Peta-scale Large-Eddy Simulation for Wind Blowing in a Wide Area of Tokyo with 2-m Resolution by Using GPU-based Lattice Boltzmann Method on TSUBAME2.0

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Background

Wind behavior in a city directly affects the living condition and health of human beings.

- Acceleration in urbanization and rapid growth of *mobile vehicles* result in serious problem of air quality in urban residence areas.
- In the event of an *NBC* (Nuclear, Biological and Chemical weapons) terrorist attack or an accidental gas leakage from a chemical facility in an urban area.
- Many complex thermally-induced flows, such as natural convection flows, land-sea breezes, mountain-valley winds, and UHI (urban heat island) circulations occur over the complex terrain in a city.
- Urban areas should be *design*ed to ensure the comfort, health and safety of their inhabitants and users. *Wind comfort and wind safety* for pedestrians are important requirements for urban areas.

Major tools: field observation, laboratory model test and numerical simulation.

Numerical simulation is less cost and more flexible in prescribing atmospheric parameters and emission conditions.

LES Turbulent Modeling

Coherent-structure Smagorinsky model (CSM) is a sofisticated turbulent model suitable for complex geometries and GPU computation.

× Conventional Smagorinsky model with a constant coefficient: **inaccurate**

× Dynamics Smagorinsky model (including Lagrangian) with a coefficient determined by taking wide-area average: **too expensive**

○ Coherent-structure Smagorinsky model can determine a model coefficient locally.

Subgrid-scale viscosity

$$\nu_{SGS} = C\Delta^2|S|$$

$$|S| = \left(\sum 2S_{\alpha\beta}S_{\alpha\beta}\right)^{1/2} \quad S_{\alpha\beta} = \frac{-3}{2\rho\tau}\sum_i (f_i - f_i^{eq})c_{i\alpha}c_{i\alpha}$$

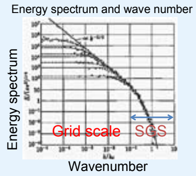
SGS model →

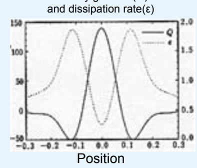
Coherent-structure Smagorinsky model

$$C = C_{CSM}|F_{CS}|^{3/2} \quad Q = -\frac{1}{2}\frac{\partial \bar{u}_j}{\partial x_i}\frac{\partial \bar{u}_i}{\partial x_j}$$

$$F_{CS} = \frac{Q}{E} \quad (-1 \le F_{CS} \le 1) \quad E = -\frac{1}{2}\left(\frac{\partial \bar{u}_j}{\partial x_i}\right)^2$$

Coherent-structure function





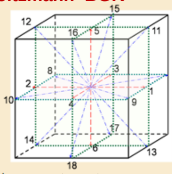
Lattice Boltzmann Method

Incompressible flow studies based on Lattice Boltzmann BGK Equation.

- Linear, microscopic, explicit time integration
- Limited directions in the velocity space and specified local equilibrium distribution function.

$$\frac{\partial f_i}{\partial t} + \mathbf{e}_i \cdot \nabla f_i = -\frac{1}{\tau}\left(f_i - f_i^{eq}\right) \qquad \text{D3Q19}$$

$$f_i^{eq} = \rho w_i\left[1 + \frac{3}{c^2}(\mathbf{e}_i\cdot\mathbf{u}) + \frac{9}{2c^4}(\mathbf{e}_i\cdot\mathbf{u})^2 - \frac{3}{2c^2}(\mathbf{u}\cdot\mathbf{u})\right] \qquad \nu = \left(\tau - \frac{1}{2}\right)c_s^2\delta t$$



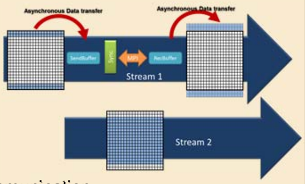
- Suitable for **GPU** computing

$$\tilde{f}_i(\mathbf{x},t) = f_i(\mathbf{x},t) - \frac{1}{\tau}\left(f_i(\mathbf{x},t) - f_i^{eq}(\mathbf{x},t)\right)$$

Collision Step: purely local

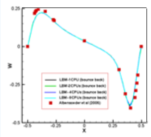
$$f_i(\mathbf{x} + \mathbf{e}_i\Delta t, t + \Delta t) = \tilde{f}_i(\mathbf{x},t)$$

Streaming Step: Uniform data shifting

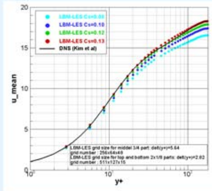


- **CUDA Program Tuning**:
  Overlapping computation with communication
  Kernel fusion of the collision step and streaming step
  Loop unrolling to save resister usage
  Using SFU (Super Function Unit) and single-precision computation

Validation



- Cavity flow Re=1000



- Channel flow: Re=180
  LBM+ LES+ grid refinement
  256x 64x 48 + 512x127x15(x2)

- Turbulent flow behind a sphere
  Re=10^4,GPU=98 , grid:2x10^9

TSUBAME 2.0 Overview

- Total Peak Performance: **2.4** Pflops
- Total GPU (Fermi core) : **4224**
- Fat-tree type Interconnection: **200** Tbps (Full bi-section bandwidth)
- Compute nodes: **1408**
- Node performance: **1.7** TFlops
  GPUs/node: **3** NVIDIA Tesla **M2050**
  CPUs/node: 2 Intel Xeon X5670
  2 Infiniband QDR/node: 4.0 GB/sec × 2
  Video Memory: **3GB** × 3.

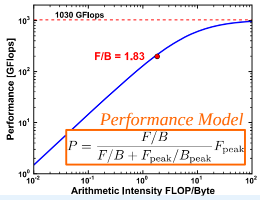
Scale-up Estimation

- Using the whole **TSUBAME2.0** resource, a possible mesh is **16,000** x **16,000** x **192** with 12 TByte memory and the computational time will be 288 min.
- Using the whole **K-computer** resource, a computation **160,000** x **160,000** x **192** (1.28 PByte) covering the major part of Kantou area with 1m mesh becomes possible.
- It will cost **2880** min to compute this area with 1m resolution for the real **60** min.

Performance: Scalability on TSUBAME2.0

Improved Roofline Model

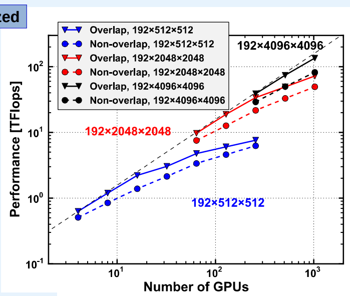
- F = Number of FP operations for applications (= 476)
- B = Byte number of memory access for applications (= 260 Byte)
- F_{peak}= Peak Performance of FP operation (M2050: 1030 GFlops)
- B_{peak}= Peak Memory Bandwidth M2050: 148 Gbyte/sec)



Our LBM code is fully optimized

Strong Scalability

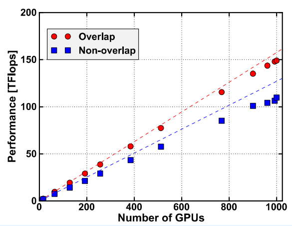
- Overlapping method can successfully hide the communication cost and has improved the strong scalability on TSUBAME 2.0.



Weak Scalability

A performance of 149 TFlops on 1000 GPUs was achieved by using overlapping method

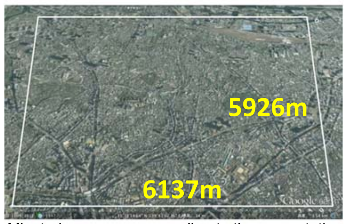
149 TFlops!!!



Simulation Result of Wind Blowing in a Wide Area of Tokyo

- Area location: E: 139.33˚ , N: 36˚ (Minato-Ku); 6137 m x 5926 m, Highest building: H_{max}=123 m;
- Resolution : 2 meter / grids;
- Grids: **6144 x 5760 x 200** using 3D decomposition;
- GPU numbers: **768** (3GPUs/node);
- Re = **10^6** $U_0(z)=U_{top}(z/H_{max})^{0.2}$
- Evolution time : 10000 LBM time step;

Computational time: 1200 s
Communication time: 300 s



Minato-ku area corresponding to the computation

Future work: Design for an ultragreen supercomputer TSUBAME3.0

References

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