Development of climate models to be run on the Earth Simulator

Taroh Matsuno
Frontier Research System for Global Change
Performance of the Earth Simulator

- Linpack Benchmark Test
  - World Rank, No.1
    - Sustained performance: 35.86 Tflops
    - Sustained efficiency: 87.5%
- Interconnected network: Single-Stage Crossbar Network

<table>
<thead>
<tr>
<th>#Processors</th>
<th>5,120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor nodes</td>
<td>640</td>
</tr>
<tr>
<td>Processors per node</td>
<td>8</td>
</tr>
</tbody>
</table>

Peek Performance

<table>
<thead>
<tr>
<th>Per node</th>
<th>64 Gflops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per processor</td>
<td>8 Gflops</td>
</tr>
<tr>
<td>Main Memory</td>
<td>10 TB</td>
</tr>
<tr>
<td>Per node</td>
<td>16 GB</td>
</tr>
</tbody>
</table>

1 cabinet (2 nodes included)
1 node
200cm
140cm
100cm
Increasing Trends of Super Computer’s Performance and Climate Model Simulation

![Graph showing the increasing trends of super computer's performance and climate model simulation over the years. The x-axis represents the year from 1970 to 2005, and the y-axis represents the peak performance in millions of floating-point operations per second (MFLOPS). The grid size for climate simulation is also indicated on the right side of the graph, ranging from 10Km to 300Km. Various markers represent different supercomputers and climate models, such as IPCC90, IPCC95, IPCC2000, and future planning.]
Activity

a. High-resolution Coupled model and Global Warming Experiment (CCSR/UT-NIES-FRSGC)
b. 20km-mesh Atmospheric GCM (Meteor. Res. Inst/JMA)
c. Next-generation Atmosphere & Ocean Models (FRSGC)
d. Integrated Earth-System Model (FRSGC-CCSR/UT-NIES---)
High-resolution Coupled model and Global Warming Experiment (CCSR/UT-NIES-FRSGC)
The CCSR/NIES/FRSGC Coupled Ocean-Atmosphere GCM on the Earth Simulator: 
*MIROC 3.2*

- **Atmosphere:** Spectral T106 (120km) 56 levels with interactive Aerosol modules
- **Ocean & Ice:** Grid $1/4^\circ \times 1/6^\circ$ 48 levels
- **Land:** $1/2^\circ \times 1/2^\circ$ MATSIRO SVATS model
- **River:** $1/2^\circ \times 1/2^\circ$ TRIP river routing model
- **Parallelized with MPI on 80PE for atmos. and 608PE for ocean (13% of whole ES)**

*No flux correction applied*
The Ocean component is too coarse to resolve eddies in the high-latitudes.

Model grid size:
- 1/4° (zonally)
- 1/6° (meridionally)

At 60°:
- \( dx = 15.4 \text{ km} \)
- \( dy = 20 \text{ km} \)

Introduce thickness-diffusion (Gent-McWilliams) only in the high-latitudes.

Rossby’s deformation radius for the first baroclinic mode (based on WOA)
SST bias

ver.0
40yr mean

ver.1
last 4yrs
Extreme events? (daily precipitation)

Frequency of daily precipitation > 50mm/day

AGCM vs. Obs

Histogram of daily precipitation
30-50N 130-150E
1997 JJA

Log$_10$(frequency distribution) vs. mm/day
Hawaiian Lee Counter Current (Xie et al., 2001)

Obs

CGCM w/o the Hawaii Islands
Time variation of the vertically integrated aerosol density
Time variation of the global mean temperature at 2m
b. 20km-mesh Atmospheric GCM  
(Meteor. Res. Inst/JMA)
Impact on typhoon simulation

old

NEW

PRECIPITATION, SFC PRESSURE
(not-tuned) TL959L60

PRECIPITATION, SFC PRESSURE
(tuned) TL959L60

日降水量
Simulation of the present day climate
Regional climate simulated by the 20 km mesh model (January precipitation)

Model (TL959L60)  

Observation
Tropical cyclones simulated by the model

(a) Observation 10 years

(b) Model (NEW) 1 year

Frequency of tropical cyclones

(a) GLOBAL
- Observation
- Model (NEW)
- Model (OLD)

(b) W.N. Pacific
- Observation
- Model (NEW)
- Model (OLD)

Max wind speed (m/s)
Kyosei Project 2

Development of an “Integrated Earth System Model” for projection of global environmental change
Kyousei 2 Project: Incorporation of biogeochemical processes into a GCM

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Double affiliates of FRSGC researchers: *Hokkaido Univ., **Univ. of Tsukuba,
***CCSR/Univ. of Tokyo
FRSGC integrated Earth System Model

Physics Core
= Kyousei 1 based
Terrestrial Carbon Cycle model (Sim-CYCLE)
Future climate scenario under SRES-A2 (2090s – 1990s)

**Land air temperature**

**Precipitation**
Plant Carbon Differences (2090s – 1990s)

CO₂ only

CCSR/NIES

CCCma

HadCM3
Soil Carbon Differences (2090s – 1990s)
Results

Soil Organic Matter

- CON_A2
- CCSRA2_A2
- CCCA2_A2
- HADCM3A2_A2

SMASS (Pg C) vs. Year

- 150 PgC
- 370 PgC
- 150 PgC
FRSGC integrated Earth System Model

KISSME
“DGVMization” of Sim-CYCLE

DGVM: Dynamical Global Vegetation Model

-> Incorporation of the effect of biome-shift into Sim-CYCLE

Individual basis model, which explicitly treat 3D forest-structure within 30m x 30m patches

<table>
<thead>
<tr>
<th>Individual characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foliage</strong></td>
</tr>
<tr>
<td>biomass, crown diameter, crown depth</td>
</tr>
<tr>
<td><strong>Stem</strong></td>
</tr>
<tr>
<td>biomass, height, sapwood &amp; heartwood diameter</td>
</tr>
<tr>
<td><strong>Root</strong></td>
</tr>
<tr>
<td>biomass</td>
</tr>
</tbody>
</table>

--- Shape of crown and stem are approximated by cylinder
FRSGC integrated Earth System Model
KISSME
Oceanic Carbon Cycle Model

- Biological Model: Oschlies & Garçon (1998) with the carbonate system
- OGCM: COCO3.4 (Hasumi, 2000)

- Horizontal Resolution: 1 deg. x 1 deg
- 54 Vertical Levels
- Forcing: Monthly mean climatology
- Integration Period: 19 years
Some Model Results

Surf. Chl.

Air-Sea CO$_2$ Exchange

Model

Obs.
Coupling of the Oceanic and terrestrial global mean CO2 flux [PgC/yr]

CO2 flux at the sea surface [molC/m^2/yr]

AGCM: T42L20,
OGCM: 0.5-1.0 deg, L44

global mean CO2 flux [PgC/yr]

global mean CO2 concentration [ppmv]
FRSGC integrated Earth System Model
KISSME
Atmospheric chemistry model (CHASER)

- 53 chemical species (ozone, NOx, etc.)
- Chemical reactions up to ~20 km altitude
- A simple reaction system in the stratosphere will be added.
Next-Generation Model Development at FRSGC

1. **Global Cloud-Resolving Atmosphere Model** (Icosahedral Geodesic Grid)
2. **Eddy-Resolving World Ocean Circulation Model** (Equal- Area Cubic Grid)
Why we need cloud-resolving model?

- Parameterization of convective clouds is impossible for 10~50km grids (no scale separation)
- Meso-scale convective cloud systems (cloud clusters) have particular structure and behave autonomously.
  -> “Large-scale control” does not hold
Mesoscale and Convective-Scale Downdrafts as Distinct Components of Squall-Line Structure

E. J. Zipser

Schematic picture of cloud cluster entirely different from Benard cell

Fig. 13. Schematic cross section through a class of squall system. All flow is relative to the squall line which is moving from right to left. Circled numbers are typical values of $\theta_w$ in °C. See text for detailed discussion.
Development of the Global Cloud Resolving Model Using the Icosahedral Grid

Frontier Research System for Global Change
Hirofumi TOMITA
Masaki SATOH
Koji Goto
Shin-ichi IGA
Tomoe NASUNO
• **Grid generation method**
  1. Start from the spherical icosahedron. (glevel-0)
  2. By connecting the mid-points of the geodesic arcs, four sub-triangles are generated. (glevel-1)
  3. By iterating this process, a finer grid structure is obtained. (glevel-n)

• **# of gridpoints**
  - 11 iterations are required to obtain the 5km grid interval.
Variations of cubic grid

gnomonic projection  Conformal projection  homogeneous projection
Held & Suarez Dynamical Core Exp.

- **(a) GME(ni=64)**
  - Zonal mean of zonal wind
  - The jet is located at 45[deg] and 250[hPa] in all cases.

- **(b) IFS**
  - Zonal wind (m/s), IFS T106
  - There is no difference of distribution and intensity between the model results.

- **(c) Our model**

- The jet is located at 45[deg] and 250[hPa] in all cases.

- There is no difference of distribution and intensity between the model results.
Lifecycle experiment of baroclinic wave

Global structure: almost same

- Results after 10 days
  - Temperature & velocity fields at z=180m

Glevel-6: 120km
Glevel-8: 30km
Glevel-10: 7.5km
Lifecycle experiment of baroclinic wave

- Local structures of glevel-10(7.5km)
## Computational Performance

- **How long time in 3.5km/L50?** (measured in ES)
  - **Target measurement**:
    LCE 1day simulation (dry version: only dynamical core)

<table>
<thead>
<tr>
<th>Horiz. grid</th>
<th>$\Delta t$ [s]</th>
<th># of Node(CPU)</th>
<th>Elapse time [h:m:s]</th>
<th>FLOPS</th>
<th>Sustained performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gl-6 (120km)</td>
<td>900</td>
<td>5 (40CPU)</td>
<td>00:00:19</td>
<td>90G</td>
<td>28%</td>
</tr>
<tr>
<td>Gl-7 (60km)</td>
<td>450</td>
<td>20 (160CPU)</td>
<td>00:00:32</td>
<td>410G</td>
<td>32%</td>
</tr>
<tr>
<td>Gl-8 (30km)</td>
<td>200</td>
<td>80 (640CPU)</td>
<td>00:00:68</td>
<td>1720G</td>
<td>33%</td>
</tr>
<tr>
<td>Gl-9 (14km)</td>
<td>100</td>
<td>80 (640CPU)</td>
<td>00:06:30</td>
<td>2260G</td>
<td>44%</td>
</tr>
<tr>
<td>Gl-10 (7km)</td>
<td>50</td>
<td>80 (640CPU)</td>
<td>00:46:50</td>
<td>2450G</td>
<td>48%</td>
</tr>
<tr>
<td>Gl-11 (3.5km)</td>
<td>25</td>
<td>320 (2560CPU)</td>
<td>01:34:10</td>
<td>9750G</td>
<td>48%</td>
</tr>
</tbody>
</table>

**Optimized version**: 1.5h $\rightarrow$ 1.1h

*In the case of including physical processes,
$\rightarrow$ Within 2 or 3 hours (rough estimate)*
• Default grid: glevel-6
  – 120km grid intv.
  • Homogenous

• Stretched grid
  – After the transformation
  • Grid interval:
    – 120km $\rightarrow 12km$ $\rightarrow 1.2km$

Reduction of earth radius: $1/10$

1.2km grid interval
Total hydrometeor at $z=1.4\text{km}$ (G1998)
Radiation-Convection Equilibrium Test

- **Configuration**
  - Initial condition:
    - An appropriate temperature profile
  - Radiation:
    - No-interaction with cloud
    - Newtonian cooling cooling rate: 2K/day in the troposphere
  - Surface condition:
    - Temperature: 300K
    - Water vapor: saturated → tropical environment
  - Scheme used:
    - Turbulence: MY-lev2
    - Microphysics: G1998
    - Surface flux: Louis et al.
  - Grid used:
    - 3.5km/ R=100km → Very very small earth
- Global mean temperature
  - Control case < Reduced cooling case < Increased flux case

- Global mean precipitable water
  - Control case < Reduced cooling case < Increased flux case
    
    Equilibrium: not yet achieved
    Less precipitable water than the typical value (60 kg/m^2)

  → Better result, if interacted with radiation process?
Cubic grid OGCM

Sea Surface Height
(after 500 yr integration)

Resolution: ~100 km

Initial condition:
isothermal (10 deg)
motionless

Surface Boundary Condition
Hellerman and
Rosenstein windstress
Levitus temperature

Simplified Physics