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

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Multi-Scale Simulator for the Geoenvironment (MSSG)

- Applicable to global, regional and local scales seamlessly
- Ying-Yang grid for globe
- Consists of 3 modes; atmos. / ocean / coupled
- Highly optimized for the Earth Simulator (ES)
MSSG-A (atmos.)

MSSG (coupled)

Typhoon ETAU in 2003

MSSG-O (ocean)

SST

heat, precip., momentum

Sea ice

the Sea of Okhotsk (1/12deg.)
## Outline of MSSG

<table>
<thead>
<tr>
<th></th>
<th>MSSG-A</th>
<th>MSSG-O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-hydrostatic AGCM</strong></td>
<td>Non-hydrostatic /hydrostatic OGCM</td>
<td></td>
</tr>
<tr>
<td><strong>governing eqs.</strong></td>
<td>Fully compressive N-S eqs.</td>
<td>Incompressive N-S eqs.</td>
</tr>
<tr>
<td><strong>grid system</strong></td>
<td>Yin-Yang grid (overlapped 2 lat-lon)</td>
<td>Yin-Yang grid (overlapped 2 lat-lon)</td>
</tr>
<tr>
<td><strong>discritization</strong></td>
<td>Arakawa-C grid (horizontal), Z* (vertical)</td>
<td>Arakawa-C grid (horizontal), Z* (vertical)</td>
</tr>
<tr>
<td><strong>time</strong></td>
<td>3rd/4th Runge-Kutta</td>
<td>3rd/4th Runge-Kutta</td>
</tr>
<tr>
<td><strong>adv. schemes</strong></td>
<td>5th flux form, WAF, CIP-CSLR</td>
<td>5th flux form</td>
</tr>
<tr>
<td><strong>non-adv. schemes</strong></td>
<td>4th flux form</td>
<td>4th flux form</td>
</tr>
<tr>
<td><strong>sound wave</strong></td>
<td>HEVI, HIVI</td>
<td>Implicit methods (2D, 3D)</td>
</tr>
<tr>
<td><strong>microphysics</strong></td>
<td>Bulk method (Qc,Qr,Qi,Qs,Qg)/hybrid-Bin method</td>
<td>-</td>
</tr>
<tr>
<td><strong>turbulence model</strong></td>
<td>static Smagorinsky scheme</td>
<td>static Smagorinsky model</td>
</tr>
<tr>
<td><strong>other models</strong></td>
<td>cloud radiation model, backet land model, UCSS urban canopy model</td>
<td>sea-ice model</td>
</tr>
<tr>
<td><strong>parallelization</strong></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>
the Earth Simulator (ES)

**current ES (since 2002)**
- Vector-type super computer
- 640 nodes (5120 CPUs)
- Theoretical Peak Performance = 40 TFLOPS.
- Main Memory= 10 TB.

**upgraded ES**
- Vector-type super computer
- 160 nodes (1080 CPUs)
- Theoretical Peak Performance = 131 TFLOPS.
- Main Memory= 20 TB.

March, 2009 replaced
Performance of the 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>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>512</td>
<td>4096</td>
<td>3,866,296,320</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>
</tr>
<tr>
<td>A</td>
<td>384</td>
<td>3072</td>
<td>2,882,764,800</td>
<td>4273.8</td>
<td>229</td>
<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>4401.9</td>
<td>229</td>
<td>99.3%</td>
<td>9.02</td>
<td>55.0%</td>
<td>94.8%</td>
<td>242.6</td>
</tr>
<tr>
<td>RA</td>
<td>384</td>
<td>3072</td>
<td>2,882,764,800</td>
<td>4575.2</td>
<td>228</td>
<td>99.5%</td>
<td>18.74</td>
<td>57.2%</td>
<td>93.6%</td>
<td>479.1</td>
</tr>
<tr>
<td></td>
<td>256</td>
<td>2048</td>
<td></td>
<td>4606.1</td>
<td>228</td>
<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>O</td>
<td>498</td>
<td>3984</td>
<td>4,954,521,600</td>
<td>4340.8</td>
<td>229</td>
<td>99.4%</td>
<td>17.78</td>
<td>54.3%</td>
<td>90.7%</td>
<td>464.4</td>
</tr>
<tr>
<td></td>
<td>398</td>
<td>3184</td>
<td></td>
<td>4401.0</td>
<td>229</td>
<td>99.4%</td>
<td>13.52</td>
<td>55.0%</td>
<td>92.9%</td>
<td>356.6</td>
</tr>
<tr>
<td></td>
<td>303</td>
<td>2424</td>
<td></td>
<td>4560.5</td>
<td>229</td>
<td>99.4%</td>
<td>9.34</td>
<td>57.0%</td>
<td>95.1%</td>
<td>243.5</td>
</tr>
<tr>
<td></td>
<td>207</td>
<td>1656</td>
<td></td>
<td>4234.3</td>
<td>240</td>
<td>99.3%</td>
<td>7.01</td>
<td>52.9%</td>
<td>90.9%</td>
<td>188.2</td>
</tr>
</tbody>
</table>

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

ES利用グループ等性能値ノード数/TFLOPS (2006.12) 64

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

Simple linearity will be kept until 2 PFLOPS.
1.9km global atmosphere simulation

$\Delta H = 1.9$ km, 32 levels
Seasonal atmosphere simulation

seasonal simulation with $\Delta H=40$ km

MSSG-A
( $\Delta H=40$ km, 32 levels, 1996JJA )

Observation
( CMAP, 1979-2001JJA )

precipitation at JJA (summer in NH)
Northern Pacific Ocean with MSSG-O

$\Delta H = 2.78 \text{km}, 40 \text{ layers}$
Coastal current with MSSG-O

The Northern Pacific Ocean nesting to Japan region

$\Delta H = 11\text{km}, 40$ vertical layers

$\Delta H = 850\text{m}, 40$ vertical layers

Tokyo Bay? where?

Tokyo Bay
Atmosphere-Ocean coupling system

non-hydrostatic AGCM

Heat flux, Fresh water, Wind stress

Unit conversion, Time averaging

non-hydrostatic/hydrostatic OGCM
Coupled simulation for Typhoon 10 of 2003

$\Delta_h = 2.7 \text{ km, 72 layers}$
Urban simulation with $\Delta = 5\text{m}$ (Tokyo station area)

Investigation of redevelopment project

Shin-Marubiru Bld.

Top view

the Imperial Palace

Tokyo station
Hybrid vertical coordinate system (\(\sigma\)- & \(z\)-system)

vertical \(\sigma\)-coordinate system

vertical \(\sigma\)- & \(z\)-coordinate system

Snapshot of wind distribution in a summer afternoon

side view

top view
Adaptive Mesh Refinement for Coupled simulation

Adaptive Mesh Refinement (AMR)
+ 2-way nesting
+ Coupling

Atmosphere

Ocean
Coupled Typhoon simulation by AMR

MSSG is selected as a core application for the next Japanese flagship supercomputer with 10PFLOPS
Concluding Remarks (intermediate)

- MSSG (Multi-Scale Simulator for the Geoenvironment) for seamless simulations
  - Applicable to global, regional and local scales seamlessly
  - Consists of 3 modes; atmos. (MSSG-A) / ocean (MSSG-O) / coupled (MSSG)
  - High performance of more than 50% of the peak performance with 4096 vector processors.
  - AMR system for efficient simulations

- MSSG is being tuned for the next Japanese flagship supercomputer with 10PFLOPS.
Research on cloud microphysics using MSSG

MSSG has Hybrid-Bin method as well as a conventional Bulk method.
MSSG-Bin method (Hybrid-Bin method)

Reisner et al. (1998)

spectral Bin method for liquid water, and conventional Bulk method for solid water

size distributions
Use of MSSG as a Mesoscale model

- MSSG has been validated in idealized tests
  - **StMIP**-Steep Mountain Model Intercomparison Project (Satomura et al., 2003)
  - **orographic precipitation** with mixed-phase microphysics (Thompson et al., 2004)
  - **RICO**-Rain In Cumulus over the Ocean (GCSS)
Droplet growth in clouds

<table>
<thead>
<tr>
<th>cloud stage</th>
<th>dominant process</th>
</tr>
</thead>
<tbody>
<tr>
<td>initiation</td>
<td>condensation (nucleation)</td>
</tr>
<tr>
<td>initiated ⇒ developing</td>
<td>condensation</td>
</tr>
<tr>
<td></td>
<td><strong>turbulent collisions</strong> of mono-dispersed (small) droplets</td>
</tr>
<tr>
<td>developing ⇒ developed</td>
<td>gravitational &amp; <strong>turbulent collisions</strong> of bi-dispersed (small &amp; large) droplets</td>
</tr>
</tbody>
</table>

How significant is the **turbulent collisions**??

**initiation**

**condensation**

**collisions**

**initiated**

**developing**

**developed**
Droplet collision growth in Bin method

**Stochastic Collection Equation (SCE)**

\[
\frac{\partial n_p(r)}{\partial t}_{\text{col}} = \frac{1}{2} \int_0^r K_c(r'', r') n_p(r'') n_p(r') \, dr' - \int_0^\infty K_c(r, r') n_p(r) n_p(r') \, dr'
\]

where

- \( n_p(r) \) is the number density function.
- \( K_c(r, r') \) is the collision kernel.

**Collision frequency**

\[
N_c(r_1, r_2) = K_c(r_1, r_2) n_p(r_1) n_p(r_2)
\]

**Note:**

- "number density function"
- change due to collision
- "collision frequency"
- "collision kernel"
Collision kernel models

Hydrodynamic (Gravitational) Collision Kernel Model
(No turbulent collisions)

\[ K_c(r_1, r_2) = \pi R^2 |V_\infty(r_1) - V_\infty(r_1)| \]

\( R : \) collision radius (=\( r_1 + r_2 \), \( V_\infty \) : settling velocity)

our Turbulent Collision Kernel Model
(with turbulent collisions)

\[ \langle K_c(r_1, r_2, l_\eta, u', \text{Re}_\lambda) \rangle = 2\pi R^2 \langle |w_r| \rangle g(R) \]

\(|w_r| : \) radial relative velocity at contact (Wang et al. 2000)

\( g(R) : \) radial distribution function at contact (original model)
RICO model intercomparison

- Initial data from “Rain In Cumulus over the Ocean” field campaign by GCSS
- Practical for investigating cloud microphysical processes

24-hour-simulation with MSSG-Bulk method

12.8×12.8×4km domain, Δ₁=100m, Δ₂=40m, Periodic B.C., 24 hours integration
extra 1-hour simulation for visualization (MSSG-Bulk)
MSSG-Bin results
(Hydrodynamic Kc v.s. Turbulent Kc)

Snapshots at 24h (blue: $r > 100\mu m$)

MSSG-Bin with Hydrodynamic (Gravitational) collision kernel
(no turbulent collisions)

MSSG-Bin with Turbulent collision kernel
### RICO intercomparison participants

<table>
<thead>
<tr>
<th>Model</th>
<th>Microphysics</th>
<th>Timestep [s]</th>
<th>Duration for 24h Integration [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MESO-NH</td>
<td>1st moment, Kessler</td>
<td>1</td>
<td>440</td>
</tr>
<tr>
<td>SAM</td>
<td>1st moment</td>
<td>2</td>
<td>320</td>
</tr>
<tr>
<td>JAMSTEC</td>
<td>1st moment</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>Utah</td>
<td>1st moment</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>EULAG</td>
<td>1st moment</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>2DSAM</td>
<td>1st moment</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>DALES</td>
<td>2nd moment, Nc fixed</td>
<td>1</td>
<td>190</td>
</tr>
<tr>
<td>UCLA</td>
<td>2nd moment, Nc fixed</td>
<td>~1.5</td>
<td>80</td>
</tr>
<tr>
<td>WVU</td>
<td>2nd moment, Nc fixed</td>
<td>~1.65</td>
<td>72</td>
</tr>
<tr>
<td>COAMPS</td>
<td>2nd moment</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>UKMO</td>
<td>2nd moment, Nc fixed</td>
<td>~0.7</td>
<td>500</td>
</tr>
<tr>
<td>RAMS</td>
<td>2nd moment+CCN</td>
<td>2</td>
<td>weeks</td>
</tr>
<tr>
<td>2DHARMA</td>
<td>Bin model (33)</td>
<td>3.5</td>
<td>10,000</td>
</tr>
<tr>
<td>RAMS@NOAA</td>
<td>Bin model (33)</td>
<td>2</td>
<td>5,400</td>
</tr>
<tr>
<td>SAMEX</td>
<td>Bin model</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>MSSG-Bulk</td>
<td>1st moment (2nd for ice), Nc fixed</td>
<td>~2.2</td>
<td>250</td>
</tr>
<tr>
<td>MSSG-Bin</td>
<td>Bin model (33)</td>
<td>~2.2</td>
<td>1,750</td>
</tr>
</tbody>
</table>

*yellow: Bulk models  
* blue: Bin models

3 bin models & 12 bulk models

Ref: Margreet van Zanten, GCSS-GPCI/BLCI-RICO Workshop, NY, 2006
Mixing Ratios of Liquid Water ($q_l$) and Rain Water ($q_r$)

graphs from GCSS-BLCwg, RICO<http://www.knmi.nl/samenw/rico/>
Mixing Ratios of Liquid Water ($q_l$) and Rain Water ($q_r$)
Mixing Ratios of Liquid Water ($q_l$) and Rain Water ($q_r$)

Large impact of turbulent collisions is shown.
Discussion

- Two Bin-models & “MSSG-Bin model with Hydr. Kc (conventional gravitational collision kernel)” have max $q_r$ at high altitude ($z=2$km).

- “MSSG-Bin with Turb. Kc” and many of Bulk-models have max $q_r$ at lower altitude.

- In conventional Bin-models, where turbulent collisions are not considered, it takes time for droplets to grow and fall, and therefore they are raised higher.

- Some Bulk-models empirically consider some turbulent collision enhancement to some extent, and therefore show similar results to those by “MSSG-Bin model with Turb. Kc”.
Concluding Remarks

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  - Consists of 3 modes; atmos. (MSSG-A) / ocean (MSSG-O) / coupled (MSSG)
  - High performance of more than 50% of the peak performance with 4096 vector processors.
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- MSSG is being tuned for the next Japanese flagship supercomputer with 10PFLOPS.

- MSSG-Bin model with turbulent collision model reveals the importance of turbulent droplet collisions in cloud development.
Thank you.