Multi-scale Wind Forecasting Research

İnanç Şenocak

15 September 2011

Wind Working Group Meeting, Boise Idaho
Acronyms

- GPU: Graphics Processing Unit (video card)
- CPU: Central Processing Unit (Intel, AMD)
- CFD: Computational Fluid Dynamics
- CUDA: Compute Unified Device Architecture
  - Language to program massively parallel GPUs from NVIDIA
- Re: Reynolds number = $\frac{U*L}{\nu}$
Why short-term wind forecasting?

- Wind power is intermittent
  - Need to balance load and generation
  - Balancing becomes challenging with increasing wind generation capacity

- Wind power is not dispatchable

- Utilities schedule generation and transmission by the hour

- Need advanced notification for wind ramps

- Forecasting is another way of storing energy

- Can be used to increase existing power line capacity
  - Dynamic vs. Static rating
Dynamic rating of power lines

\[
\frac{dT_c}{dt} = \frac{1}{mC_p} \left[ q_s(t) + I^2(t)R(T_c) - q_c(t, T_c, T_a, V_w, \theta) \right],
\]
Structure of Atmospheric Boundary Layer

- **Outer layer**
  - Length scale $\sim h$
  - Time scale $\sim$ few hours or less

- **Inertial sublayer**
  - Length scale $<< h$

- **Roughness sublayer**

- Much more complex than a BL in aerodynamics
  - Thermal convection due to heat & moisture exchange at the surface, radiation, shallow cloud formation
  - Earth’s rotation
  - Complex topography

- **Surface layer**
  - $Z=100-3000 \text{ m}$
  - $Z=0.1 \text{ h}$
Flow over Mountainous Terrain: Day vs. Night

Diurnal Cycle

Convective Boundary Layer (CBL)

Fig. 1.4. Schematic of convective boundary layer circulation and entrainment of air through the capping inversion (from Wyngaard, 1990).

Source: Wyngaard (1990)
Stable Boundary Layer (SBL)

Fig. 1.5. Schematic of stable boundary layer flow showing eddy structure, waves, and elevated inversion layer (from Wyngaard, 1990).

Source: Wyngaard (1990)
Fig. 1.1. Mean vertical profiles of wind speed, wind direction, and potential temperature in the convective boundary layer.
SBL Profiles

Fig. 1.2. Mean vertical profiles of wind speed, wind direction, and potential temperature in the stable boundary layer.
Flow past a ridge

Source: Kaimal & Finnigan (1994)
Multi-scale Short-term Wind Forecasting Engine
GPU Computing Infrastructure at BSU

An end-to-end approach to simulation science
Simulation Engine for Multiscale Wind Forecasting
CPU vs. GPU

All performance numbers are theoretical peak!

Courtesy of NVIDIA
# The Top 5 from TOP500 (June 2011)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Site</th>
<th>Computer/Year Vendor</th>
<th>Cores</th>
<th>$R_{\text{max}}$</th>
<th>$R_{\text{peak}}$</th>
<th>Power (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RIKEN Advanced Institute for Computational Science Japan</td>
<td><strong>K computer</strong> - SPARC64 VIIIfx 2.0GHz, Tofu interconnect Fujitsu</td>
<td>548352</td>
<td>8162</td>
<td>8773</td>
<td>9899</td>
</tr>
<tr>
<td>2</td>
<td>National Supercomputing Center in Tianjin China</td>
<td><strong>Tianhe-1A</strong> - NUDT TH MPP, X5670 2.93Ghz 6C, <strong>NVidia GPU</strong>, FT-1000 8C</td>
<td>186368</td>
<td>2566</td>
<td>4701</td>
<td>4040</td>
</tr>
<tr>
<td>3</td>
<td>Oak Ridge National Laboratory United States</td>
<td><strong>Jaguar</strong> - Cray XT5-HE Opteron Six Core 2.6 GHz</td>
<td>224162</td>
<td>1759</td>
<td>2331</td>
<td>6951</td>
</tr>
<tr>
<td>4</td>
<td>National Supercomputing Centre in Shenzhen (NSCS) China</td>
<td><strong>Nebulae</strong> - Dawning TC3600 Blade, Intel X5650, <strong>NVidia Tesla</strong> C2050 GPU</td>
<td>120640</td>
<td>1271</td>
<td>2984</td>
<td>2550</td>
</tr>
<tr>
<td>5</td>
<td>GSIC Center, Tokyo Institute of Technology Japan</td>
<td><strong>TSUBAME 2.0</strong> - HP ProLiant SL390s G7 Xeon 6C X5670, <strong>Nvidia GPU</strong>, Linux/Windows</td>
<td>73278</td>
<td>1192</td>
<td>2287</td>
<td>1399</td>
</tr>
</tbody>
</table>
GIN3D: GPU-accelerated Incompressible Navier-Stokes 3D solver

- Designed for multi-GPU
  - 4+ years effort
- Bouyancy-driven incompressible flows
- Multi-GPU parallel
  - Phtreads-CUDA
  - MPI-CUDA (three flavors)
  - Hybrid MPI-OpenMP-CUDA
- Time advancement
  - 2nd order Adams-Bashforth
  - 1st order Euler

- Advection schemes
  - Staggered uniform mesh
  - 2nd order central difference
  - 1st order upwind

- Poisson Equation
  - Jacobi (initial efforts)
  - Multi-GPU parallel multigrid

- Complex terrain
  - DEM files for terrain
  - GIS files for urban areas
  - Embedded boundary (on-going)

- Turbulence modeling
  - Dynamic LES model
Performance of three generations of GPU

GIN3D Performance on Lid Driven Cavity
1024 x 16 x 1024

Number shows speedup over 1 CPU
Turbulence Closure / Subgrid-scale modeling

\[
\frac{\partial (u_i)}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \nu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right]
\]

Reynolds averaging (RANS) or filtering (LES)

\[
\tau_{ij} = \overline{u'_iu'_j} = u_i u_j - \overline{u_i} \overline{u_j}
\]

\[
\tau_{ij} = -2\nu_T \overline{S_{ij}} \quad \text{Eddy viscosity}
\]

\[
\nu_T = C_\mu \frac{k^2}{\varepsilon} \quad \text{RANS, k-\varepsilon}
\]

\[
\nu_T = C \Delta^2 \vert S \vert \quad \text{LES, Smagorinsky}
\]
Large-eddy Simulation of Turbulent Flows

Re=180

Mean Velocity Profile on a Uniform Grid

Re=300
Neutrally stratified PBL
Mean wind profile

Mean flow structure:
- Logarithmic velocity profile within surface layer (150-200 m)
- Ekman spiral due to rotation of the Earth

Senocak et al. (2007), BLM
Preliminary Results: IPCo/INL Collaboration
Preliminary Results
Thank you!