High Performance Computing of MSSG and its Physical Performance

Keiko Takahashi, Ryo Onishi, Takeshi Sugimura, Yuya Baba, Shinichiro Kida, Koji Goto and Hiromitsu Fuchigami
Earth Simulator Center, Japan Agency of Marine-Earth Science and Technology (JAMSTEC)
NEC Cooperation, NEC Informatec Systems LTD
Outline of Seamless Simulations with MSSG

Positive Dipole Mode

Negative Dipole Mode

Urban area

Bay and Kuroshio area

Japan region

with MSSG

Global warming

2020-29

2090-99

Earth

with MSSG

Extremes

Source: Intergovernmental Panel on Climate Change

The New York Ti

Bay and Kuroshio area

Urban area

with MSSG

Japan region

with MSSG
Multi-Scale Simulator for the Geoenvironment (MSSG)

Scalability

Seasonal ~ Annual Projection
2-40 km for horizontal, 100 vertical layers

Urban Weather/Climate Forecasting
$O(1)m \sim O(100)m$ for horizontal, 200 vertical layers
(Data: Geographical Survey Institute)

Days ~ Weeks forecasting
Typhoon, Baiu rain etc.
$O(100) \ m \sim 2\ km$ for horizontal
100 vertical layers
Results from MSSG on Google Earth
Our Grand Challenge

Prediction/Forecasting

Unser the Global Warming
Under the IOD/ El Nino
⇔ Seasonal Forecasting, Regional Climate
Urban Climate

Impact of
Cloud Scale Synoptic Scale
Weather Climate Change

For Seamless Simulation between Weather and Climate

MSSG
(Multi-Scale Simulator for the Geoenvironment)
Coupled Atmosphere-Ocean-Land Model as “Google Earth Model”

• Key words:
  - Down-scaling & Up-scaling
  - Climate/Seasonal Variability
  - Atmosphere-Ocean Interactions
  - Urban weather/climate
# Earth Simulator (ES2)

## Hardware

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak performance/CPU</td>
<td>102.4 Gflops</td>
</tr>
<tr>
<td>Peak performance/PN</td>
<td>819.2 Gflops</td>
</tr>
<tr>
<td>Shared memory/PN</td>
<td>128 GByte</td>
</tr>
<tr>
<td>CPUs/PN</td>
<td>8</td>
</tr>
<tr>
<td>Total number of CPUs</td>
<td>1280</td>
</tr>
<tr>
<td>Total number of PNs</td>
<td>160</td>
</tr>
<tr>
<td>Total peak performance</td>
<td>131 Tflops</td>
</tr>
<tr>
<td>Total main memory</td>
<td>20 TByte</td>
</tr>
</tbody>
</table>

**Interconnection Network**

(Fat-Tree 8GB x 8 x 2)
Ultra High Resolution Simulation

Global Simulation
Regional Simulation

Up to the Limitation of Computational Power of the Earth Simulator
Grid System
Yin-Yang Grid System

- Orthogonal coordinates.  (same as the lat-lon geometry)
- No polar singularity.
- Relax of CFL condition.
- The same grid structure of N and E component.
- Easy to nest.
- High parallelization.
- But need to take care of conservation law.

Mass conserving numerical scheme

For flux $F_{EF}$ on a circular arc EF shown as red circle is computed by the budget of fluxes $f_N$ by on grid ABCD of N system and flux $f_E$ estimated on a circular arc GHI of E system.

Computation all of fluxes on computational grids  
Correction for conserving


This conservative scheme, we have evaluated that time evolution of relative error of the mass has changed within the limit of rounding error.
Wave propagation characteristics on overset grid system

High order computational schemes and interpolation are required.

Dispersion relation is important to avoid errors on interface of overset grid system.
Global Atmosphere Simulation with MSSG-A
03-08AUG2003, Horizontal resolution: **1.9 km**, 32 vertical layers
05 Oct 2009
Horizontal resolution: 2.6 km for global
32 vertical layers
Ocean Component of Multi-Scale Simulator for the Geoenvironment: MSSG-O

The Northern Pacific Ocean

Horizontal Resolution: 2.78km, Vertical Layers: 40 layers, 15 years integration
Boundary condition: monthly data from NCAR
monthly data from OFES simulation (10km global simulation)
Simulation Results in Coastal Region with MSSG-O
The Northern Pacific Ocean nesting to Japan region

Horizontal: 11 km, 40 vertical layers

Tokyo Bay

Horizontal: 850 m, 40 vertical layers

Tokyo Bay

08/01 06:00 UTC

Tokyo Bay

08/01 06:00 UTC
### Outline of MSSG

<table>
<thead>
<tr>
<th></th>
<th><strong>MSSG-A</strong></th>
<th><strong>MSSG-O</strong></th>
</tr>
</thead>
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<tr>
<td>governing eqs.</td>
<td>Fully compressive N-S eqs.</td>
<td>incompressive N-S eqs.</td>
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<tr>
<td>grid system</td>
<td>Yin-Yang grid (overlapped 2 lat-lon)</td>
<td>Yin-Yang grid (overlapped 2 lat-lon)</td>
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<td>discretization</td>
<td>Arakawa-C grid (horizontal), $Z^*$ (vertical)</td>
<td>Arakawa-C grid (horizontal), $Z^*$ (vertical)</td>
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<td>time</td>
<td>$3^{rd}/4^{th}$ Runge-Kutta</td>
<td>$3^{rd}/4^{th}$ Runge-Kutta</td>
</tr>
<tr>
<td>adv. schemes</td>
<td>5$^{th}$ flux form, WAF, CIP-CSLR</td>
<td>5$^{th}$ flux form</td>
</tr>
<tr>
<td>non-adv. schemes</td>
<td>4$^{th}$ flux form</td>
<td>4$^{th}$ flux form</td>
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<tr>
<td>sound wave</td>
<td>HEVI, HIVI</td>
<td>Implicit methods (2D, 3D)</td>
</tr>
<tr>
<td>microphysics</td>
<td>Bulk method ($Q_c, Q_r, Q_i, Q_s, Q_g$)/hybrid-Bin method</td>
<td>-</td>
</tr>
<tr>
<td>turbulence model</td>
<td>static Smagorinsky scheme</td>
<td>static Smagorinsky model</td>
</tr>
<tr>
<td>other models</td>
<td>cloud radiation model, bucket land model, UCSS urban canopy model</td>
<td>sea-ice model</td>
</tr>
<tr>
<td>parallelization</td>
<td>horizontal 2D decomposition by MPI/vertical decomposition by micro-task</td>
<td>horizontal 2D decomposition by MPI/vertical decomposition by micro-task</td>
</tr>
</tbody>
</table>
Dynamical Framework (1)

- Atmosphere: Fully compressible, non-hydrostatic equations

\[
\begin{align*}
\frac{\partial \rho'}{\partial t} + \frac{1}{G^2 a \cos \varphi} \frac{\partial (G^2 \rho u)}{\partial \lambda} + \frac{1}{G^2 a \cos \varphi} \frac{\partial (G^2 \cos \varphi \rho v)}{\partial \varphi} + \frac{1}{G^2} \frac{\partial (\rho w^*)}{\partial z^*} &= 0 \\
\frac{\partial \rho u}{\partial t} + \frac{1}{G^2 a \cos \varphi} \frac{\partial (G^2 p')}{\partial \lambda} &= -\nabla \cdot (\rho u \vec{v}) + 2 f_r \rho v - 2 f_\varphi \rho w + \frac{\rho uv \tan \varphi}{a} - \frac{\rho w u}{a} + F_\lambda \\
\frac{\partial \rho v}{\partial t} + \frac{1}{G^2 a} \frac{\partial (G^2 p')}{\partial \varphi} &= -\nabla \cdot (\rho v \vec{v}) + 2 f_\lambda \rho w - 2 f_r \rho u - \frac{\rho uu \tan \varphi}{a} - \frac{\rho w v}{a} + F_\varphi \\
\frac{\partial \rho w}{\partial t} + \frac{1}{G^2} \frac{\partial p'}{\partial z^*} + \rho' g &= -\nabla \cdot (\rho w \vec{v}) + 2 f_\varphi \rho u - 2 f_\lambda \rho v + \frac{\rho uu}{a} + \frac{\rho vv}{a} + F_r \\
\frac{\partial p'}{\partial t} + \nabla \cdot (p \vec{v}) + (\gamma - 1) p \nabla \cdot \vec{v} &= (\gamma - 1) \kappa \nabla^2 T + (\gamma - 1) \Phi \\
\text{State equation} &\quad p = \rho RT \\
G^2 = \frac{\partial z}{\partial z^*} = 1 - \frac{z^*}{H} &\quad \text{is a metric term.}
\end{align*}
\]
Dynamical Framework (2)

- Ocean: in-compressive and hydrostatic equations with the Boussinesq approximation

\[
\frac{\partial c}{\partial t} = -\mathbf{v} \cdot \nabla c + F_c \quad \frac{\partial T}{\partial t} = -\mathbf{v} \cdot \nabla T + F_r
\]

\[
0 = \nabla \cdot \mathbf{v} = \left( \frac{1}{r \cos \varphi} \frac{\partial u}{\partial \lambda} + \frac{1}{r \cos \varphi} \frac{\partial (\cos \varphi v)}{\partial \varphi} + \frac{1}{r^2} \frac{\partial (r^2 w)}{\partial r} \right)
\]

\[
\frac{\partial u}{\partial t} = -\mathbf{v} \cdot \nabla u + 2 f_r v - 2 f_\varphi w + \frac{\nu u \tan \varphi}{r} - \frac{w u}{r} - \frac{1}{\rho_0 r \cos \varphi} \frac{\partial P'}{\partial \lambda} + F_\lambda
\]

\[
\frac{\partial v}{\partial t} = -\mathbf{v} \cdot \nabla v + 2 f_\lambda w - 2 f_r u - \frac{uu \tan \varphi}{r} - \frac{w v}{r} - \frac{1}{\rho_0 r} \frac{\partial P'}{\partial \phi} = +F_\varphi
\]

\[
\frac{\partial w}{\partial t} = -\mathbf{v} \cdot \nabla w + 2 f_\varphi u - 2 f_\lambda v + \frac{uu}{r} + \frac{vv}{r} - \frac{1}{\rho} \frac{\partial P'}{\partial r} - \frac{\rho'}{\rho_0} \mathbf{g} + F_r
\]

\[
\frac{d}{dr} P_0 = -\rho_0 g(r)
\]

\[
\rho = \rho(T, c, P_0) \quad (\text{: UNESCO scheme})
\]
**MSSG as a Multi-Scale Coupled Model with nesting schemes**

MSSG is available for the hierarchy of broad range of space and time scales of weather/climate phenomena as follows,

- Global non-hydrostatic atmospheric circulation model: **Global MSSG-A**
- Regional non-hydrostatic atmospheric model: **Regional MSSG-A**

- Global non-hydrostatic/hydrostatic ocean model: **Global MSSG-O**
- Regional non-hydrostatic/hydrostatic ocean model: **Regional MSSG-O**

- Coupled Global MSSG-A Global MSSG-O: **MSSG**
- Coupled Regional MSSG-A Regional MSSG-O: **Regional MSSG**

- MSSG (global) coupled with Regional MSSG using nesting schemes


## Computational Performance of MSSG on the Earth Simulator

<table>
<thead>
<tr>
<th>CASE</th>
<th>TPN</th>
<th>TAP</th>
<th>grid pts</th>
<th>MFlops/AP</th>
<th>Vector Length</th>
<th>V.OP ratio</th>
<th>Tflops</th>
<th>Peak ratio</th>
<th>Parallel efficiency</th>
<th>Speed up</th>
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<td>C</td>
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<td>4096</td>
<td></td>
<td>4166.7</td>
<td>229</td>
<td>99.3%</td>
<td>17.07</td>
<td>52.1%</td>
<td>90.0%</td>
<td>461.0</td>
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<td></td>
<td>256</td>
<td>2048</td>
<td></td>
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<td>99.3%</td>
<td>9.02</td>
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<tr>
<td>A</td>
<td>384</td>
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<td>3,866,296,320</td>
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<td>99.3%</td>
<td>13.13</td>
<td>53.4%</td>
<td>92.3%</td>
<td>354.6</td>
</tr>
<tr>
<td></td>
<td>256</td>
<td>2048</td>
<td></td>
<td>4091.9</td>
<td>229</td>
<td>99.3%</td>
<td>9.02</td>
<td>55.0%</td>
<td>94.8%</td>
<td>242.6</td>
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<td>RA</td>
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<td>57.2%</td>
<td>93.6%</td>
<td>479.1</td>
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<td>3072</td>
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<td>4666.1</td>
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<td>99.5%</td>
<td>14.15</td>
<td>57.6%</td>
<td>95.1%</td>
<td>365.2</td>
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<tr>
<td></td>
<td>256</td>
<td>2048</td>
<td></td>
<td>4692.4</td>
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<td>9.61</td>
<td>56.7%</td>
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<tr>
<td>O</td>
<td>498</td>
<td>3984</td>
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<td>17.73</td>
<td>54.3%</td>
<td>96.7%</td>
<td>464.4</td>
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<td></td>
<td>398</td>
<td>3154</td>
<td></td>
<td>4400.1</td>
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<td>13.52</td>
<td>55.0%</td>
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<td>356.6</td>
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<tr>
<td></td>
<td>303</td>
<td>2424</td>
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<td>4580.9</td>
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<td>9.34</td>
<td>57.0%</td>
<td>95.1%</td>
<td>243.5</td>
</tr>
</tbody>
</table>

C: Coupled; A: Atmos.; RA: regional Atmos.; O: Ocean

Simple linearity will be kept until 2 PFLOPS

MSSG is selected as a core application for the next Japanese flagship supercomputer with 10PFLOPS
MSSG:

**global forecasting with 11km horizontal, 40 vertical layers**

- **5 days (120 hours) integration** → about 5 hours on 48 nodes of ES2
- **3 month integration** → about 2.5 days on 80 nodes (1/2) of ES2

### Computational Performance of MSSG on the Earth Simulator

<table>
<thead>
<tr>
<th>EXCLUSIVE TIME[sec]</th>
<th>%</th>
<th>MFLOPS</th>
<th>V.OPER RATIO</th>
<th>AVER. V.LEN</th>
<th>I-CACHE MISS</th>
<th>O-CACHE MISS</th>
<th>BANK CONFLICT</th>
<th>CPU PORT</th>
<th>NETWORK</th>
<th>PROC.NAME</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(A1) main loop</td>
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<tr>
<td>19777.543</td>
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<td>18592.9</td>
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<td>256.595</td>
<td>772.348</td>
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<td>6554.572</td>
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<td>4479.512</td>
<td>22.6</td>
<td>22277.2</td>
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<td>239.2</td>
<td>90.681</td>
<td>198.871</td>
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<td>2632.633</td>
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<td>24765.7</td>
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<td>238.7</td>
<td>26.207</td>
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<td>4649.974</td>
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<td>34140.6</td>
<td>99.80</td>
<td>238.7</td>
<td>16.851</td>
<td>60.720</td>
<td>20.966</td>
<td>566.511</td>
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<td>3996.377</td>
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<td>213.7</td>
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<td>172.9</td>
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<td>3.569</td>
<td>1.977</td>
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<td>352.960</td>
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<td>448.958</td>
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<tr>
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<td>0.134</td>
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<td>0.091</td>
<td>0.001</td>
<td>0.013</td>
<td></td>
<td>(A2) restart</td>
</tr>
</tbody>
</table>

- Over 30% computational performance to theoretical peak performance of ES
- Computational cost of main loop: 18GFLOPS/1CPU
- Dynamical core (N-S eq., HEVI, tracer eq.): 60%
- Physics: 20%
- Communications: (boundary, boundary(side)): 5%
- Others: 15%
Heat, Flesh water, Momentum fluxes

MSSG-A
Horizontal: 1.9km, Vertical: 32 layers, 14 days integration

MSSG
Typhoon ETAU in 2003

MSSG-O
Horizontal: 2.78 km, vertical: 40 layers, 15 years integration

Sea Ice

Okhotsk-sea (1/12deg.)

15 Nov.
MSSG: Coupled Atmosphere-Ocean Model

non-hydrostatic AGCM

SST
Heat flux, Fresh water, Wind stress
Unit conversion, Time averaging

non-hydrostatic/hydrostatic OGCM

Flux Coupler

Each node
5 Days Forecasting of Typhoon 10 of 2003

MSSG, non-hydrostatic Global Ocean-Atmosphere Coupled Simulation

Horizontal resolution : 2.7 km
Vertical resolution : 72 layers

Typhoon ETAU
Sea Surface Temperature after Typhoon 11 tracking (2005)


Aqua, NASA
Sea Surface temperature
averaged for 5 days (24th August~28th August)
Real time simulation for Typhoon T1306
(12-19, Sept 2006)

Globe: 11km, 32 layers
Japan area: 2.78km, 32 layers
3 days simulation every 12 hours
Cumulus should be resolved, and $O(100)m$ horizontal resolution is required, but

Even if Earth Simulator is used, it is impossible for the whole

Downscaling & Upscaling!
Dynamic Adaptive Mesh Refinement

In MSSG

Dynamic Adaptive Mesh Refinement
+ 2-way nesting
+ Coupling

Atmosphere

Ocean
Dynamic Adaptive Mesh Refinement

- High Performance Computing
  - No Overhead Computation for Moving Grid
  - Ultra High Parallelization
- Multiple fine meshed regions are available
- Not only Horizontal Refinement, but Vertical Mesh refinement
- Refinement Criterion:
  - low surface layer pressure
  - Vorticity
  - gradient of physical parameters
Physical performance on coarse grid system v.s. fine grid system in AMR
AMR on Global Yin-Yang Grid System

\[ \text{slp} \cdot 3/100 \quad (z=1, \ 1) \quad 2009/09/30 \ 14:00 \ \text{UTC} \]

\[ \text{slp} \cdot 4/100 \quad (z=1, \ 1) \quad 2009/09/30 \ 14:00 \ \text{UTC} \]

\[ \text{precip} \cdot 86400 \quad (z=1, \ 1) \quad 2009/09/30 \ 14:00 \ \text{UTC} \]

\[ \text{precip} \cdot 2 \cdot 86400 \quad (z=1, \ 1) \quad 2009/09/30 \ 14:00 \ \text{UTC} \]
## Computational cost

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<th>Merids</th>
<th>steps</th>
<th>Merids*steps</th>
<th>%</th>
<th>elaspe</th>
<th>%</th>
<th>nest</th>
<th>%</th>
<th>reinit</th>
<th>%</th>
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<td>181</td>
<td>17738</td>
<td>3210578</td>
<td>69%</td>
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</tr>
<tr>
<td></td>
<td>1,1</td>
<td>34</td>
<td>17738</td>
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### Depth of Levels for AMR

Is it efficient for the focused events?

Furthermore,

validate the conservation for loner integrations.
relax the length of time step for fine girds system.
Grid Moving Tests

- Validate the grid moving scheme on the Global Soroban grid.
- Initial condition: realistic pressure state (2003/08/01).
- Criterion: gradient of pressure.

※No time integration

Initial grid position and pressure value
Near Future Plan:

• Requirement:
  • Validation of multi-scale circulation in MSSG
    • Horizontal
    • Vertical
    • Extremes in IOD and Monsoon
  • Resolving urban canyon in MSSG
    • Heat-island phenomena, Heavy rain
  • Computational Optimization
    for Multi-scale & Multi-physics simulations
    on the Peta-flops machine K-computer.

• For the trend of many cores
• To consider memory Band Width
• To control hierarchy of memory
  ⇔ hierarchy of programming to keep the HPC