# J19.6 Integrating a complete Lagrangian dispersion model into an urban GPU-based simulation system

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## Introduction

A GPU (Graphics Processing Unit) based Lagrangian dispersion model, GPU Plume, has been developed to model the turbulent dispersion of a passive scalar in urban environments. GPU Plume is based on the Langevin equations for transport and dispersion of a passive scalar. The mean wind field required for solving the Langevin equations is obtained from a diagnostic wind model, QUIC-URB - the wind model of QUIC (Quick Urban and Industrial Complex) dispersion modeling system (see Pardyjak et al., 2001a&b; Pardyjak et al., 2002; Pardyjak et al., 2003; Gowardhan et al., 2007; Singh et al., 2008; Singh et al., 2004; Bagal et al., 2004a; Bagal et al., 2004b). QUIC-URB wind model is a fast response 3D wind model that computes a mass consistent mean wind field (using empirical parameterizations) around buildings in an urban setting.

In the previously reported validation studies, our team has shown that the GPU based Lagrangian dispersion model reduces simulation time by two orders of magnitude as compared with the CPU version of the code (Willemsen et al., 2007; Pardyjak et al.,2007). The highly parallel and inexpensive data processing present on the GPU are utilized to enhance the performance of the GPU Plume model. In addition to enhanced performance, computations on the GPU allow for rapid visualization of the particle field. The authors and their colleagues are presently using the methodology developed here to model environmental flows in virtual environments (Kulkarni et al., 2007). Specifically, the dispersion model developed here is being integrated into a novel environmental wind tunnel that allows users to explore a virtual city and experience realistic wind and scalar (e.g. odors). This haptic visualization tool is called the Tread Port Active Wind Tunnel (TPAWT) and can be utilized for applications such as emergency response training exercises.

The current GPU Plume model utilizes the simplified Langevin equations based on the assumptions of a horizontally homogenous flow. To apply these simplified Langevin equations to a complex flow field encountered in urban areas, the coordinate system must be aligned in the direction of the streamlines to partially accommodate the horizontally homogenous flow assumptions (Williams et al., 2004). However, the complex building configurations present in the urban areas generates complex flow field having strong velocity gradient (e.g. shear layers, strong vortices). To fully describe the dispersion in the urban areas, the 3D generalized Langevin equations (GLEs) (Thomson, 1987; Wilson et al., 1996; Rodean, 1996; Yee et al., 2006) model without the horizontally homogenous assumptions are required.

In the work presented here, an attempt has been made to implement the 3D GLEs in a modified version of the GPU Plume model. This paper presents preliminary results obtained from two idealized baseline test cases to validate the performance of the GPU Plume based on the GLEs against available analytical solutions for simple flows.

## Methodology

GPU Plume is based on QUIC-Plume (Williams et al., 2004) – the dispersion model of the QUIC dispersion modeling system. The mean turbulence field required for solving the GLEs is obtained from the mean wind field by utilizing a turbulence model based on the Prandtl (1945) mixing length theory (see Williams et al., 2004).

The structure and organization of the programs written for the GPU is significantly different from that of programs written in C or FORTRAN for standard CPUs. To take advantage of the highly parallel stream processing elements of the GPU, particle dispersion parameters must comply with the constraints imposed by the GPU architecture. For the model presented here, code is written in a combination of Open GL and C++. Further information on the structure and organization of GPU Plume can be found in Willemsen et al. (2007) and Pardyjak et al. (2007).

The 3D GLEs are considered to be stiff stochastic differential equations, i.e. these equations consist of several widely different rate constants or time scales which tend to cause numerical instabilities (Yee et al., 2006). For

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solving the stiff 3D GLEs, the GPU Plume utilizes the fractional step methodology outlined by Yee et al. (2006). For further details on the solution method, please refer to Yee et al. (2006).

**Model Evaluation**

The performance of the GPU Plume model has been evaluated against two idealized test cases. The primary goal of these validations was to ensure the performance of the GPU Plume with the newly implemented 3D GLEs against the available analytical solutions.

a. *Test case-I: Continuous release in uniform flow:*

In this test case, the performance of GPU Plume has been tested against an existing analytical solution for an elevated continuous point source release in a uniform flow. The normalized concentration profiles from the GPU Plume calculations have been compared against the classical Gaussian solution (Seinfeld et al., 1998) for a steady state, horizontally homogenous, neutral atmospheric stability, constant wind speed, and constant eddy diffusivity (see Singh et al., 2004 for details). For this test case, the turbulence model of GPU Plume was simplified for the horizontally homogenous and constant eddy diffusivity conditions (Willemsen et al., 2007). The plume parameters required to run the test case have been described in detail by Singh et al. (2004).

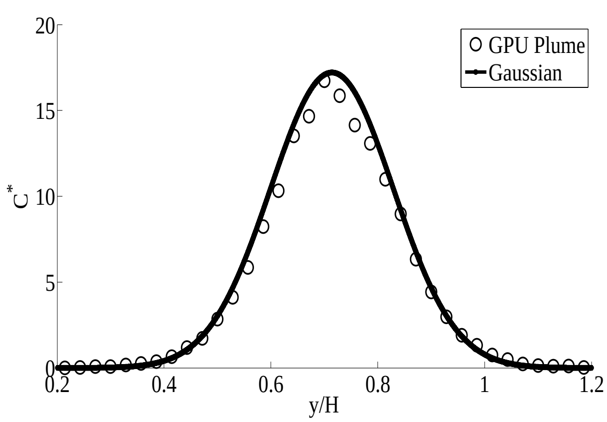


Figure 1: Lateral normalized concentration profile comparison between GPU Plume and Gaussian Solution at *x/H*=0.964.

To obtain near statistically stationary concentration estimates, 100,000 particles were continuously released from a spherical source (0.2*m* diameter) at a height, *H*= 70*m*. The rate of emission was 100 particles per second with a time step of 1 second (*dt* = 1*s*) for a duration of 1000*s*.

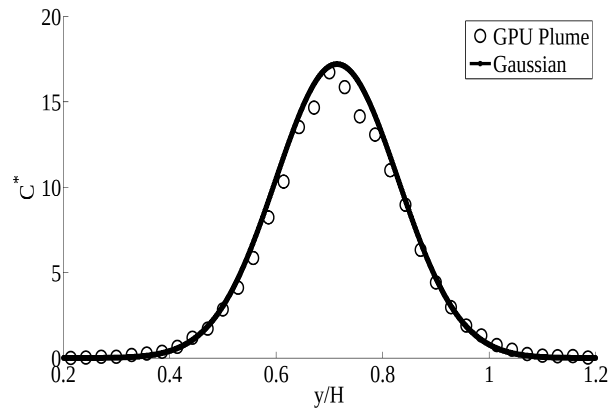


Figure 2: Lateral normalized concentration profile comparison between GPU Plume and Gaussian Solution at *x/H*=1.179.

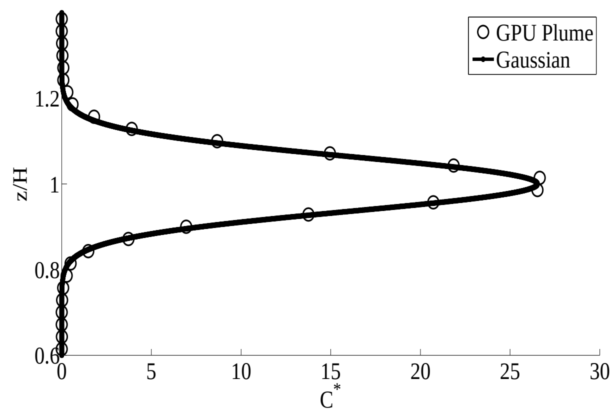


Figure 3: Vertical normalized concentration profile comparison between GPU Plume and Gaussian Solution at *x/H*=0.964.

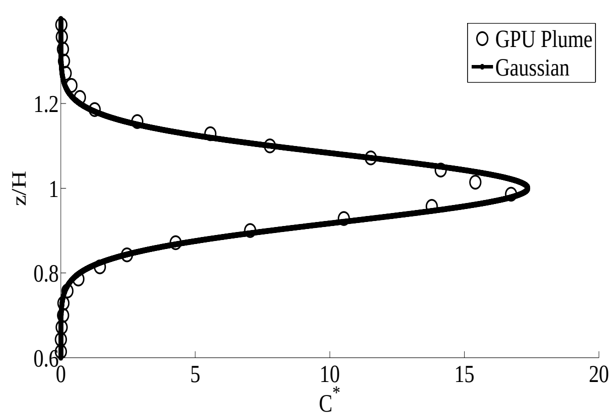


Figure 4: Vertical normalized concentration profile comparison between GPU Plume and Gaussian Solution at *x/H*=1.179.

The uniform wind speed was, *U*=2*m/s*, with a friction velocity of, $u_*$=0.18*m/s*. The concentration was averaged over 800 seconds with a starting time of 200 seconds after the beginning of the release. The physical domain was broken up into a 20, 50 and 50 sampling boxes in *x*, *y* and *z* directions respectively over a domain size of 100 m X 100 m X 100 m. The source was specified to be at *x*=20*m*, *y*=50*m* and *z*=*H*=70*m*.

Figures 1 and 2 shows the lateral concentration profiles at two streamwise locations (*x/H*=0.964 and *x/H*=1.179). The concentration has been normalized ($C^* = CUH^2/Q$) for comparison purposes. The lateral profiles are in agreement with the analytical solution. Similar trends have been observed in the vertical profiles (Figures 3 and 4).

*b. Test case-II: Continuous release in a power-law boundary layer flow:*

In this test case, the performance of GPU Plume has been tested against an existing analytical solution for a continuous point source release in a boundary layer flow. The emission source was relatively close to the ground (*H*=4*m*) to allow reflection of the emitted particles off the ground.

The normalized concentration profiles from the GPU Plume calculations have been compared against the classical Non-Gaussian solution (Brown et al., 1993) for a steady state, horizontally homogenous, neutral atmospheric stability, power law wind profile and power law eddy diffusivity (see Singh et al., 2004 for details). The plume parameters required to run the test case have been described in detail by Singh et al. (2004).

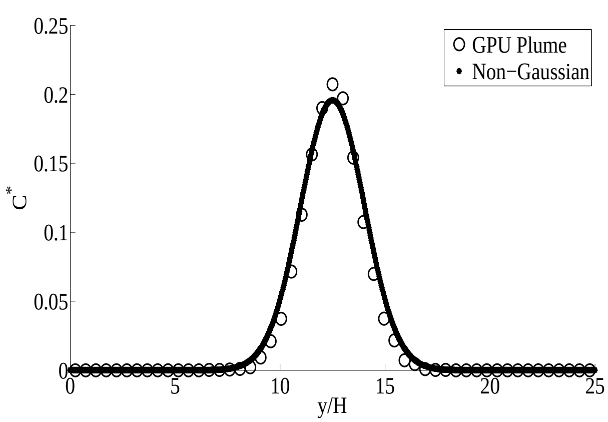


Figure 5: Lateral normalized concentration profile comparison between GPU Plume and Non-Gaussian Solution at *x/H*=10.97.

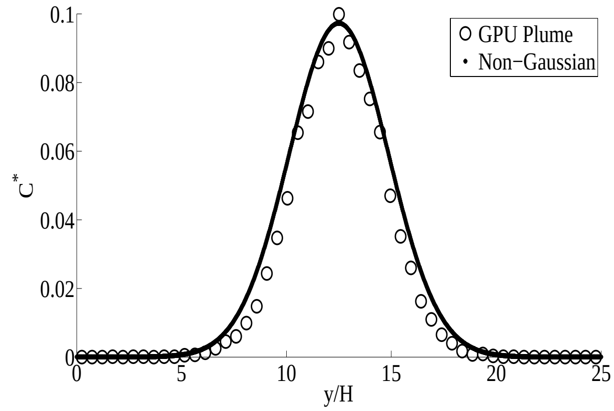


Figure 6: Lateral normalized concentration profile comparison between GPU Plume and Non-Gaussian Solution at *x/H*=19.31.

To obtain near statistically stationary concentration estimates, 100,000 particles were continuously release from a point source. The rate of emission was 100 particles per second with a time step of 1 second (*dt* = 1*s*) for a duration of 1000*s*. The power law exponent for the velocity profile was 0.15 with a reference velocity, U=5.90*m/s* at a reference height, H=4*m*. The concentration was averaged over 800 seconds with a starting time of 200 seconds after the beginning of the release. The number of sampling boxes in the *x*, *y* and *z* directions were 18, 51 and 20 respectively over a domain size of 100 m X 100 m X 20 m. The source was specified to be at *x*=20*m*, *y*=50*m* and *z*=*H*=4*m*.

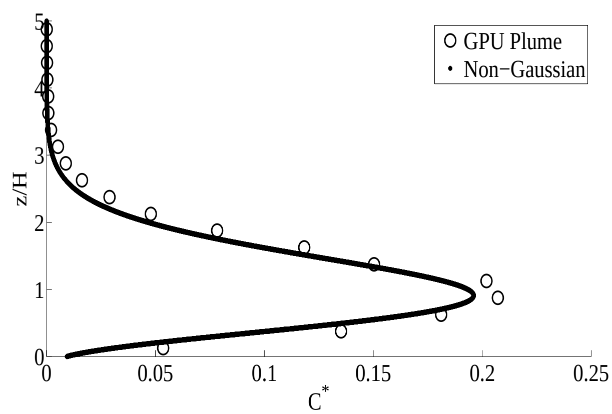


Figure 7: Vertical normalized concentration profile comparison between GPU Plume and Non-Gaussian Solution at *x/H*=10.97.

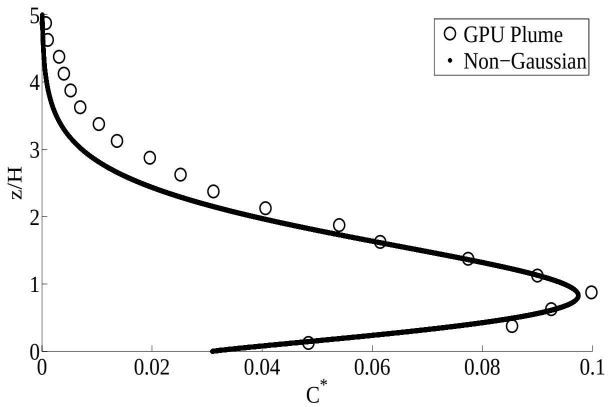


Figure 7: Vertical normalized concentration profile comparison between GPU Plume and Non-Gaussian Solution at *x/H*=19.31.

Figures 4 and 5 shows the lateral concentration profiles at two streamwise locations (*x/H*=10.97 and *x/H*=19.31). The concentration is normalized ($C^* = CUH^2 / Q$) for the comparison purposes. The lateral profiles are in agreement with the analytical solution. Similar trends have been observed in the vertical profiles (Figures 6 and 7).

**Summary and future work**

The purpose of this work was to evaluate the GPU Plume Lagrangian dispersion model with the newly implemented 3D GLEs under certain set of idealized conditions. This was accomplished by comparing the GPU plume results with the Gaussian and Non-Gaussian analytical solutions using uniform and power-law wind profiles, respectively. Comparisons of lateral and vertical profiles of concentration show that the GPU Plume model matches both the Gaussian and non-Gaussian solutions well. In future, we will present validation studies for a more realistic urban geometry.

**References**

Bagal, N., Pardyjak, E.R., Singh, B. and Brown, M.J., 2004a. Implementation of rooftop recirculation parameterization in the QUIC fast response urban wind model. in Fifth AMS Symp. Urban Env. Vancouver, BC.

Bagal, N., Pardyjak, E.R. and Brown, M.J., 2004b. Improved Upwind Cavity Parameterization for a Fast Response Urban Wind Model. in 84th Annual AMS Meeting. Seattle, WA.

Brown, M.J., P. Arya, and W.H. Snyder, (1993) "Vertical Dispersion from Surface and Elevated Releases: An Investigation of a Non-Gaussian Plume Model", J. Appl. Meteor., 32,490-505.

Gowardhan, A.A., Brown, M.J. and Pardyjak, E.R., 2007. Evaluation of a fast response pressure solver for flow around an isolated cube, submitted to J. Wind Eng. Ind. Aerod.

Kirkman, R., M. Deaver, E. Pardyjak & M. Metzger, 2007: Sensitivity Analysis of a Three-Dimensional Wind Tunnel Design, 2006 ASME Joint U.S.-European Fluids Engineering Summer Meeting, FEDSM 2006, July 17-20, Miami, FL, pp. 10.

Kulkarni, S.D., M.A. Minor, M.W. Deaver & E.R. Pardyjak, 2007: Output feedback control of wind display in a virtual environment, Proc. IEEE Intl. Conf. Robotics and Automation, Rome, Italy, April 10-14, 2007.

Nelson, M.A., B. Addepalli, D. Boswell, M.J. Brown, 2006: The QUIC v. 4.5 Start Guide. LA-UR-07-2799.

Pardyjak, E.R., B. Singh, A. Norgren and P. Willemsen, 2007. Using Video Gaming Technology to Achieve Low-cost Speed up of Emergency Response Urban Dispersion Simulations. AMS Conf. on Urban Air Quality and Dispersion Studies, San Diego, CA, USA.

Pardyjak, E. and M. Brown, 2002. Fast response modeling of a two building urban street canyon, 4th AMS Symp. Urban Env., Norfolk, VA, May 20-24 2002, LA-UR-02-1217.

Pardyjak, E.R., N. L. Bagal and M. J. Brown, 2003.Improved velocity deficit parameterizations for a fast response urban wind model, AMS Conf. on Urban Zone, Seattle, WA, LA-UR-03-8512.

Pardyjak, E. and M. Brown, 2001a. Evaluation of a fast response urban wind model – comparison to single-building wind-tunnel data, Int. Soc. Environ. Hydraulics, Tempe, AZ, Dec. 2001, LA-UR-01-4028, 6 pp.

Pardyjak, E. and M. Brown, 2001b. Evaluation of a fast response urban wind model – comparison to single-building wind-tunnel data, Int. Soc. Environ. Hydraulics, Tempe, AZ, Dec. 2001, LA-UR-01-4028, 6 pp.

Pardyjak, E.R. & M. Brown, 2002: Fast response modeling of a two building urban street canyon, 4th AMS Symp. Urban Env., Norfolk, VA.

Rodean, H.C., 1996: Stochastic Lagrangian models of turbulent diffusion, The American Meteorological Society, Boston, MA, pp. 82.

Seinfeld, J.H. and S.N. Pandis, 1998. Atmospheric Chemistry and Physics, John Wiley and Sons, Inc., New York, pp.1326

Singh, B., Hansen, B., Brown, M.J. and Pardyjak, E.R., Evaluation of the QUIC-URB Fast Response Urban Wind Model for a Cubical Building Array and Wide Building Street Canyon, Environmental Fluid Mechanics, 8(4), 281-312, 2008.

Singh, B., M.D. Williams, E.R. Pardyjak and M.J. Brown, 2004. Testing of an urban Lagrangian dispersion model using Gaussian and non-Gaussian solutions, in 4th AMS Symp. Urban Env. Norfolk, VA.

Thomson, D. J., 1987. Criteria for the selection of stochastic models of particle trajectories in turbulent flows. J. Fluid Mech., 180, 529–556.

Willemsen, P., A. Norgren, B. Singh and E.R. Pardyjak, 2007: Development of a new methodology for improving urban fast response Lagrangian dispersion simulation via parallelism on the graphics processing unit. Proceedings of the 11th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Queen's College, University of Cambridge, United Kingdom, July 2-5, 2007.

Williams, M.D., M.J. Brown & E.R. Pardyjak, 2002: Development and testing of a dispersion model for flow around buildings. in 4th AMS Symp. Urban Env. Norfolk, VA.

Williams, M.D., M.J. Brown, B. Singh & D. Boswell, 2004: QUIC-Plume Theory Guide. LANL Report: LA-UR-04-0561

Wilson, J. D. and B.L. Sawford, 1996. Review of Lagrangian Stochasitc Models for Trajectories in the Turbulent Atmosphere, Boundary-Layer Meteorol. 78, 191–210.

Yee, E and J.D. Wilson, 2006. Instability in Lagrangian stochastic trajectory models, and a method for its cure, Boundary-Layer Meteorology. 122, 243-261