Adaptation Oriented Simulations for Climate Variability

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A coupled atmosphere-ocean-land model MSSG has been developed in the Earth Simulator Center, which is designed to model multi-scale interactions among the atmosphere, the ocean and the coupled system. The MSSG is designed and optimized to be run with high performance computation on the Earth Simulator (ES2) and attained about 32.2 % of the theoretical peak of ES2. Adding to the computational optimization, implementation and its impacts of new computational schemes, several time-space scale simulation results are shown in this report.

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 atmosphere-ocean-land global circulation model, has been developed for seamless simulation based on multi-scale multi-physics modeling strategy in order to predict not only weather but climate variability. Because of the necessary of high performance computation to realize seamless simulation, MSSG is optimized to be run on the Earth Simulator with high computational performance and it is designed to be available with flexibility for different space and time scales.

In this fiscal year, we focus on the following issues

- Improvement of computational performance on the Earth Simulator 2 (ES2) to be fit the architectures of discritization schemes for ultra high resolution simulation,
- Improvement of physical performance of each component of MSSG; MSSG-A and MSSG-O,
  and
- Trial simulation aimed to multi-scale multi-physics simulations

This report summarizes results of our project in FY2010.

2. MSSG Model Improvement

MSSG can be defined not only a coupled model but regional coupled model simulates phenomena with ultra high resolution such as several meters for horizontal which is required in simulations in urban canyon. Furthermore, global simulations are such that global/regional MSSG-A, global/regional MSSG-O, and global/regional MSSG, where MSSG-A and MSSG-O are atmospheric and oceanic components of MSSG, respectively.

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[1], Smagorinsky-Lilly type parameterizations[2][3] for sub-grid scale mixing. In addition, for increasing usage flexibility, MYNN level-2.5 scheme, which is set as new planetary boundary layer scheme, increases predictability at the equatorial region and produces sustainable deep-convection. Surface fluxes[4][21] is adopted in MSSG. Cloud microphysics with mixed phases[5] and cumulus convective processes[6][7] are selected depending on grid scales. Simple cloud-radiation scheme based on the scheme in MM5 for long wave and shortwave interactions with both explicit cloud and clear-air are adopted and a new radiation scheme, MSTRNX

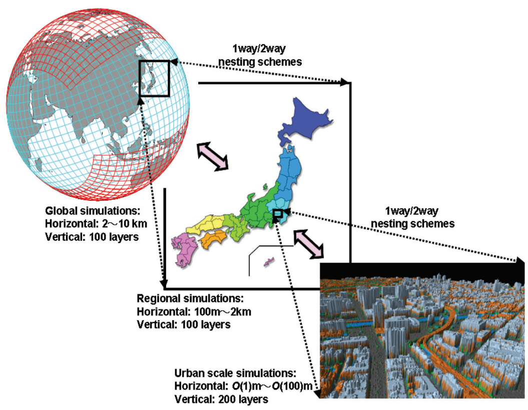

Fig. 1 Scale of MSSG as global/regional models with nesting schemes and resolution.

which solves large negative temperature bias in global scale, are introduced in this fiscal year. 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/nonhydrostatic equations with the Boussinesq approximation are introduced based on Marshall's methods[8][9]. Smagorinsky type scheme[2][3] are used for the sub-grid scale mixing. Algebraic Multi-Grid (AMG) method[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[11], which has been developed by Fuji Research Institute Corporation.

In both MSSG-A and MSSG-O, Yin-Yang grid system for the global[20] and Arakawa C grid is used. In MSSG-A, both the terrain following vertical coordinate with Lorenz type variables distribution[12] and z-coordinate are introduced. Each of coordinate are adopted to be suitable to grid scale objectives. MSSG-O uses the z-coordinate system for the vertical direction with partial cell which is introduced in this fiscal year. In MSSG-A, the 2nd, 3rd and 4th Runge-Kutta schemes and leap-flog schemes with Robert-Asselin time filter are available. In MSSG-O, leap-flog schemes with Robert-Asselin time filter is used. For momentum and tracer advection computations, several discritization schemes are available. In this study, the 5th order upwind scheme is used for the MSSG-A and central difference is utilized in MSSG-O. In this fiscal year, WENO scheme is introduced and its impact is analyzed as described in flowing section. Horizontally explicit vertical implicit (HEVI) scheme [15] is adopted in MSSG-A.

Conservation scheme was discussed [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[17] [18] [19].

3. High performance computing of MSSG

Considered those characteristics of the architecture of the Earth Simulator (ES2), MSSG is further optimized on it. The computing performance of MSSG-A is tuned as follows,

- loop interchange for the increased loop length,

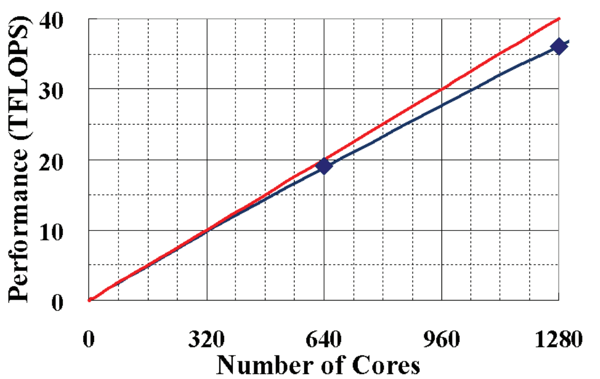

Fig. 2 Sustained performance of MSSG-A.

- shortening of computing time by eliminating redundant arithmetic operations using sqrt (square root) and cbrt (cubic root),
- reduction of Byte/Flop ratio with loop unrolling and exploitation of ADB,

and

- mitigation of interdependency among arithmetic operations by rearrangement of instructions with the assembler language.

After the performance tuning, the wall-clock time for the entire MSSG program on the 160 ES2 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%). Computational performance statistics of main modules of MSSG-A on ES2 has achieved 18GFLOPS per one CPU of ES2.

Horizontal resolution 3 km and 32 vertical layers for the global was also conducted with the 80 ES nodes (640 cores). The measured wall-clock time is 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 2 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%. As the results of optimizing, MSSG demonstrates excellent strong scaling.

4. Physical performance improvements in MSSG

State-of-the-art tracer advection schemes, Weighted essentially non-oscillatory (WENO) scheme was introduced to MSSG-A in this fiscal year. In addition, physical validation of WENO scheme (WM) , monotonic (MO) flux limiters, modified PD (MPD) and Wicker and Skamarock (WS) scheme are examined by cloud-resolving simulations of the squall-lines. In fig. 3, lateral structure of the squall-lines simulated by different tracer advection schemes using 1-km resolution are compared. Simulated structure of the squall-lines is different comparing among the results with individual advection schemes. Those impacts to physical performance imply that the accuracy of tracer advection scheme has a great influence on the reproducibility and predictability of atmospheric state.

In MSSG-Ocean model, two major model components "Open Boundary Condition" and "Surface forcing" were pursued. Off-line nesting was set by clamping temperature, salinity, and velocity fields to external file or prescribed setting at the boundaries. Restoring and damping regions were also implemented near the lateral boundaries for reducing numerical noise. To improve external forcing and temperature fields at the sea surface, bulk flux formula based on COARE3.0 was also implemented. Furthermore, tidal mixing on the sea surface temperature, its 1st order process was implemented based on a simple parameterization scheme. It was clear that vertical mixing with the tide was intensified in the Indian Ocean (Fig. 4). The numerical stability of partial cell method and Mellor-Yamada 2.5 Mixing scheme was also improved for long-term integration in highly varying topographic region such as the Indonesian Seas.

5. Trial simulations for adaptation to climate variability

After tuning in computational and physical schemes, for the first step to execute simulations for the adaptation in climate variability, we focus on two of different time-space scales. One is a trial simulation to validate the reproducibility of Madden Julian Oscillation (MJO) which is well known as multi-scale phenomena. The other is a simulation with urban scale resolution.

MSSG-A was set to 20 km horizontal resolution and 53 vertical layers and one month integration from 15th December 2006. Figure 5 shows a simulation result of precipitation to represent MJO with MSSG-A. Although volume of precipitation

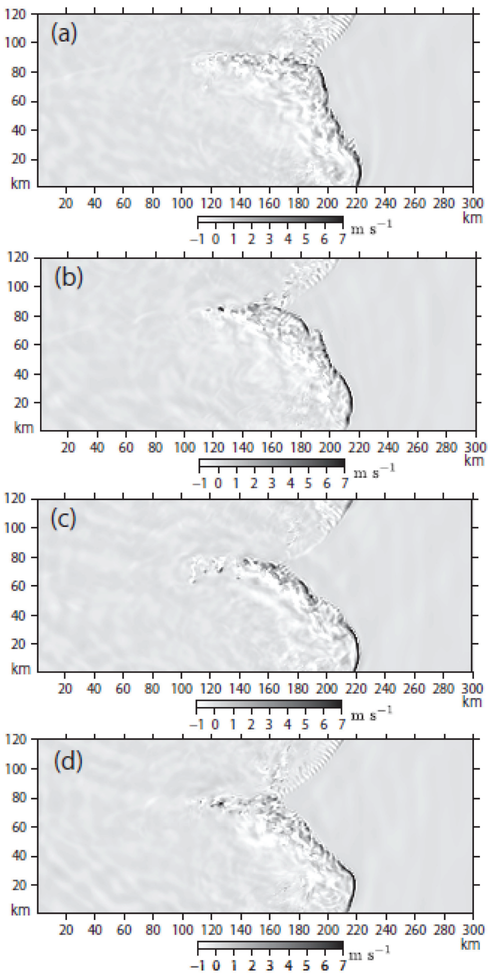

Fig. 3 Lateral distributions of vertical wind speed (left) and temperature (right) at 1400m height and at 5 hour. Results with (a) WS,(b) WM,(c) MPD and (d) MO, respectively in cloud-resolving simulations of the squall-lines with 1-km horizontal resolution.

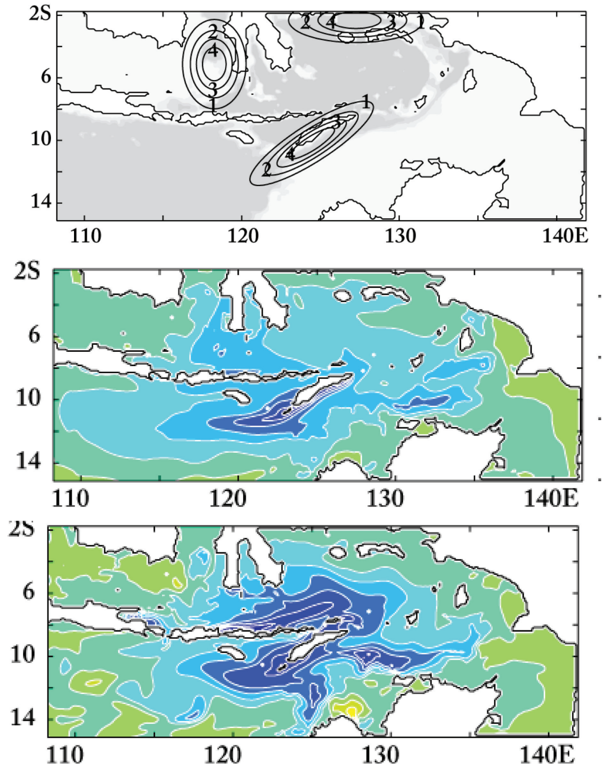

Fig. 4 The impact of tidal mixing to sea surface temperature. Top: region of the Indian Ocean with strong tidal mixing, middle: effect of tidal mixing on annual sea surface temperature and bottom: effect on summer season.

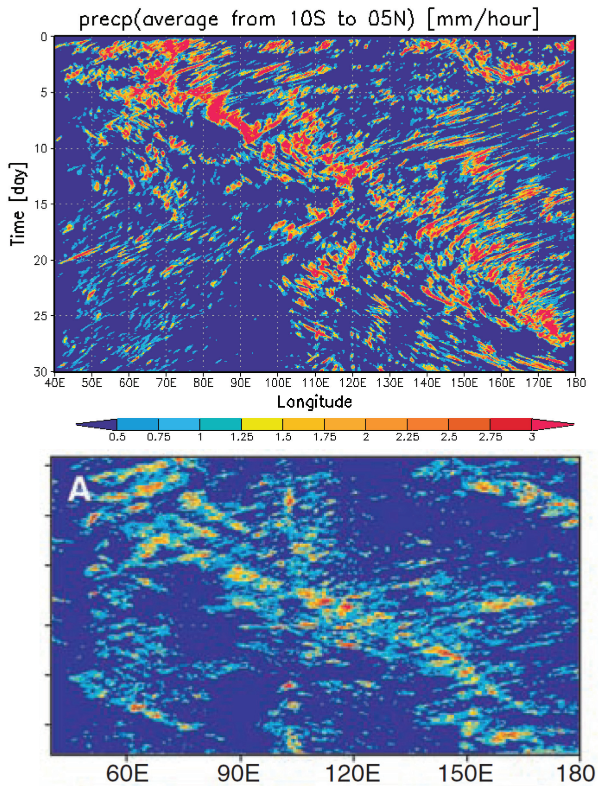

Fig. 5 Longitude-time plot of precipitation (mm/h) averaged in the area 10S-5N. Upper: a simulation result with MSSG-A, bottom: observational data by TRMM 3B42.

tends to be more than the observational data by TRMM, typical multi-scale structure of MJO has been captured in the simulation.

In urban scale simulations with O(1m) resolution, river reproduction such as Sakura river and Kyobashi river in Kyobashi-ku is considered as one of the possible strategies to adapt climate variability (Fig. 6). In figure 6, simulation results under conditions that both Sakura river and Kyobashi river are reproduced or not produced. Simulation results show the impact of settled water surface such as rivers in urban area. The existence of a river suggests the change of not only temperature and horizontal wind field (Fig. 7) but of vertical wind field structure up to 300-500m height (data not shown).

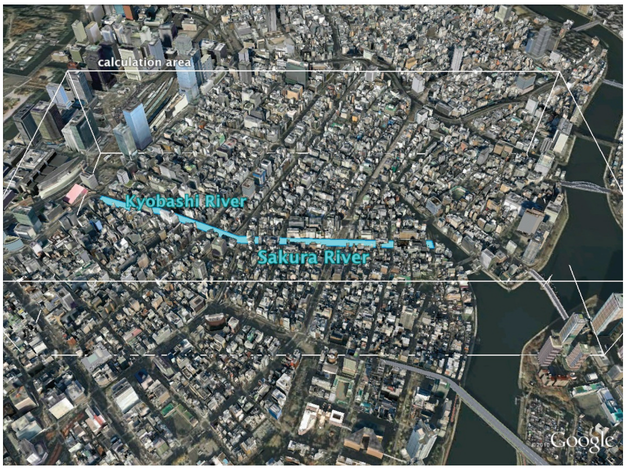

Fig. 6 Region for urban scale simulation with 5m of horizontal and vertical resolution.

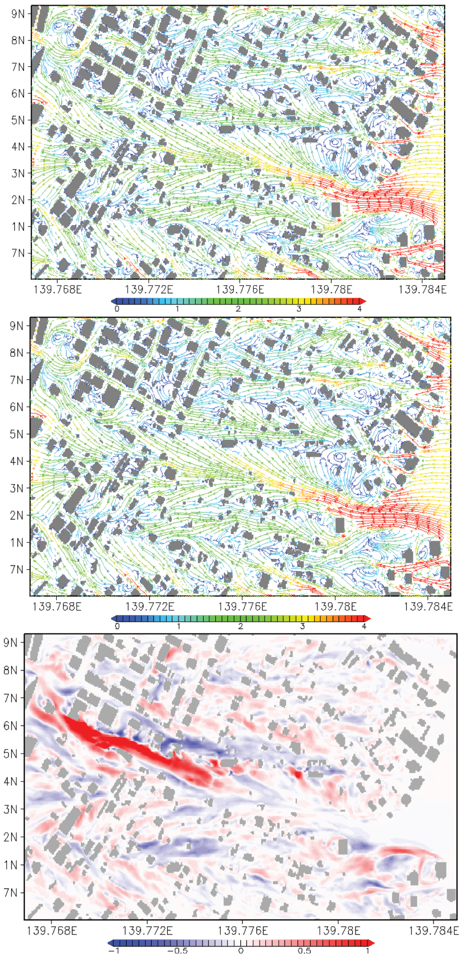

Fig. 7 Lateral wind velocity field (m/s) at 32.5m height, (a) without rivers, (b) with rivers and (c) differences between (a) and (b).

6. Future work

In this report, we presented optimized computational performance of MSSG and improvements of physical performance in MSSG due to state-of-art schemes were introduced. Furthermore, preliminary results were shown in order to perform multi-scale simulations to estimate strategies of adaptation in climate variability. Simulation results were comparable to observational data for each of scale simulation. These results encourage us to promote further large multi-scale simulations. In near future, we are planning to validate the representation of El Niño by longer integration. The further possibility of multi-scale simulations will be validated by showing whether climate in urban area will be predictable or not under the condition of climate variability.

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気候変動に適応可能な環境探索のための マルチスケールシミュレーション

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ES2 上における計算性能最適化をさらに推進した結果、ES2 160 ノード上で 42.2TFLOPS、理論ピーク性能比 32.2% を達成した。また、高速化とともに並列性能を向上させ、1280 コアと 640 コアから推定した並列化率は 99.9915% であり、非常に高いスケーラビリティを実現した（図 1)。

MSSG のモデル開発では、トレーサ移流計算手法に新たなスキームを導入し（Weighted essentially non-oscillatory (WENO) スキームなど）、それらのスキームの精度が鉛直対流現象にどのような影響を与えるかを評価し、WENO スキームの再現性がよいことがわかった。また、海洋コンポーネント MSSG-O において、潮汐混合モデルを新たに導入し、鉛直混合過程へのインパクト再現実験を行った結果、観測とよい一致を得た。

また、季節変動現象を予測し、その変動が都市 / 領域スケールの気象・気候現象へどのような影響を与えるかを予測する本プロジェクトの本来の目的のためのテストシミュレーションとして、まず、MSSG-A を用いて、1 か月積分のテストとして MJO の再現実験を行った。観測と比較した結果、東進、西進のマルチスケールな雲構造が再現できることを確認した（図 2)。さらに、時間･空間スケールが最も詳細な都市計画の施策の評価のために、水平、鉛直ともに 5m メッシュで京橋地区の河川の再現の有無に対する大気状態の変化をシミュレーションし、解析した。その結果、京橋川、桜川の再生により、再生地域の大気の水平構造だけでなく、鉛直構造へも影響を与えることがわかった。

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

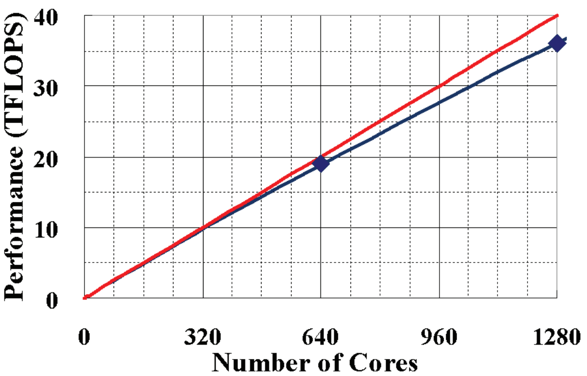

図 1.　MSSG-A の計算性能スケーラビリティ

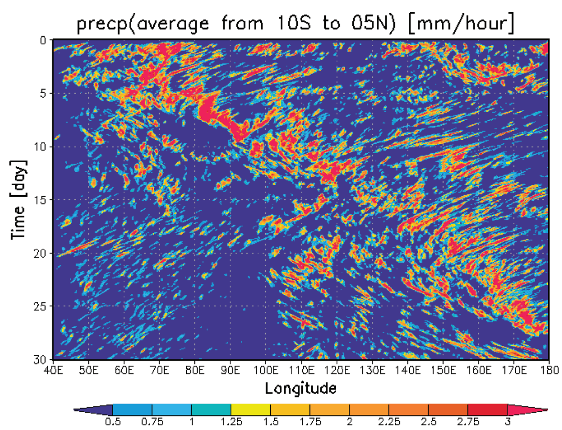

図 2.　MSSG-A による MJO 再現のためのテストシミュレーション結果