Challenge toward the prediction of typhoon behaviour and down pour

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Abstract. Mechanisms of interactions among different scale phenomena play important roles for forecasting of weather and climate. Multi-scale Simulator for the Geoenvironment (MSSG), which deals with multi-scale multi-physics phenomena, is a coupled non-hydrostatic atmosphere-ocean model designed to be run efficiently on the Earth Simulator. We present simulation results with the world-highest 1.9km horizontal resolution for the entire globe and regional heavy rain with 1km horizontal resolution and 5m horizontal/vertical resolution for urban area simulation. To gain high performance by exploiting the system capabilities, we propose novel performance evaluation metrics introduced in previous studies that incorporate the effects of the data caching mechanism between CPU and memory. With a useful code optimization guideline based on such metrics, we demonstrate that MSSG can achieve an excellent peak performance ratio of 32.2% on the Earth Simulator with the single-core performance found to be a key to a reduced time-to-solution.

1. Introduction

Intense research effort is focused on understanding the climate/weather system using coupled atmosphere-ocean models. It is widely accepted that the most powerful tools available for assessing future weather/climate are fully coupled general circulation models. Not only interactions between atmosphere or ocean components, but also various other components have been coupled with various interactive ways and influence on the Earth system. In order to get further information on perspectives of future weather/climate and the Earth system, the whole Earth system should be simulated using coupled models.

The Earth Simulator Center has been developing coupled non-hydrostatic atmosphere-ocean-land general circulation models to be run on the Earth Simulator with ultra high resolution and really high performance computing architectures. When development of the coupled model has been completed and various simulations are possible on the Earth Simulator, the ambitious task of simulating and understanding the Earth system should bring us further detail information on the Earth System. Simulations with target scale shown in figure 1 will be planned in near future.

In this paper, outline of the Multi-scale Simulator for the Geoenvironment (MSSG) is described in section 2. Computational performance is reported in section 3. Validation results for several
time/space scale phenomena are presented in section 4 and conclusions and near future plans are shown in section 5.

Figure 1. (a): Yin-Yang girds system for global simulations. The coloured grids are the Yin and Yang grids. (b): Japan region is nested with two-way interaction to the global grid. (c): Urban scale weather/climate simulations will be allowed with two-way interactions to the global/regional scale simulations. Urban topography was given by the Geographical Survey Institute.

2. Model description

2.1. The atmosphere component: MSSG-A

The atmosphere component consists of non-hydrostatic, fully compressive flux form of dynamics [1] and Smagorinsky-Lilly type parameterizations [2][3] for subgrid scale mixing, surface fluxes [4][5], cloud microphysics with mixed phases [6], cumulus convective processes [7][8] and simple radiation scheme. The set of the prognostic equations is presented as follows:

\[
\frac{\partial \rho'}{\partial t} + \int \frac{G^2}{G^2_{a} \cos \varphi} \left[ \frac{1}{\lambda} \frac{\partial (G^2 G^{11} \rho_f)}{\partial \lambda} + \frac{1}{G^2 a \cos \varphi} \frac{\partial (G^2 G^{22} \cos \varphi \rho_f)}{\partial \varphi} + \frac{1}{G^2} \frac{\partial (\rho_f \varphi)}{\partial z} \right] = 0, \tag{1}
\]

\[
\frac{\partial \rho_v}{\partial t} + \int \frac{G^2}{G^2_{a} \cos \varphi} \frac{\partial (G^2 G^{11} \rho_v)}{\partial \lambda} = - \nabla \cdot (\rho_f \rho_v) + 2 f_s \rho_v - 2 f_s \rho_u + \frac{\rho_u \tan \varphi}{a} - \frac{\rho_v}{a} + F_v, \tag{2}
\]

\[
\frac{\partial \rho_u}{\partial t} + \int \frac{G^2}{G^2_{a} \cos \varphi} \frac{\partial (G^2 G^{22} \rho_u)}{\partial \lambda} = - \nabla \cdot (\rho_f \rho_u) + 2 f_s \rho_u - 2 f_s \rho_v - \frac{\rho_u \tan \varphi}{a} - \frac{\rho_v}{a} + F_v, \tag{3}
\]

\[
\frac{\partial P'}{\partial t} + \frac{1}{G^2_{a} \cos \varphi} \left( \frac{\partial P'}{\partial \lambda} + \rho' G \right) = - \nabla \cdot (\rho_f \varphi_v) + 2 f_s \rho_u - 2 f_s \rho_v + \frac{\rho_u \tan \varphi}{a} + \frac{\rho_v}{a} + F_v, \tag{4}
\]

\[
\frac{\partial P}{\partial t} + \nabla \cdot (P \varphi) + (\gamma - 1) P \nabla \cdot \varphi = (\gamma - 1) \nabla \cdot (\kappa \nabla T) + (\gamma - 1) \phi, \tag{5}
\]

\[
P = \rho RT, \tag{6}
\]

\[
\rho v' = \frac{1}{G^2} \left( \frac{G^2 G^{11} \rho_f + G^2 G^{22} \rho_v + \rho_v}{G^2} \right). \tag{7}
\]
In (1)-(7), prognostic valuables are momentum $\rho \mathbf{v} = (\rho u, \rho v, \rho w)$, $\rho'$, which is calculated as $\rho' = \rho - \bar{\rho}$, and $P'$, defined by $P' = P - \bar{P}$. $\rho$ is the density; $P$ is the pressure; $\bar{\rho}$ is a constant reference pressure; $T$ is the temperature; $R$ is the gas constant; $f$, $K$, and $\gamma$ are the Coriolis force, the diffusion coefficient and the ratio of specific heat, respectively. $\phi$ is the heat source term and $F$ is the viscosity term, respectively. $G$ is the metric term for vertical coordinate; $\phi$ is latitude; $\lambda$ is longitude. In addition, $a$ is the radius of the Earth and $g$ is the gravitational acceleration.

The treatment of cloud and precipitation is controlled by selecting a parameterization scheme due to horizontal resolution. For grid spacing greater than 10 km, the Kain and Fritsh scheme [7][8] is used and cloud microphysics based on mixed phase micro cloud physics [6] is used for below 5km spacing. Over land, the ground temperature and ground moisture are computed by using a bucket model as a simplified land model. As upper boundary condition, Rayleigh friction layer is set. For the lateral boundary condition of regional version, a sponge type boundary condition [9] is used.

Regional version of the atmosphere component is utilized with one way nesting scheme by choosing the target region on the sphere, although two-way nesting is available as an option. Any large regions can be selected from the global, because both Coriolis and metric terms are introduced in the regional formulation. As another option, multiple regions are allowed to be selected at the same time and computed in parallel.

2.2. The ocean component: MSSG-O

In the ocean component: MSSG-O, the in-compressible and hydrostatic equations with the Boussinesq approximation are used based on the description in [10][11]. The set of equations in the ocean component becomes as follows:

$$\frac{\partial c}{\partial t} = -\nabla \mathbf{v} \cdot c \mathbf{F} + F_c$$

$$\frac{\partial T}{\partial t} = -\nabla \mathbf{v} \cdot T \mathbf{F} + F_T$$

$$0 = \nabla \cdot \mathbf{v} = \left( \frac{1}{r \cos \phi} \frac{\partial}{\partial \lambda} + \frac{1}{r \cos \phi} \frac{\partial}{\partial \phi} + \frac{1}{r} \frac{\partial}{\partial r} \right)$$

$$\frac{\partial u}{\partial t} = -\nabla \mathbf{v} \cdot u \mathbf{F} + \frac{\mu u \tan \phi}{r} - \frac{u w}{r} - \frac{1}{\rho \rho_0 r \cos \phi} \frac{\partial}{\partial \lambda} + F_u$$

$$\frac{\partial v}{\partial t} = -\nabla \mathbf{v} \cdot v \mathbf{F} + \frac{\mu v \tan \phi}{r} - \frac{v w}{r} - \frac{1}{\rho \rho_0 r \cos \phi} \frac{\partial}{\partial \phi} = F_v$$

$$\frac{\partial w}{\partial t} = -\nabla \mathbf{v} \cdot w \mathbf{F} + \frac{\mu w \tan \phi}{r} - \frac{w w}{r} - \frac{1}{\rho \rho_0 r} \frac{\partial}{\partial \phi} = F_w$$

$$\rho = \rho(T, c, P_c)$$

$$\frac{d}{dr} P_0 = -\rho \cdot g(r)$$

where the Boussinesq approximation is adopted in (9) and all variables are defined as above for the atmospheric component. In (14), UNESCO scheme [12] is used.

A Smagorinsky type scheme [2][3] is used as the subgrid-scale mixing in identical experiments with the ocean component. The level-2 turbulence closure of Mellor Yamada [13] has been also introduced to the ocean component as one of optional schemes.

In MSSG-O, sponge layers are used for lateral boundary in the open ocean. The lateral boundary condition between ocean and land is defined as $\partial T / \partial t = \partial S / \partial t = 0$ and $\mathbf{v} = 0$. Bottom condition is defined by the Neumann condition without vertical velocity. The upper boundary conditions are given as momentum fluxes by wind and heat fluxes from observational data of atmosphere.
2.3. Grid configuration
The Yin-Yang grid system [14] is used both for the atmosphere-land and ocean components. The Yin-Yang grid system as shown in figure 1(a) is characterized by two overlapping panels that cover the sphere. Basically, one component grid is defined as a part of low-latitude region covered between 45N and 45S and 270 in longitude of the usual latitude-longitude grid system and the other component of the grid system is defined in the same way but in different spherical coordinates. The region covered by a panel can change by rotating the axes of the panels.

By using the Yin-Yang grid system, we can find a solution to the issue of how to avoid singular points such as the south and north poles on a latitude/longitude grid system. In addition, the advantage to enlarge the time step is compared to conventionally utilized latitude/longitude grid systems.

2.4. Differencing schemes
In both the MSSG-A and MSSG-O, the Arakawa C grid is adopted. The MSSG-A utilizes the terrain following vertical coordinate with Lorenz type variables distribution [15]. The MSSG-O uses the z-coordinate system for the vertical direction. In discretization of time, the 2nd, 3rd and 4th Runge-Kutta schemes and leap-flog schemes with Robert-Asselin time filter are available; the 3rd Runge-Kutta schemes is adopted for the atmosphere component. In this study, leap-flog schemes with Robert-Asselin time filter is used for the ocean component.

For momentum and tracer advection computations, several discretization schemes are available [16][21]. In this study, the 5th order upwind scheme is used for the atmosphere and central difference is utilized in the ocean component.

The vertical speed of sound in the atmosphere is dominant comparing the horizontal speed, because vertical discretization tends to be finer than horizontal discretization. For those reasons, a horizontally explicit vertically implicit (HEVI) scheme [21] is adopted in the atmosphere component. The speed of sound in the ocean is three times faster than it is in the atmosphere, an implicit method is introduced, and the Poisson equation (16) is solved with that method. The Poisson equation is described as

\[ \nabla \cdot \text{grad} P = B, \]

\[ B = \rho_0 \nabla \cdot G_v - \frac{\rho_0}{r \cos \psi} \frac{\partial}{\partial \lambda} G_v + \frac{\rho_0}{r \cos \psi} \frac{\partial}{\partial \phi} (\cos \psi G_v) + \frac{\rho_0}{r^2} \frac{\partial}{\partial r} (r^2 G_v), \]

which are solved under Neumann boundary condition of \( n \cdot \text{grad} P = n \cdot G_v \).

Computational noise over the interface of an overlapped grid system such as Yin-Yang grid was avoided by using a new interpolation scheme validated by various benchmark experiments [16][17][18][19][20].

2.5. Algebraic multigrid method in a Poisson solver
Algebraic Multi-Grid (AMG) method [22] is used in order to solve the Poisson equation mentioned in section 2.4. AMG is well known as an optimal solution method. We used the AMG library which has been developed by Fuji Research Institute Corporation. The AMG library has the following characteristics.

- AGM in the library has been developed based on aggregation-type AMG [22].
- In the library, AMG is used as a pre-conditioner in Krylov subspace algorithms.
- Incomplete LU decomposition (ILU) is adopted as a smoother in the library, which shows good computational performance even for ill-structured matrices.
- Local ILU is used for parallelization, in addition, fast convergence speed has been kept.
- Aggregation without smoothing is adopted with recalling procedure, because remarkably fast convergence has been obtained by using the aggregation.
2.6. Coupling between the atmosphere and ocean components
The coupling interface between the atmosphere and ocean should be taken into account to maintain a self-consistent representation in the coupled model. Generally, the time step in the ocean component is set longer than that of the atmosphere component. The heat fluxes, moisture and momentum fluxes are computed and averaged over larger time step. The averaged fluxes are used as the upper boundary condition of the ocean component. Precipitation computed in the atmosphere component is transferred to the ocean as a source term as fresh water. Sea surface temperature is defined in the uppermost layer in the ocean component and is transferred to the atmospheric component as one heat source. The SST is fixed in the atmosphere during all time substeps within any large step.

2.7. Distribution architecture and communications
The architecture and data structures are based on domain decomposition methods. In the Yin-Yang grid system, communication cost imbalance might occur by adopting one-dimensional decomposition. The case of decomposition with 16 processes is considered in figure 2. Each color corresponds to a process. The number of arrows linking different colored areas corresponds to the amount of communication between processes. For example, in figure 2(a) for one dimensional domain decomposition, black colored process called A communicates to 8 different colored processes. In figure 2(b) for two-dimensional decomposition, a black colored process called A communicates two processes. In figure 2(a), communication data size is small and the number of communications is increased. If the same number for decompositions is used in both (a) and (b), it is clear that the amount of communications is smaller in figure 2(b). Two dimensional decomposition was adopted for both atmosphere-land and ocean components due to these reasons.

![Diagram of domain decomposition]

(a) One dimensional domain decomposition  
(b) Two dimensional domain decomposition

Figure 2. Schematic features of domain decomposition on Yin-Yang grid system.

3. Formatting the text performance of MSSG on the Earth Simulator
3.1. System configuration of Earth Simulator
The Earth Simulator (hereinafter called ES) upgraded and put into operational use in 2009 is a distributed-memory type parallel vector supercomputer that inherits the NEC SX-9 architecture [23]. The ES consists of 160 processor nodes interconnected by the (two-stage) fat-tree network [24]. One processor node is made up of 8 CPUs, each having a vector-type arithmetic processing unit and sharing 128GB of memory within a node. The CPU consists of the world fastest single core of 102.4GFLOPS. The whole ES is comprised of 1280CPUs with 20TB of main memory, thus giving a peak performance of 131TFLOPS (figure 3). The ES features Assignable Data Buffer (ADB) within a CPU for the selective buffering of data, enabling the effective use of memory bandwidth by suppressing the transfer of reusable data assigned to the ADB. The ADB is software-controllable, which makes possible the effective use of the ADB.
3.2. Performance of MSSG-A on Earth Simulator

By tuning the performance using the novel performance evaluation metrics introduced in the previous studies [25], the wall-clock time for the entire MSSG program on the 160 ES nodes (1280 cores) was successfully reduced by 37% from 172.0 sec to 108.2 sec with the achieved sustained performance of 42.2 TFLOPS (peak performance ratio of 32.2%). The 3km global simulation run was also conducted with 80 ES nodes (640 cores). The measured wall-clock time was 108.2 sec and 205.7 sec for 160 and 80 nodes, respectively with the parallelization ratio of 99.9915%, which can be derived from the Amdahl’s law. Figure 4 shows the sustained performance measured with 1280 and 640 cores, the resulting performance curve using the parallelization ratio based on the Amdahl’s law and the line representing the ideal parallelization ratio of 100%.

Figure 3. System configuration of the Earth Simulator.

Figure 4. Strong scaling of MSSG-A on the ES. Blue marker: sustained performance measured with 1280 and 640 cores; blue line: the resulting performance curve using the parallelization ratio based on Amdahl’s law; red line: the line representing the ideal parallelization ratio.
4. Simulation results

4.1. Stand alone simulations with atmospheric component of MSSG-A

A global simulation has been performed to validate physical performance under the condition of 5.5 km horizontal resolution and 32 vertical layers. A 72-hours integration was executed with the atmospheric component. Initialized data was interpolated at 00UTC08Aug2003 from Grid Point Value (GPV) data provided by Japan Meteorological Business Support Center. Sea surface data was also made by GPV data at 00UTC08Aug2003 and fixed during the simulation. Figure 5 shows averaged precipitation distribution one hour before 00UTC10Aug2003. The unit is mm per hour. Precipitation distribution has been computed through cloud microphysics and is comparable to observation data. In this simulation, the diurnal cycle of precipitation in Indonesian region and fine structure of fronts are captured.

![Global precipitation distribution simulated with MSSG-A for a 1.9km horizontal resolution.](image)

4.2. Synoptic simulation results

Regional coupled simulations with MSSG for physical validation has been performed with one way nesting from 11 km global to Japanese region with 2.7km horizontal resolution. Horizontal resolution was set to the same condition in the oceanic component of MSSG. Initialized data was interpolated by
using GPV data at 00UTC08Aug2003 provided by Japan Meteorological Business Support Center the boundary condition was made by interpolation the above simulation with 5.5km horizontal resolution. Sea surface temperature was also fixed to data at 00UTC08Aug2003 during the simulation. 72-hours integration has been performed. Figure 6 shows the result of the 72-hours integration. White gradation distribution in the typhoon shows cloud water distribution corresponding to cloud distribution. The fine rain band structure has been captured and is shown in figure 6. In the ocean part, distribution of sea surface temperature (SST) is presented as well in figure 8. SST responses to a strong wind due to typhoon and disturbance of SST are simulated. Not only SST but also vertical velocity in the ocean has been dramatically changed in the Kuroshio region (data not shown).

![Image](image.png)

**Figure 6.** Regional validation simulation results of typhoon.

### 4.3. Regional heavy rain

Validation simulation with 1km horizontal resolution and 32 vertical layers for regional heavy rain was performed for the case during 21:00-24:00 JST on 4th September in 2005. Initial data were interpolated from the Grid Point Value (GPV) data at 06UTC04Sep2005 provided by Japan Meteorological Business Support Center and results after 6 model hours integration was used for initial data for prediction validation. Figure 7 and figure 8 show the observation data and simulation results of precipitation distribution averaged over one hour. The simulated precipitation distribution results were weak and the line shaped distribution of the observational data had not been captured. Initial data and representation of instability in the boundary layers must be considered.

### 4.4. Toward weather and climate variability prediction in urban area

We especially focus on developing MSSG for prediction of urban scale weather/climate phenomena which will be one of the key parts of seamless simulation from global to urban scale. As the first step of validation, the Marunouchi area in the center of Tokyo was selected for the simulation with MSSG-A due to the impacts of Large Eddy Simulation scheme for boundary layer. The initial state was settled at 15:00 on 5th August in 2005 and initial thermal condition was set taking account of shade in a day. In simulations with 5m horizontal resolution (figure 9), buildings can be resolved with
anthropogenic heating source. The result shows a snapshot of horizontal temperature distribution during non-stationary computation from the initial time 15:00. Dynamics of thermal plume have been well represented.

Figure 7. Observation data from radar echo (mm/h).

Figure 8. Simulation results (mm/h).

Figure 9. Temperature distribution of urban scale simulations for Marunouchi area in Tokyo.

5. Conclusions and perspectives
Development of MSSG was almost completed with high computational performance, although further optimization remains to be achieved in communications. Simulation results with each time/space scale encourage us toward seamless simulations with MSSG. As challenging issues, more various forecasting experiments are going to be performed and longer integration will be executed in order to estimate the accuracy of forecasting.
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