Coupled Urban Outdoor and Indoor Synthetic Dispersion Environments

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Distribution A: Approved for public release, distribution is unlimited
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

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

Urban Outdoor Virtual Environments

Winds and Turbulence

CB Concentrations

Indoor Virtual Environments

Analytical Models

\[ k_2 \quad C_2 \quad k_{12} \quad C_1 \quad k_1 \]

Multi-zone Models

Air Quality Analysis Outcomes

Individual Scenario Consequence

Outcome Distribution

Use Improve Our Understanding of Indoor-Outdoor Contaminant Exchanges

Image sources:
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
Enabling Technologies
(Background on GPU and CPU Hardware Designs)

- 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

- CPU
  - Advection
  - Radiation
  - Surface
  - Routine 5
  - Routine 6

- GPU
  - Routine 4
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
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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)

• Indoor-outdoor contaminant transport: No activity yet
GPU-LES Dispersion Model System Validation
(Incremental Approach From More Simple to More Complex)

- Meteorological validation: *Completed*

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- “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
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
Allow the Turbulence to Spin Up in the Model
Open Terrain Validation
(Model Simulation Design)

Create Uncorrelated Dispersion Realizations
Realization = 01
Minutes since release: 00.0
Open Terrain Validation
(Model Simulation Design)

Create Uncorrelated Dispersion Realizations
(Example – 6 Minutes After Start of Release)
Open Terrain Validation
(Plume Height Calculations)

GPU-LES Average Plume Height

CONDORS Obs.
- Oil fog
- Chaff
- Pds. 32,33

Weil et al. (2012) Analysis

a) $z_p / z_i = 0$

Dimensionless Downwind Distance

$$X = \frac{w_x x}{U z_i}$$

Open Terrain Validation
(Cross Wind Integrated Concentration (CWIC) Calculations)

Weil et al. (2012) Analysis

GPU-LES Average CWIC
Realizations: 130


Dimensionless Downwind Distance

\[ X = \frac{w_* x}{U z_i} \]

Concentration

\[ CWIC = \frac{C^* U z_i}{Q} \]
Open Terrain Validation
(CWIC Vertical Profile Calculations)

Weil et al. (2012) Analysis

GPU-LES Vertical Profiles of CWIC

Dimensionless Downwind Distance

\[ X = \frac{w_x x}{U z_i} \]

Concentration

\[ CWIC = \frac{C^* U z_i}{Q} \]

Open Terrain Validation
(Surface Cross Wind Integrated Concentration (CWIC) Calculations)

Weil et al. (2012) Analysis

Dimensionless Downwind Distance

\[ X = \frac{w_{x,x}}{U z_i} \]

Concentration

\[ CWIC = \frac{C^v U z_i}{Q} \]

Open Terrain Validation
(Surface Cross Wind Dispersion Calculations)

Weil et al. (2012) Analysis

Dimensionless Downwind Distance

$$X = \frac{w_s x}{U z_i}$$

GPU-LES Surface Cross Wind Dispersion

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Open Terrain Validation
(Surface Vertical Dispersion Calculations)

Weil et al. (2012) Analysis


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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/m²
  - 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

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/m²
  - 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)