Multi-Scale Weather/Climate Simulations with Multi-Scale Simulator for the Geoenvironment (MSSG) on the Earth Simulator

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Multi-Scale Simulator for the Geoenvironment (MSSG), which is a coupled non-hydrostatic atmosphere-ocean-land model, has been developed in the Earth simulator Center. Outline of MSSG is introduced and characteristics are presented. In MSSG development procedure, impact of CIP-CSLR schemes is explored and of turbulence on cloud droplet collisions in meso-scale convective clouds have been investigated. Regarding validations of physical performance with MSSG, simulation results of global/regional MSSG are presented.

Keywords: Coupled atmosphere-ocean model, multi-scale, multi-physics, high performance computing, the Earth Simulator

1. Introduction

Multi-Scale Simulator for the Geoenvironment (MSSG), which is a coupled non-hydrostatic atmosphere-ocean-land global circulation model, has been developed for the purposed of promoting advanced projection/prediction simulation. MSSG is optimized to be run on the Earth Simulator with high computational performance. Not only high performance computation but also accurate calculation or precise discritization schemes are required for ultra high resolution simulations. Furthermore, improvement of physical performance is required in order to understand mechanisms of weather/climate phenomena. This report summarizes the technical and scientific achievements of following themes; (1) the impact of improvement of accuracy of discritization schemes, (2) the impact of improvement of turbulent effects on collision processes in micro cloud physics and (3) validation and exploration of MSSG for multi-scale simulations.

MSSG configuration is designed for multi-scale multi-physics simulations of weather/climate. Fig. 1 shows schematic figure scaled levels in MSSG. MSSG is available with flexibility for different 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,

and

- MSSG with Regional MSSG using nesting schemes.

The regional version MSSG-A, MSSG-O and MSSG are utilized with one-way or two-way nesting schemes. Any regions in the global can be defined for the regional version models, because both Coriolis and metric terms have been introduced in the regional formulation. Fig. 2 presents a coupling strategy for global and regional components of MSSG.

The purpose of this report is to show preliminary simulation results in order to validate physical performance of MSSG. An outline of MSSG configuration is described in section 2. Regarding accurate computational schemes, impact of CIP-CSLR schemes is presented. Impacts of turbulence on cloud droplet collisions in meso-scale convective

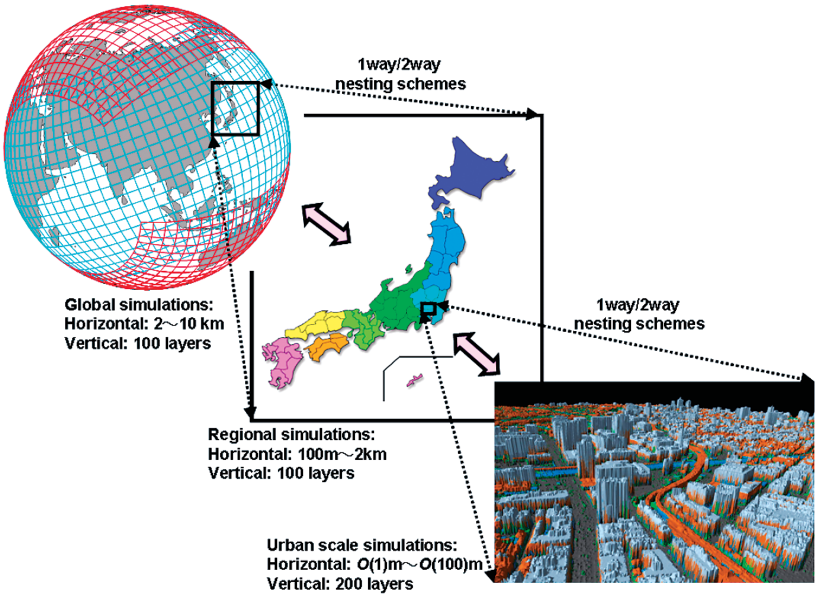

Fig. 1 Scale of MSSG as global/regional models with nesting schemes and resolution.

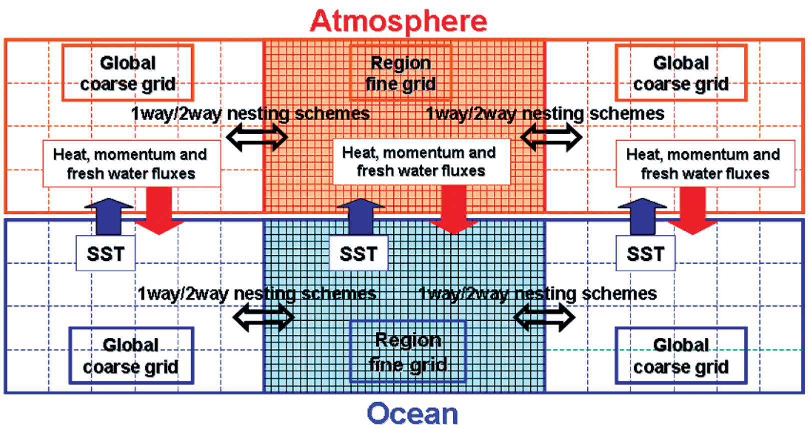

Fig. 2 A coupling strategy of MSSG for global and regional components of atmosphere and ocean.

clouds have been investigated in MSSG-A with sufficiently high numerical resolutions to capture the in-cloud turbulence. Those impacts are presented in section 3. Results of global/regional simulation results with MSSG are shown in section 4. In section 5, future work is described.

2. MSSG model configuration

An atmospheric component of MSSG, which we call it MSSG-A, is a non-hydrostatic global/regional atmosphere circulation model. MSSG-A is compromised of fully compressive flux form of Satomura (2003)[1], Smagorinsky-Lilly type parameterizations by Lilly (1962)[2] and Smagorinsky (1965)[3] for sub-grid scale mixing, surface fluxes by Zhang (1982)[4] and Blackadar (1979)[21], cloud microphysics with mixed phases by Reisner (1998)[5] and cumulus convective processes by Kain (1993)[6] and Fritsch (1980)[7]. Cloud-radiation scheme for long wave and shortwave interactions with both explicit cloud and clear-air are adopted which is based on the scheme in MM5. Over land, the ground temperature and ground moisture are computed by using a bucket model. As upper boundary condition, Rayleigh friction layer is set.

In the ocean component, which we call it MSSG-O, incompressive and hydrostatic/non-hydrostatic equations with the Boussinesq approximation are introduced based on describing in Marshall (1997a)[8] and Marshall (1997b)[9]. Smagorinsky type scheme by Lilly (1962)[2] and Smagorinsky (1965)[3] is used for the sub-grid scale mixing. Algebraic Multi-Grid (AMG) method in Stuben (1999)[10] is used in order to solve a Poisson equation in MSSG-O. In MSSG, we used the AMG library based on aggregation-type AMG in Davies (1976)[11], which has been developed by Fuji Research Institute Corporation.

In both the atmospheric and ocean components, Yin-Yang grid system presented in Kageyama (2004)[20] and Arakawa C grid is used. The atmospheric component utilizes the terrain following vertical coordinate with Lorenz type variables distribution in Gal-Chen (1975)[12]. The ocean component uses the z-coordinate system for the vertical direction. In discritization 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 scheme presented in Wicker (2002)[13] is adopted for the atmosphere component. In the ocean component, leap-flog schemes with Robert-Asselin time filter is used for the ocean component. For momentum and tracer advection computations, several discritization schemes introduced in Peng (2004)[14] are available. 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 with horizontal speed. Therefore, horizontally explicit vertical implicit (HEVI) scheme in Durran (1991)[15] is adopted in MSSG-A.

Conservation scheme was discussed in Peng (2006)[16] and no side effects of over lapped grid system such as Yin-Yang grid were presented due to validations results of various benchmark experiments in Takahashi (2004a,b)[17][18] and Takahashi (2005)[19].

3. Computational / physical model improvements

3.1 Impact of accurate advection scheme: CIP-CSLR

Advection computation with CIP-CSLR in MSSG showed improvement not only computational accuracy but also conservation of mass. The concept of control-volume is adopted in CIP-CSLR. By utilizing a rational function as the interpolation formula, the advection is constructed to be conservative and non-negative.

The heavy rainfall in Kyushu during July 20-25 2006 is simulated with MSSG-A including the CIP-CSLR scheme. 20-km global model was run on 12 nodes on the Earth Simulator. 108-hour forecasting simulation showed much improved rainfall distribution in Kyushu area in comparison with results from simulation used the second-order finite deference scheme. No negative vapor is confirmed in those experiments.

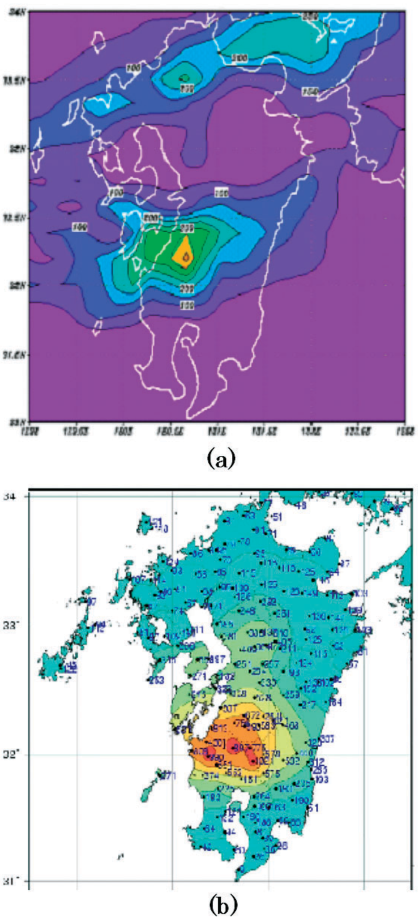

Fig. 3 (a) Distribution results of heavy rain simulation by MSSG-A with 20km horizontal resolution and CIP-CSLR scheme (b) Observational data presented by Fukuoka district Meteorological Observatory.

3.2 Impact of turbulence on cloud droplet collisions

The turbulence strongly impacts to collision growth rate of cloud droplets in-cloud turbulence. Numerical simulations have been performed focused on orographic convective clouds over a mountain. In the simulations, the new collision model is adopted, which we had developed to predict the collision frequency in turbulence. Simulation results have shown that the particle collision growth is dramatically promoted by turbulence (Fig. 4). The total amount of rainfall over the mountain is increased by as much as 20% as shown in Fig. 5. These results suggest that failure to treat the turbulence effect on droplet collision growth leads to significant errors in local weather predictions.

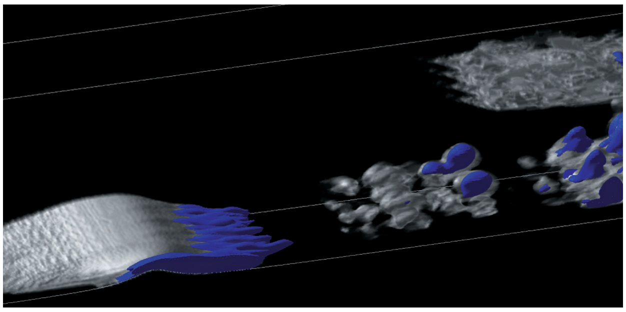

Fig. 4 Volume rendering of water content. (The water content of large droplets (r>100μm) is greater than 0.1 g/m^3 in blue region.).

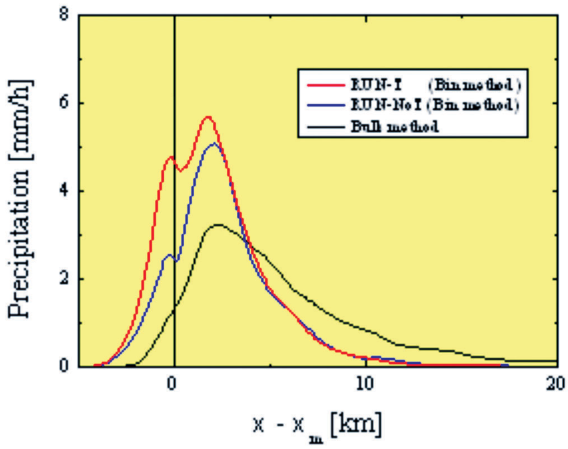

Fig. 5 Spanwise- and time-averaged rainfall rates over the mountain.

4. Global/regional simulations for physical performance validation of MSSG

4.1 Global simulation with 1.9 km horizontal resolution and 32 vertical layers

In MSSG, sophisticated coding style such as memory management and information communication schemes optimized on the Earth Simulator enable us huge simulation. Fig. 6 shows precipitation distribution snapshot of MSSG-A simulation results with 1.9 km for horizontal and 32 vertical layers. In this simulation, diurnal cycle of precipitation in Indonesian region and fine structure of fronts are represented.

4.2 Seasonal rainfall simulation with global MSSG-A

Summer seasonal simulations forced SST of each year during 1996-2005 have been performed. Simulations are performed using MSSG-A with 20km resolution for horizontal and 32 vertical layers. In Fig. 7, precipitation distribution results averaged during 1996-2005 are shown, which are comparable with observational data in CMAP. Additional simulation with more fine resolution (10 km resolution for global) are underway. These simulations are the first step to longer integration experiments.

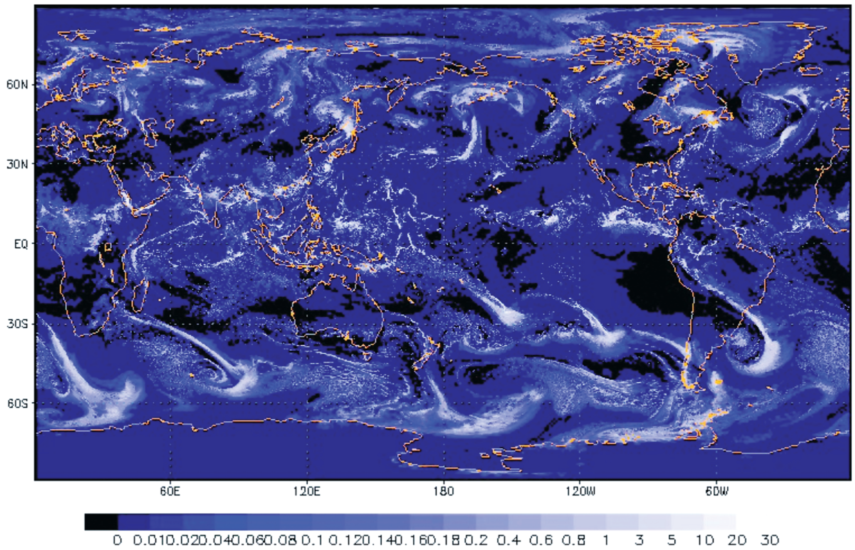

Fig. 6 Precipitation distribution snapshot of global simulation with 1.9 km horizontal resolution (mm/h).

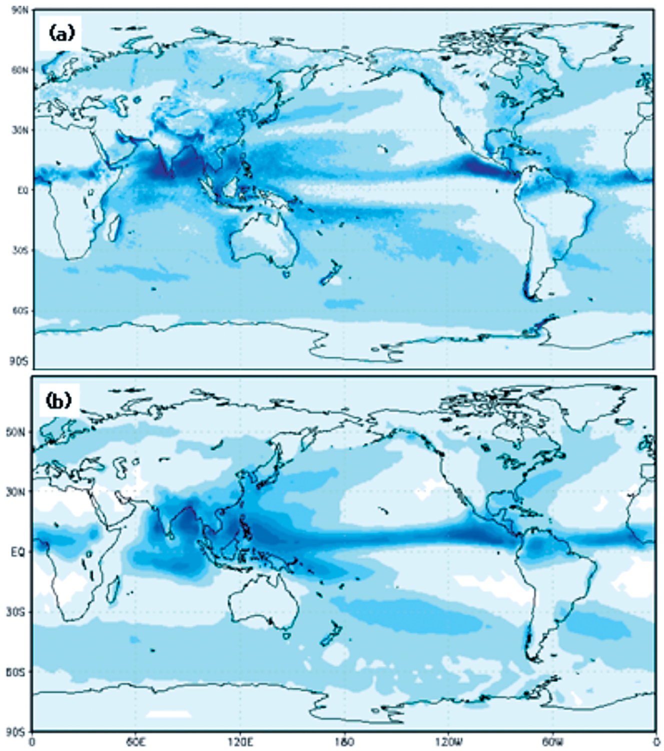

Fig. 7 (a) Simulation results averaged presipitation distribution during summer season, June, July, and August during 1996–2005. (b) Observational data CMAP.

4.3 Simulations of Tracking and intensity simulation of typhoon SHANSHAN in 2006

Validation experiments for forecasting tracking and intensity of typhoons have been performed by global/regional MSSG-A with 1-way nesting schemes. Fig. 8 shows results of real time simulations for 72 hours forecasting of SHANSHAN in 2006. Each colored circle presents every 12 hours initial points of the lowest pressure. Tracking traces results from the initial points are shown as the lines with the same color. Results are comparable with simulation results from other models.

4.4 Simulation results with high resolution regional MSSG-O

In order to validate regional MSSG-O, 1-year integration has parformed with both horizontal resolution 11km for global and horizontal resolution 850 m for regional area surrounded in Tokyo bay, Sagami bay and Suruga bay. In both cases, 40 vertical layers are used. After 10 year spin-up integration by climatological data provided by World Ocean Atlas (WOA), the 1-year integration has been performed. Fig. 9 shows velocity distribution snapshot of each resolution results. Especially, Fig. 9 (b) shows strong impacts of eddies due to disturbances behind islands. Further detail analysis is underway to understand how they modify mean state of the regional ocean.

4.5 Urban scale simulations in central Tokyo

The impacts of LES scheme for boundary layer such as urban can be explored by simulation with MSSG. Marunouchi area in the center of Tokyo is set for the simulation. Experiments were performed with 5m horizontal or vertical resolution. Therefore, buildings can be resolved with anthropogenic heating source. Fig.10 shows horizontal temperature distribution at each height. Dynamics of thermal plume have been represented. Further statistical analysis is underway in order to compare with observational data.

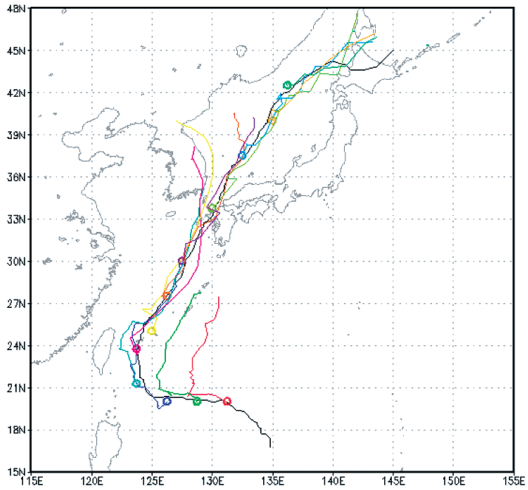

Fig. 8 Real time simulations results every 12 hours of tracking of SHANSHAN.

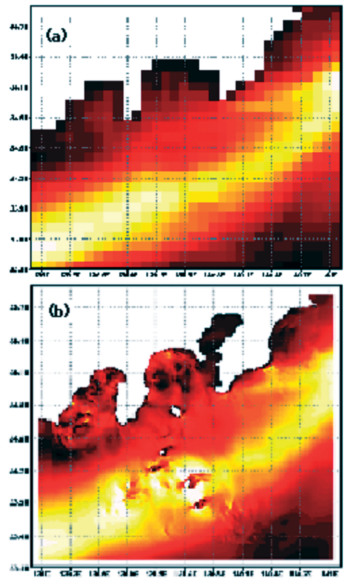

Fig. 9 Velocity distribution in the depth of 100m with global/regional MSSG-O. (a) Zoomed up results of 11 km horizontal resolution simulations with MSSG-O global simulation. (b) Results of 850 m horizontal resolution simulations with MSSG-O.

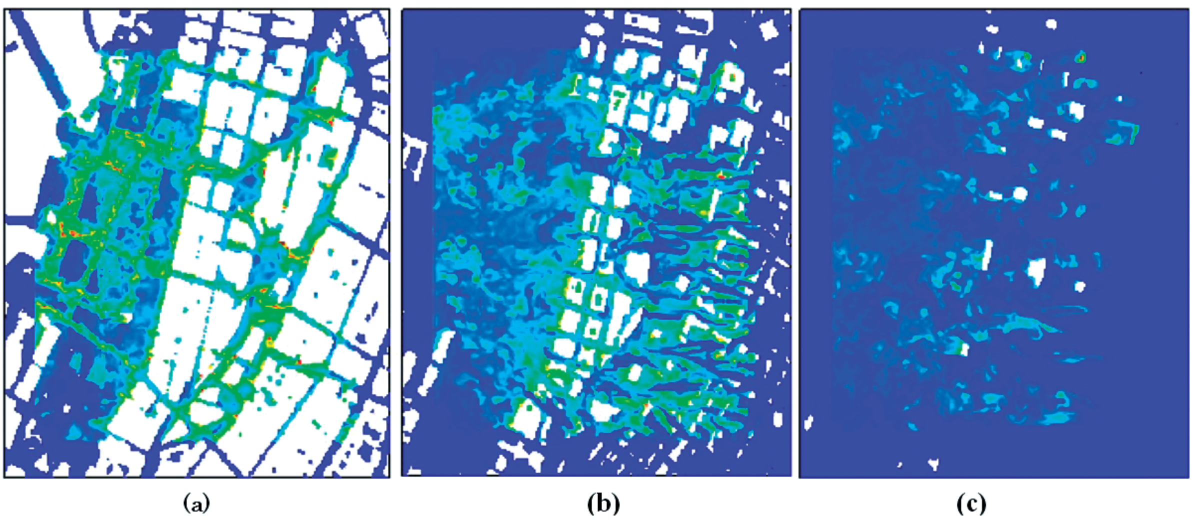

Fig.10 Horizontal temperature distribution at each height. (a) at 7.5 m height, (b) at 32.5 m height and (c) at 102.5 m height.

5. Near future work

In this report, preliminary results of MSSG have presented with some impact. It was clear that process of precipitation was sensitive to high resolution, as previous studies pointed out. Further detail analysis is required for each scale phenomena in order to understand multi-scale mechanics. In addition, implementation of dynamic AMR (adaptive mesh refinement) schemes on MSSG has been almost completed (Fig.11). Multi-scale and multi-physics simulations with MSSG will be ready in real earnest. Experiments for various scale interaction of both atmosphere and ocean will be begun in near future.

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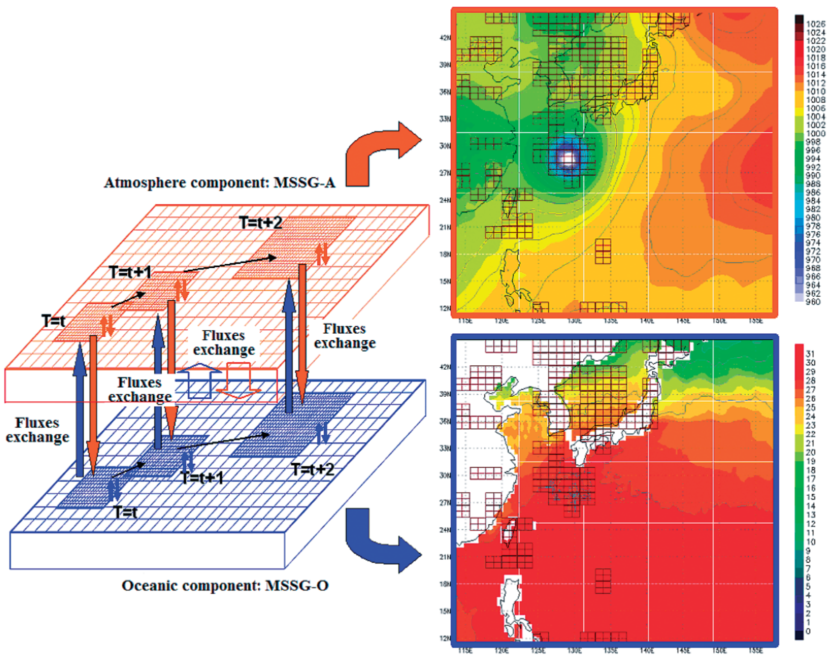

Fig.11 Dynamic adaptive mesh refiment schems in MSSG.

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地球シミュレータセンターにおいて開発している全球および領域対応の非静力学・大気海洋結合モデルMulti-Scale Simulator for the Geoenvironment (MSSG) は、以下の3つの指針を基盤として開発を進めている。

- 高精度な新しい計算手法の研究開発
- 高精度な新しい物理モデルの研究開発
- 地球シミュレータ上での計算性能の最適化

まず、シミュレーションで用いる方程式系の高精度かつ安定に計算可能な数値計算スキームを開発し、それを応用し、そのインパクトを解析し、有効性を示す。ふたつめは、大気、海洋大循環モデルにおける物理過程に着目し、できるだけ現実に即すような、高度なプロセスモデルを研究開発し、そのインパクトを示すことである。さらに、開発した計算スキームや物理モデルを、地球シミュレータ上において計算性能を最適化し、それらを実装したシミュレーションコードMSSG全体としても計算性能を最大限に高めることである。

この開発指針に基づいて、本年度は、下記の成果を挙げることができた。高精度な新しい計算手法という観点からは、

(1) 高精度の移流スキームであるCIP－CSLR法の導入とMSSGへの実装とインパクト評価
(2) 新しい計算格子系としてVoronoi Reduced Gridの提案と計算精度の評価
(3) 全球と領域のそれぞれに対して大気海洋結合モデルとして実装を完了、加えて、全球と領域結合モデルのネスティングスキーム導入による階層スキームの実装
(4) MSSGの大気コンポーネント (MSSG-A) と海洋コンポーネント (MSSG-O) の各コンポーネント、および大気海洋結合モデルMSSGへの動的適応型格子 (dynamic adaptive mesh refinement: dynamic AMR) の導入とマルチスケールモデルへの拡張

高精度な新しい物理モデルの研究開発の観点から、

(5) 乱流効果を考慮した新しい雲微物理モデルの開発とMSSGへの実装
(6) 雲の乱流衝突頻度因子を同定するための新しい逆解析手法の提案
(7) MSSGの大気海洋結合部における風の強さに対する感度実験
(8) 都市スケールに適用する鉛直格子系の開発とMSSGへの実装

地球シミュレータ上での計算性能の最適化アプローチから、

(9) 開発された各計算スキームおよび物理スキームの計算性能最適化
(10) MSSG全体としての高い計算性能の達成。

本報告では、主に (1) と (5) の成果について紹介するとともに、MSSGの物理的性能の検証として、全球、および領域モデルとして設定したMSSG を使用して、高解像度のシミュレーションを行って得られた以下の結果を示す。

- (1) のCIP－CSLR法の導入により、より安定な計算が可能となり、また、高精度の移流計算が可能となった。このスキームの導入により、降水過程における分布を改善し、より観測値に近いものとなった。
- (5) は、乱流効果の雲微物理過程の粒子の生成過程に乱流の効果を取り入れた新しい雲微物理過程モデルである。山岳実験に適用して、乱流効果を考慮することにより、降雨量が約20％増強する結果が得られた。
- MSSG のコーディングをさらに洗練化させることにより、全球1.9km、鉛直32層でのシミュレーションが可能となり、その物理的性能を検証した。
- 夏季3ヶ月の平均場を検証し、特に降雨分布は水平40km、20km、10km (現在も継続中) の異なる解像度での結果を比較検証し、妥当な結果を得た。

- 粗い解像度（水平解像度11km）の全球と日本領域を1-way ネスティング結合したMSSG-Aを用いて、台風の進路と強度のリアルタイム予測実験を行い、観測値と比較して妥当な結果を得た。
- 海洋コンポーネントMSSG-Oを用いた高解像度シミュレーション（水平解像度850m）を行うことにより、外洋と湾内の流れの相互作用、および流れにおける島々の影響を検討した。
- 水平解像度5mの丸の内地区における非定常な天気の流れのシミュレーションを実行した。この都市スケールシミュレーションにおける大気境界層およびLES乱流モデルの物理的な性能を検証するために、サーマルプリュームのダイナミックス、および境界層の発達についての検証を行った。

上記の結果から、本格的なマルチスケール、マルチフィジックスシミュレーションが可能となる段階に入ったといえる。今後は、MSSGのさらなる高解像度の数値計算、および物理過程の高度化を進めるとともに、現在ほぼ実装が完了しているダイナミック適応型格子系を導入したMSSGを使用した際の、気象現象、気候変動現象に対するインパクトの解析を推進する。大気海洋相互作用に対する影響評価を目的に、高解像度のMSSGによるシミュレーションを行い、さらに詳細な解析と評価も並行して推進する予定である。

キーワード：Coupled atmosphere-ocean model, multi-scale, multi-physics, high performance computing, the Earth Simulator