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Multi-GPU-based CityFFD Solver for Urban Microclimate Simulations

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ABSTRACT

Real-time, high-fidelity computational fluid dynamics (CFD) simulations for urban microclimate analysis remain challenging due to constraints in computational resources, difficulties in data collection, and the use of oversimplified physical models. Lately, with rising interest in smart city initiatives—such as urban air mobility (UAM) integration and advanced urban planning—the need for fast, high-resolution microclimate analysis has become more urgent. For example, simulating a typical urban area of 5 km × 5 km × 0.1 km (length × width × height) with a 1 m^3 grid resolution requires around 2.5 billion grid cells, leading a massive load on both computational resources and memory that is impractical with current technology.

To address these computational constraints, this study introduces a new computational framework that combines the Message Passing Interface (MPI) and Compute Unified Device Architecture (CUDA) C++ with the CityFFD solver. This integration enables scalable, GPU-accelerated parallel simulations, significantly improving efficiency for large-scale computations while alleviating memory bottlenecks. The framework features a parallel high-order Semi-Lagrangian (SL) solver for efficiently solving advection equations with large CFL (Courant–Friedrichs–Lewy) values, a modified PaScal_TDMA 2.0 library for distributed tridiagonal matrix algorithm (TDMA) calculations, and an enhanced parallel Jacobi algorithm with improved convergence properties for solving the Poisson equation. These components collectively make the framework well-suited for scalable, GPU-accelerated parallel environments.

The proposed solver is evaluated through three benchmarks: (1) a 3D isothermal lid-driven cavity problem, (2) a 3D isolated building, and (3) a 3D high-rise building surrounded by low-rise buildings.