Adaptation Oriented Simulations for Climate Variability

Project Representative
Keiko Takahashi
Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology

Authors
Keiko Takahashi*1, Ryo Ohnishi*1, Takeshi Sugimura*1, Yuya Baba*1, Shinichiro Kida*1, Koji Goto*2 and Hiromitsu Fuchigami*3

*1 Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology
*2 NEC Corporation
*3 NEC Informatec Systems LTD

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). Adding to the computational optimization, advanced cloud micro-physics with turbulence effects, implementation of new computational schemes enables to show preliminary results of multi-scale simulations. Several preliminary results to understand mechanism with several different scales are presented 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. MSSG is designed to realize seamless simulations with difference scales from global scale to urban city scale, in other words, from climate to weather (Fig. 1). Because 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 [1, 2, 4].

In this fiscal year, we focus on the following issues

- Improvement of accuracy of computational schemes and physical performance of MSSG-A and MSSG-O.
- Computational performance index to show the effect strategy to optimize on the Earth Simulator 2 (ES2), actually the index will be useful on other type of super computers.
- Several simulations have been performed to validate physics in multi-scale multi-physics simulations.

This report summarizes a part of results of this project in FY2011.

2. MSSG Model Improvement

For improving cloud-resolving model using MSSG, developments of both advection scheme were conducted. In the development of advection scheme, WENO scheme is focused

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

Fig. 2 Solutions of 1-dimensional advection-condensation problem to compare computational accuracy among schemes.
on as the advection scheme which can capture cloud edge well and has similar formulation with ordinary flux limiter scheme (Fig. 2). The WENO scheme is tested using several idealized experiments, and is found that the scheme can capture the cloud edge especially its energy properties. It is also found that convection cycle in deep convection is enhanced when the cloud edge is captured sharply with the WENO scheme. As the results of those validations, due to the fact that the WENO scheme can capture cloud edge more sharply, buoyancy of the cloud edge is simulated without numerical diffusion, and thus the condensation is enhanced (Fig. 3). This suggests that numerical methods play important roles to improve physical performance of models.

In addition to computational schemes in MSSG-A, cloud microphysical scheme has been improved (Fig. 4). The MSSG-Bin, an original warm-bin/cold-bulk hybrid cloud microphysical model, provides accurate simulations of liquid droplet growth, free from the approximations made in bulk parameterizations. The bulk formulation for cold-rain processes avoids the uncertainties in the governing equations for complex-shaped ice particles. This hybrid approach is believed to provide an attractive alternative to the so-called full-spectral bin models, which consume greater computational resources but still require tuning parameters for cold-rain processes. The size independent interface (SII) was implemented in the MSSG-Bin as an
interface between the bin and bulk components. In this fiscal year, the size-dependent interface (SDI) has been developed and implemented in the MSSG-Bin. This enables to keep the size information and computes the interaction between each bin and the ice categories separately. The comparison between the SII and SDI has provided insight into the sensitivity to the hybrid interface (Fig. 5) [3].

MSSG-Ocean model (MSSG-O) is developed to simulate oceanic flow field and tracer fields on various spacial and time scales along with numerical stability and reasonable precision. For this fiscal year, the development of the MSSG-O [5] was focused for its usage as a high-resolution regional model and a basin scale model based on hydrostatic primitive equations. Various process models were also implemented to MSSG-O for complex simulations needed to simulate coastal features and radionuclides.

As a high-resolution regional model, a dispersion model with a focus on radionuclides, a river inflow model, and a tidal forcing model were developed. The dispersion model successfully simulates the C134s along the coasts of Fukushima. The river inflow model also successfully simulates the steady inflow of freshwater input within Tokyo bay. The high-resolution basin scale model was validated using biharmonic mixing or COARE3.0 bulk-flux formula.

3. Trial simulations for adaptation to climate variability

In the evaluation of urban thermal environment, effect of river existence in urban area was focused on (Fig. 6 and Fig. 7).

The results of idealized experiments showed that net effective temperature in the urban area decreases due to the open space which is created by the existence of the river. The river has two effects on heat flux, i.e., it decreases sensible heat flux whereas increases latent heat flux. Therefore the results indicate that urban design intending to improve the thermal environment should consider the balance between such sensible heat decrease and latent heat increase (Fig. 8).

Interaction between urban area environment and ocean/water front affects temperature distribution over the land and

![Fig. 6 Simulation conditions to validate heat storage mechanism in urban area.](image)

![Fig. 7 Simulation conditions of each case.](image)

![Fig. 8 Differences of temperature distribution in the case of existence of a river or not, which is corresponding to (a), (b) and (c). (d) and (e) show temperature distribution differences due to building-to-land ratio. (f) shows temperature distribution in difference cases of water front area.](image)

![Fig. 9 Temperature (upper) and wind speed (bottom) distributions in the case of warm ocean are showed. Blue lines present the results at 0m (bottom line), 10 km (middle) and 20 m (upper) far from water front. Red dot line shows temperature or wind speed distributions at 10 km far from ocean front in the case of cold ocean simulation.](image)
ocean. Figure 9 shows the results from the differences of heat transfer by land and sea breeze. Those results suggest its impact to environment in the urban area may change due to climate variability.

Several heavy rain simulations over Kanto metropolitan area are performed to test model reproducibility for urban meteorology. Simulated rainfall is in good agreement with observation in terms of timing and location, however, statistical properties for the heavy rain reproducibility is still uncertain if the number of simulation cases is too small. Therefore regional climate model for Kanto metropolitan area is now being constructed.

4. High performance computing of MSSG

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 its simulation results with the world-highest 1.9 km horizontal resolution for the entire globe and a 5 m resolution for an urban area. To gain high performance by exploiting the system capabilities, we propose novel performance evaluation metrics that incorporate the effects of the data caching mechanism between CPU and memory. A potentially attainable computational performance is also introduced by evaluating both computational and memory intensities. The performance indicators introduced in this study are found to be effective in assessing the performance of actual application programs and obtaining a guideline for performance optimization (Fig. 10). By fully utilizing such information, MSSG-A was successfully optimized with a high sustained performance of 42.2 TFLOPS (peak performance ratio of 32.2%) on the 160-node full Earth Simulator system [6].

5. Future work

In this report, we presented advanced schemes introduced in MSSG and improvements of physical performance in MSSG due to state-of-art schemes were introduced. The novel index to optimize computational performance of MSSG. Furthermore, preliminary results were shown in order to perform multi-scale simulations to estimate strategies of adaptation in climate variability. In near future, we are planning to validate the representation such as El Nino and Indian Ocean Dipole 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.

References

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

プロジェクト責任者
高橋 桂子 海洋研究開発機構 地球シミュレータセンター
著者
高橋 桂子*1, 大西 領*1, 杉村 剛*1, 馬場 雄也*1, 木田新一郎*1, 後藤 浩二*2
渕上 弘光*3
*1 海洋研究開発機構 地球シミュレータセンター
*2 NEC 株式会社
*3 NEC インフォマティックシステム株式会社

MSSG-A（大気大循環モデルコード）、MSSG-O（海洋大循環モデルコード）、MSSG（大気海洋結合モデルコード）それぞれに対して、短期の事例再現シミュレーションを実行し、特に豪雨については、再現性を飛躍的に向上した。この再現性の向上は、移流スキーム、雲微物理過程スキーム、放射過程スキーム、境界層スキームそれぞれのスキームとモデルの高度化とそれらの検証結果の積み上げが基盤となっている。MSSG-Oにおいて、水平Bi-harmonic粘性・拡散を新たに導入し、高解像度かつ長期シミュレーションが安定して実行できるようにモデルを高度化した。その結果、潮汐・黑潮・親潮等、強いる流れの影響を受ける海域でも安定な実験が可能となり、東京湾・日本海・オホーツク海と外洋の相関作用が再現可能であることを示した。さらに、領域モデルからはIOD、ENSO、インドネシア通過流が経年変動を引き起こす季節と領域が限定されていることが明らかになった（図参照）。

世界にも着目されている複数の物理過程の連成モデルの開発に注力し、特に、乱流と降雨過程の関連性は、予測精度に大きな影響を与えることを明らかにした。加えて、雲乱流を扱えるハイブリッド法を提案し、高い信頼性と精度で積雲を再現できることを示した。

事例予測シミュレーションとして様々なスケールでダウンスケーリングシミュレーションを実施し、MSSGの有用性を明らかにした。対象は、都市を対象とした微気象現象、メソスケール気象現象、低気圧の生起から消滅までの総観スケール現象を対象とした系統的実験を実施し、現在、その統計的解析と検証を行っている。また、都市スケールにおける気象現象への海洋の影響について、MSSGを用いて理想実験を実施し、海面温度、海陸風の影響によって、都市域の気象が数時間スケールで影響を受ける可能性を明らかにした。

計算最適化については、計算性能をどのような最適化指針に基づいて実施してゆくべきか、という課題に取り組み、この指針を与えるための新たな計算性能指標を提案した。この新しい指標は、従来から用いられてきたメモリアクセス負荷と計算負荷の混在を許容する指標とは異なり、メモリと計算負荷のいずれに起因する計算コスト負荷であるかを解析した、実機のハードウェア動作に基づいた指標である。この指標に基づいて、実アプリケーション（MSSG）の計算性能最適化を行った結果、計算性能を効率的向上可能であることを示した。

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

図: インドネシア多島海における潮汐混合法と季節変動