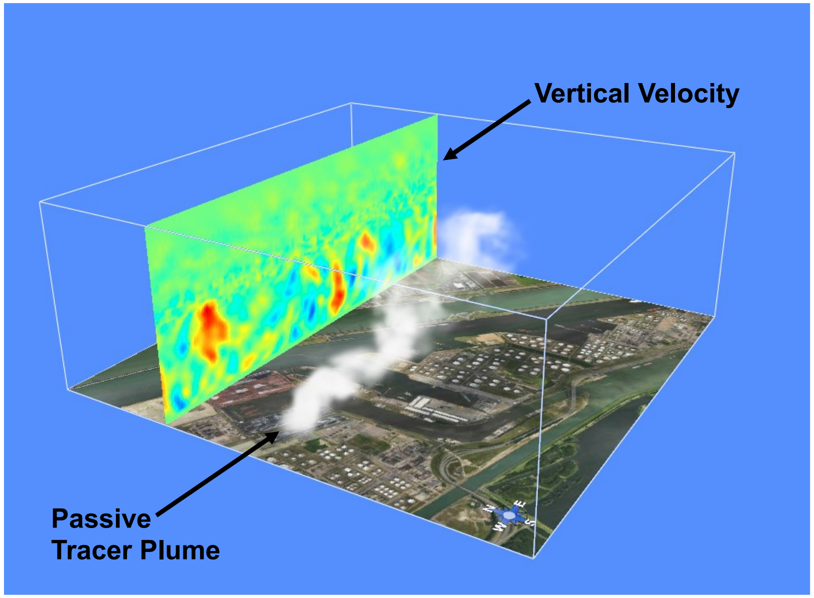
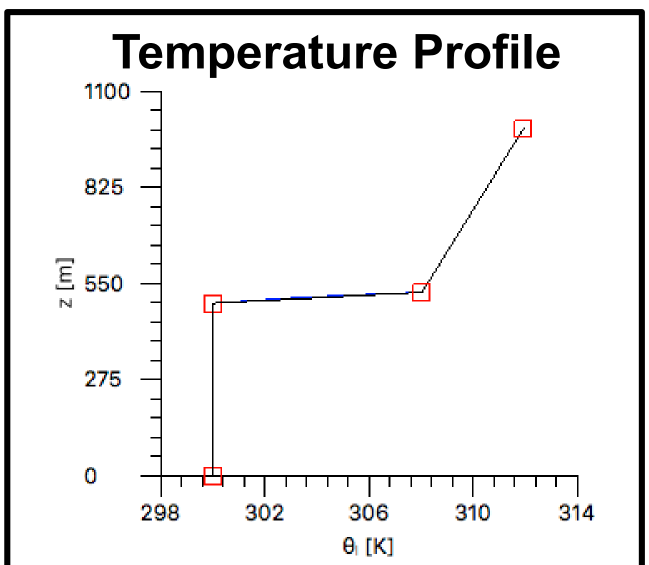
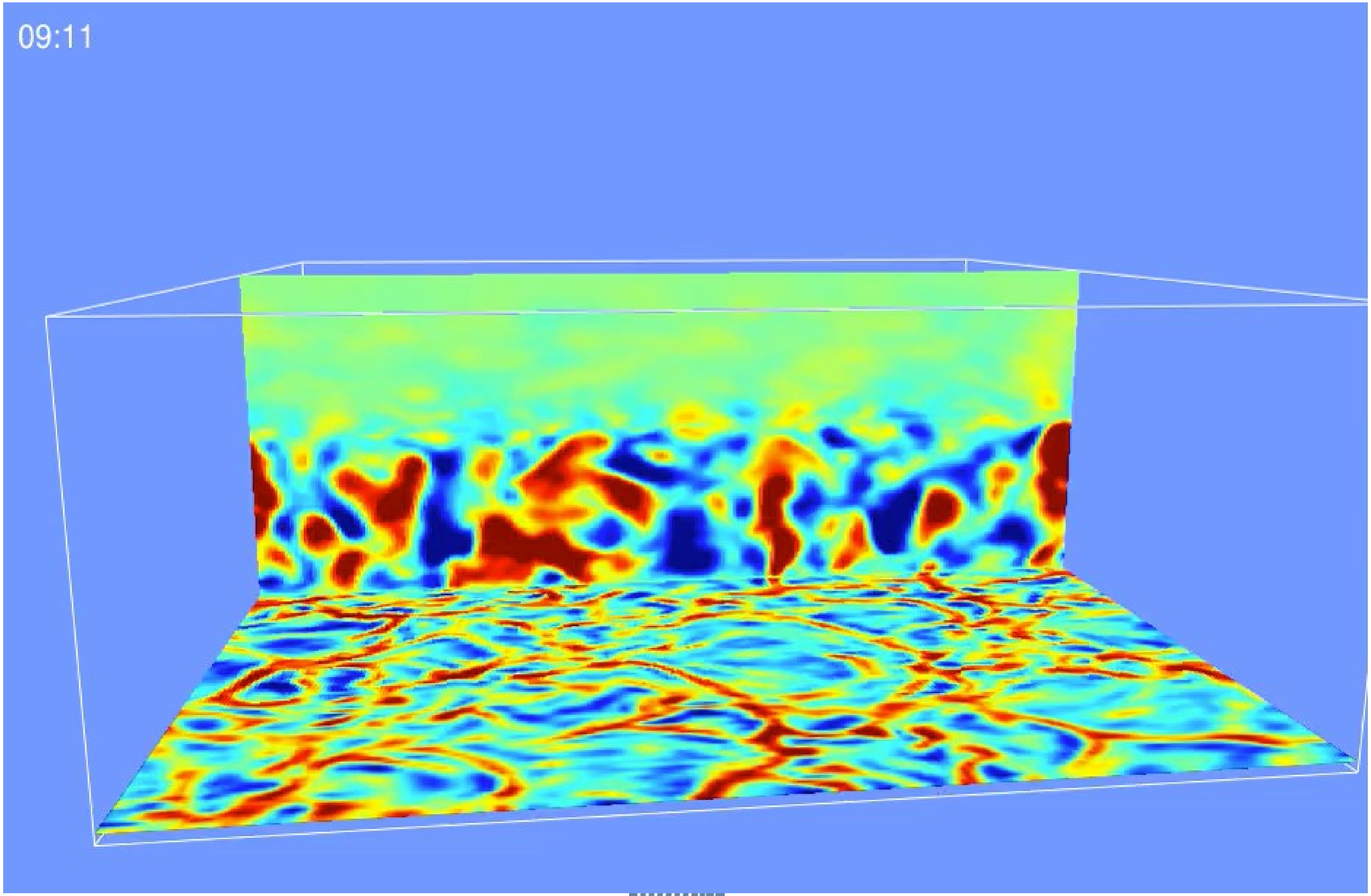
Demonstration
(Open Terrain Example)





- **Open terrain simulation specifications**
  - 128 x 128 x 64 grid
  - Horizontal resolution: 20 m
  - Vertical resolution ~17 m
- **Simulation scenario**
  - Boundary layer (BL) depth: 550 m
  - Surface heating: 50 W/m^2
  - Winds:
    - 3 m/s in PBL
    - 4 m/s above PBL
- **Simulation time on NVIDIA K40**
  - 2880 ALU cores
  - 12 Gb of onboard memory
  - 1-hr simulation takes ~ 36s

Demonstration
(Open Terrain Example)



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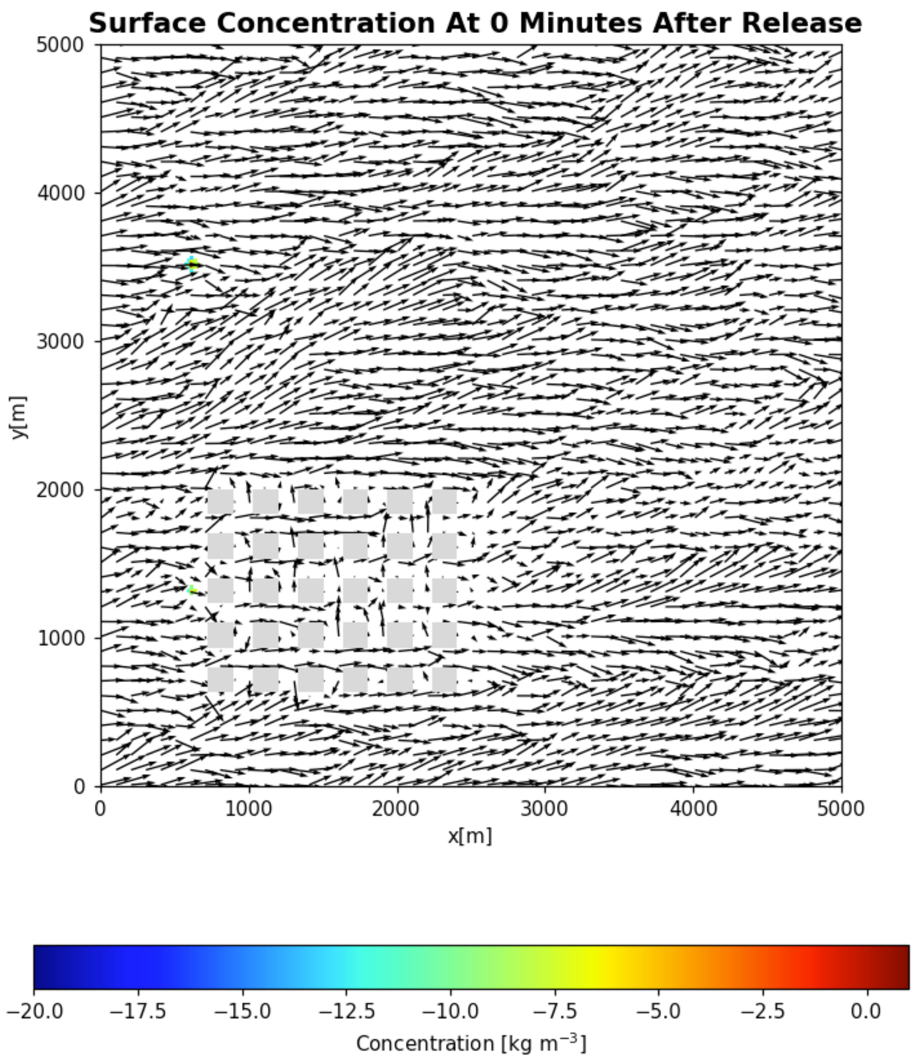
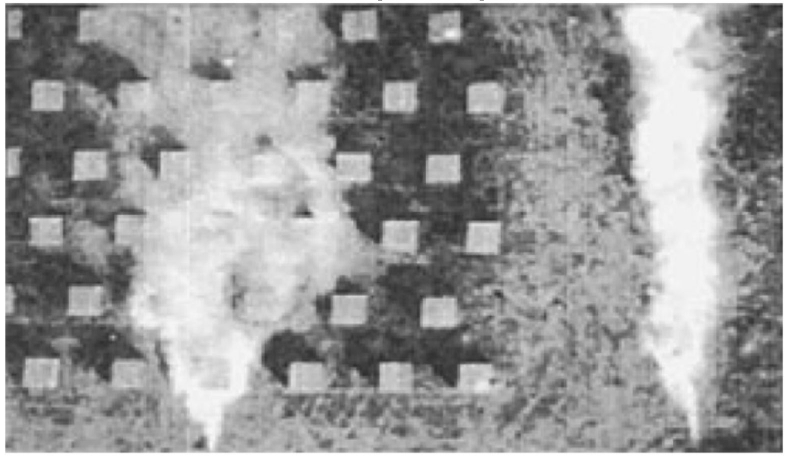
Looking Forward
(Incorporation of Buildings)



Davidson et al. (1995) Experiment



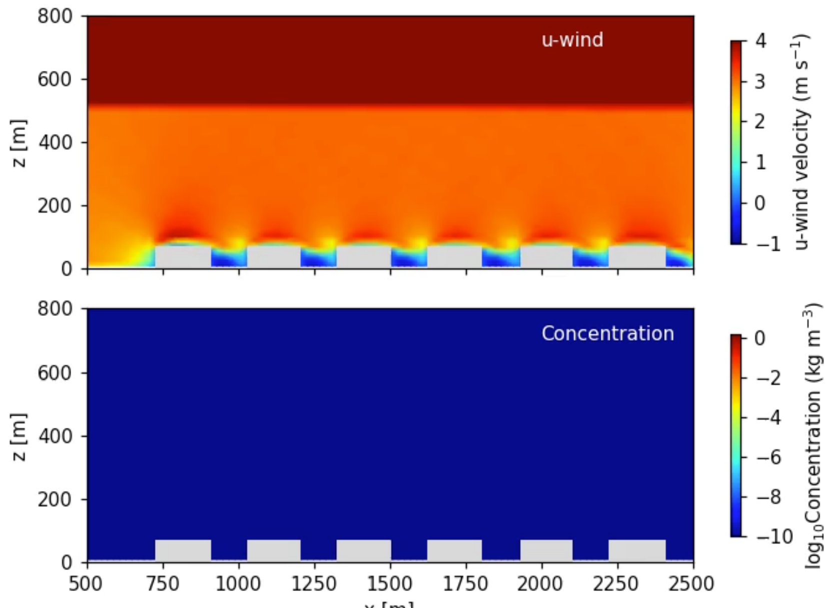
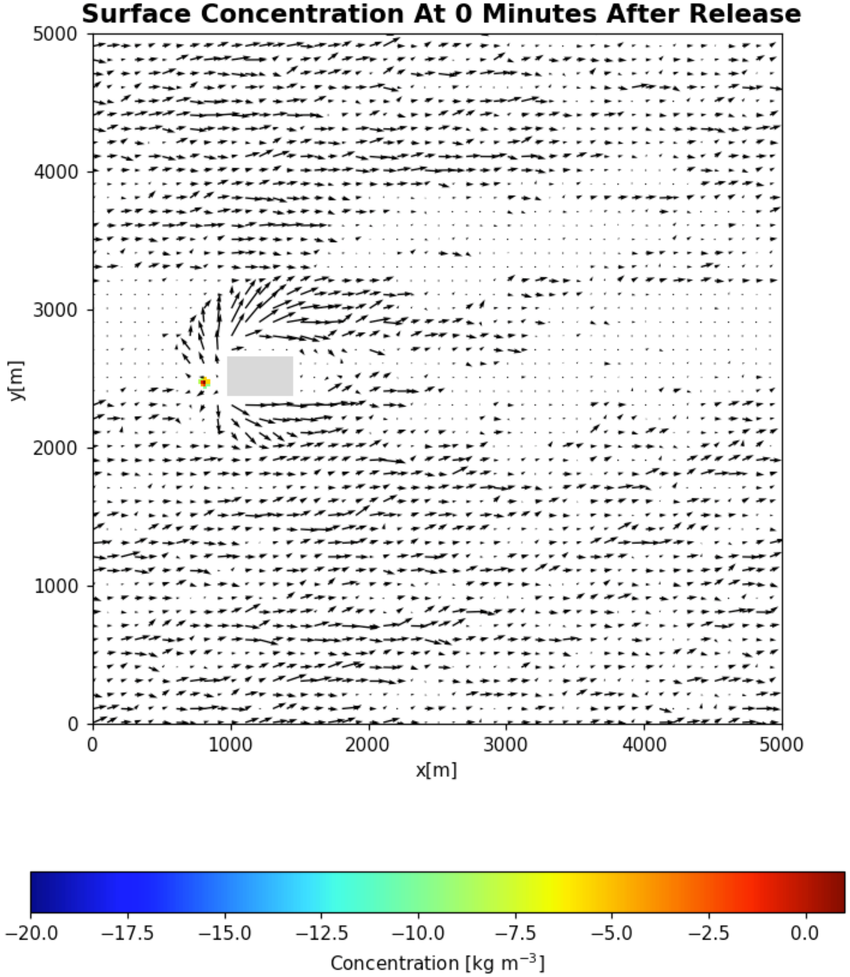
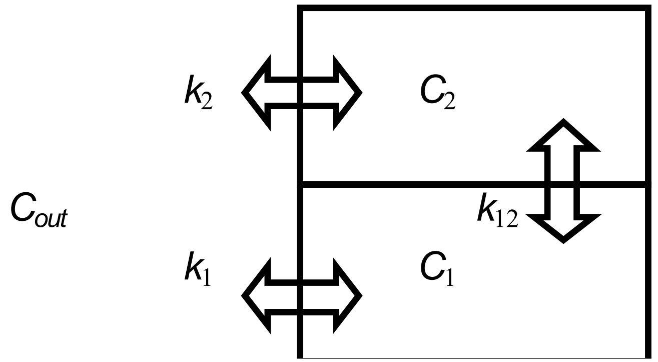


Image Source: Davidson, M., Mylne, K., Jones, C., Phillips, J., Perkins, R., Fung, J., Hunt, J., 1995. Plume dispersion through large groups of obstacles e a field investigation. Atmos. Environ. 29, pp. 3245-3256.

Looking Forward
(Linking the Indoors to the Outdoors)



Two Zone Box Model



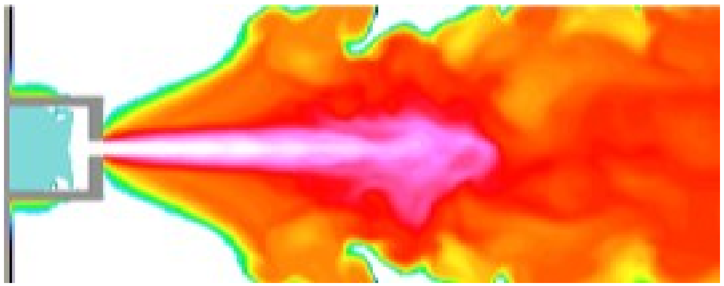
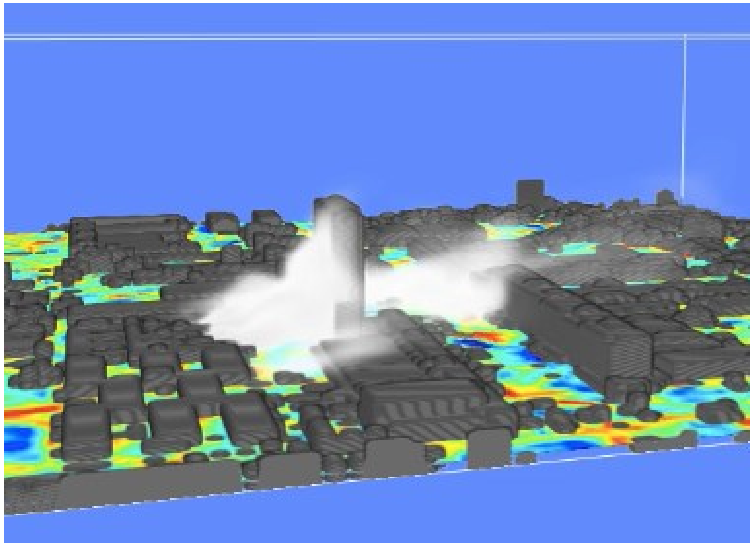
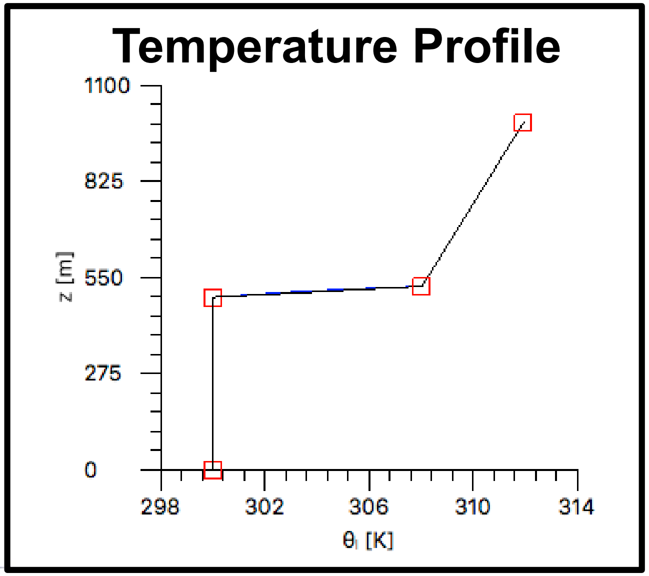


Image Courtesy of Darrel Johnston SWRI – 2015

Demonstration
(Building Aware Example)





- "Building-aware" terrain simulation specifications
  - 256 x 256 x 128 grid
  - Horizontal resolution: ~4 m
  - Vertical resolution ~8 m
- Simulation scenario
  - Boundary layer (BL) depth: 550 m
  - Surface heating: 25 W/m^2
  - Winds:
    - ~3 m/s in PBL
- Simulation time
  - 2880 ALU cores
  - 12 Gb of onboard memory
  - 1-hr simulation takes ~ 155s

Demonstration
(Building Aware Example)