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. Aiming to seamless simulation, cloud micro-physics from the both view points of the accuracy of advection computation and high computational performance and oceanic part downscaling were improved and those results are summarized. In addition, three dimensional radiation scheme was developed and its impact was shown. The trial simulation for investigate regional climate variability was performed and its result was 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 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, 3, 4]. In this report, summarizes a part of results of this project in FY2012 that focus on the following themes to execute seamless simulations with MSSG.

- In order to improve one of the main performance in seamless simulation, cloud micro-physics from the both view points of the accuracy of advection computation and high computational performance were improved.
- Oceanic part downscaling is also important for seamless simulation with a coupled model MSSG. We developed the numerical model is based on a three dimensional particle random-walk model for improvement in the coastal region and validated improvement of physical performance in coastal region.
- Development of three dimensional radiation model regional climate model with MSSG for seamless simulation to consider an adaptation strategy for climate variability.

2. Advection scheme improvement in cloud physics process

The weighted essentially non-oscillatory (WENO) scheme is applied to a cloud resolving model and is used for the cloud edge problem [5]. Validity is tested using three idealized experiments and the results are compared with those of recent

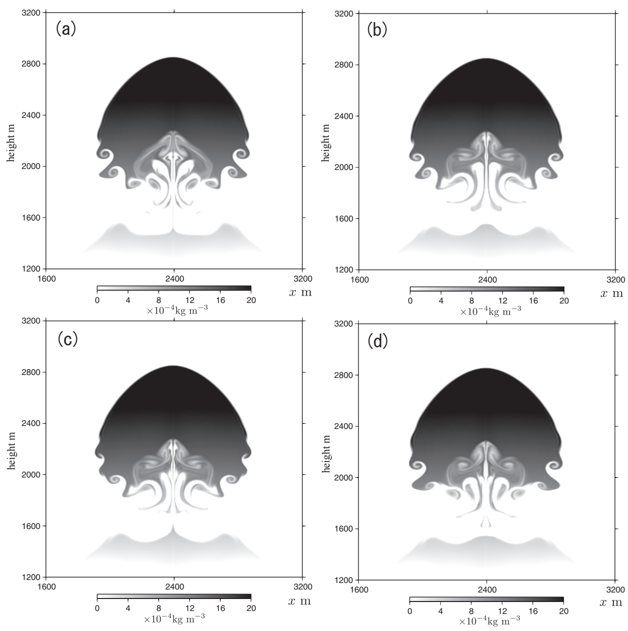

Fig. 1 Simulation results comparison on cloud water distributions. (a)WE5: (b) WE5-PUP: (c)WS5-PUP: and (d)WS5-MUP. 5m resolution was used [5].

flux corrected transport (FCT) schemes, i.e., PD and MO flux limiters. The WENO scheme simulates the energy properties of cloud edges better than the FCT schemes do [5].

A one-dimensional advection–condensation problem is first performed to investigate the advection scheme's ability to capture the cloud edge. The original WENO scheme is found to be able to capture the cloud edge well. The WENO scheme with PD flux limiter avoids disadvantage that it produces a negative mixing ratio, and the scheme shows the smallest errors for all prognostic variables, especially for potential temperature. An ordinary PD flux limiter cannot capture the potential temperature jump, since it was originally developed to avoid a negative mixing ratio. On the other hand, the accuracy of the MO flux limiter is lower than that of the WENO scheme because it has numerical diffusion at the cloud edge [5].

In a two-dimensional shallow cumulus convection experiment, the WENO scheme was applied to the advection of mass and energy, accuracies for temperature and cloud water increase. Cross-sectional analysis on the shallow cumulus indicates that the cloud edge properties correspond to the overall temperature and cloud water trends, and the WENO scheme simulates less evaporative cooling and cloud water evaporation. These facts indicate that the WENO scheme also works well to capture the cloud edge compared to the FCT schemes (Fig. 1)[5].

Squall line experiment was performed to verify the effect of advection schemes in simulating deep convection. When the WENO scheme is applied to advections of mass and energy, enhancements of both buoyancy and condensation, resulting in production of more water species, occur. It was found that the enhancements are caused by a larger and colder cold pool formed below the squall line, which is formed by the enhanced convective downdraught cloud mass flux due to the employed advection scheme [5].

3. Development of high performance computational scheme for droplet collision process: BiSM (the binary-based superposition method)

While moving in a flow medium, a particle induces a flow disturbance in its neighborhood. The disturbance may intervene between particles for the so-called hydrodynamic interaction (HI). The particle Reynolds number based on the gravitational settling velocity for cloud droplets in the atmosphere is of the order of 0.01-1.0. It is a good start to assume the disturbance flow to be a Stokes flow. Wang et al.(2005) pointed out that the original superposition method (OrgSM, hereafter) does not satisfy the no-slip boundary conditions for multiple particles in the system. Ayala et al. (2007) developed an iterative superposition method (ItrSM, hereafter). ItrSM is more reliable but computationally expensive due to its iteration procedure. For example, it was reported that about 95% of the computational time was consumed for the ItrSM in a simulation for a system of 200,000 monodisperse particles in a turbulent flow on a 64^3grid. The developed the binary-based superposition method (BiSM) proposes an intermediate method between OrgSM and ItrSM in terms of both computational cost and reliability [6].

In the binary-particle system shown in Fig. 2(a), the solution is directly obtained by BiSM and iteratively obtained by ItrSM. There is no error in BiSM compared to ItrSM. In a system containing three particles is shown in Fig. 2(b), BiSM ignores interactions via three or more particles [6].

Figure 3 shows the collision efficiency E_c between r_1 and r_2 particles in a stagnant flow. The solid line is from results which adopts ItrSM. The results from OrgSM tend to produce larger values than ItrSM and BiSM. The consistency among ItrSM and

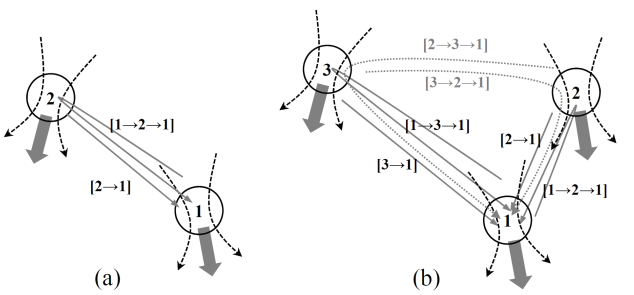

Fig. 2 (a) binary-particle system and (b) triplet-particle system.

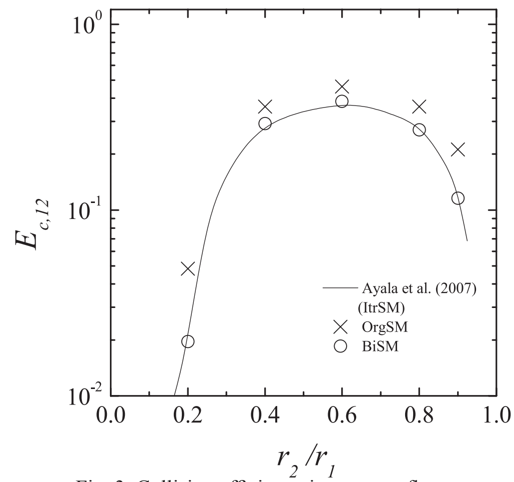

Fig. 3 Collision efficiency in stagnant flow.

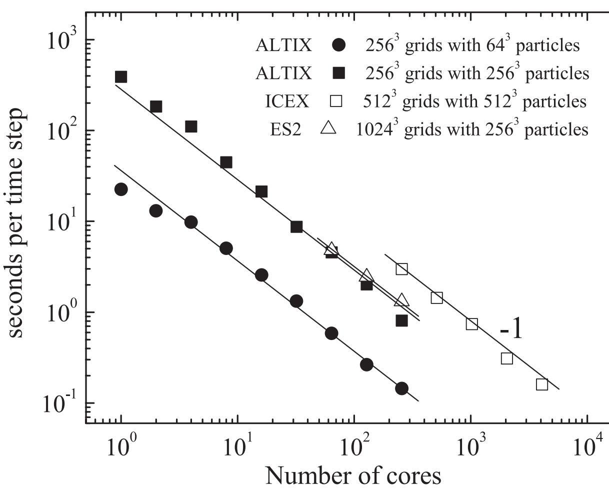

Fig. 4 Wall clock time versus number of cores for different number of particles and flow grids on ALTEX, ICEX, and ES2.

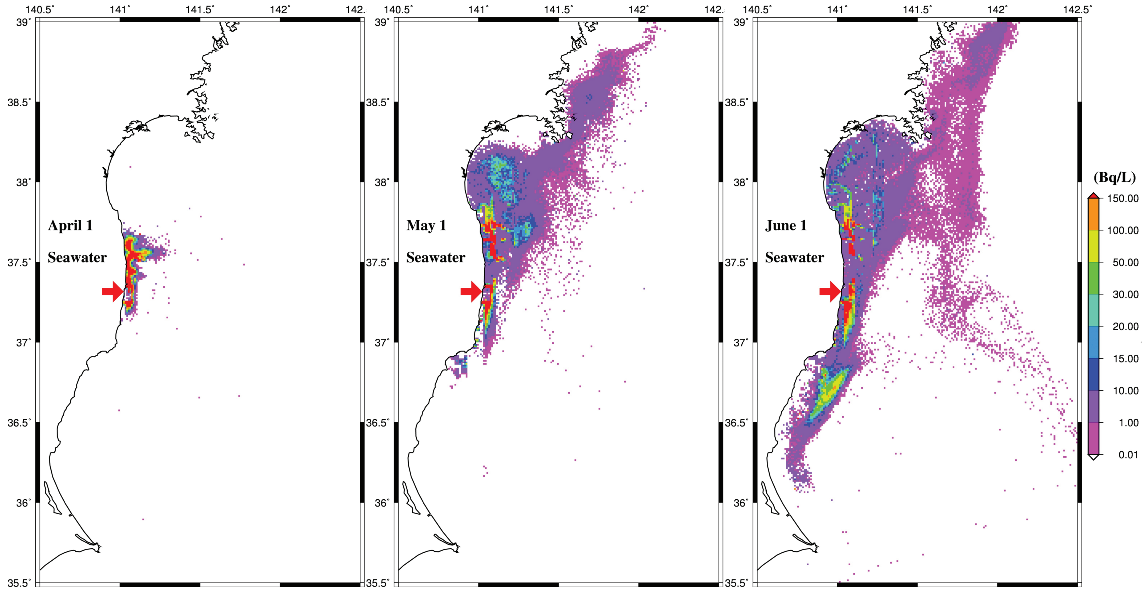

Fig. 5 Simulation results of 134/137 Cs in seawater (Bq/L) at April 1st (left), May 1st (center), and June 1st (right), respectively [5] .

BiSM confirms the reliability of BiSM for collision efficiency calculations in a stagnant flow [6].

Under a typical dilute condition as in atmospheric clouds, the computational cost of BiSM is smaller by order of 10 than that of ItrSM, whereas an error of BiSM compared to ItrSM is insignificant. Coupling of the cell-index method with BiSM can reduce the computational cost for paritcle interactions to O(N_p^{σ}), where N_p is the total number of particles and $1<\sigma<2$, from O(N_p^2) (Fig. 4)[6].

4. Coastal region downscaling improvement in ocean part of MSSG

In the seamless simulation, oceanic part downscaling is also important scheme. For the improvement and validation of physical performance in coastal region, we developed the numerical model is based on a three dimensional particle random-walk model and a z-coordinate ocean general circulation model MSSG-O. The simulation for radionuclide concentrations obtained from the density of particles per unit volume water was performed and validated. Experiments have been carried out for 137Cs for 4 months and the results show that coastal currents and meso-scale open oceanic eddies having large influence on the behavior of the radionuclides. The radionuclides in coastal currents remain along the coast where as the one in meso-scale open oceanic eddies rapidly escape to the interior of the Pacific along the Kuroshio extension. Depositions of radionuclides on sediments are mainly occurred during the first several months [7].

Figure 5 shows the distribution of 134/137 Cs in seawater. The initial peak is very well reproduced in the simulation results with our model MSSG-O. A too fast decrease in concentrations is again produced. During the first 2 weeks after the discharge, the great part of radionuclides flow into the Sendai Bay by the northward currents in the Sendai Bay. After 40 days, the radionuclides are distributed into the open oceans. In June 1st, the radionuclides discharge into the North Pacific. The discharge route to the North Pacific has two branches. The reason could maybe be related to the existence of the eddy which is observed and reproduced by the ocean model. The first one passes through the anti-cyclonic eddy while the other one follows the cyclonic path along the Kuroshio extension [7].

The most of sediment phase radionuclides deposit in the continental shelf regions (Fig. 6). This suggests that the radionuclides cannot penetrate into deep layers by advection and vertical mixing. The simulated radionuclides in bottom sediments may be caused by the rapid vertical mixing process in the ocean mixed layers [7].

5. Impact of three-dimensional radiation for urban climate

Factors of the heat island effect include three points of (1) increase in thermal capacity of the city with the change of the land use, (2) change of the emission heat transfer with the building and the convection heat transfer and (3) artificial exhaust heat by the use and the industrial activity of a car and the air conditioning. The impact of three-dimensional radiation which is described in (2) is analyzed. The three-dimensional radiation scheme for building-resolved simulation was improved which had been implemented in the MSSG model. The effect of three-dimensional radiative heat transfer on the urban thermal condition is investigated. Simulations started at 15:00 of August 5, 2005 and MSM data of the Meteorological Agency was used as a boundary condition.

Figure 7 and 8 show the three dimensions spatial distribution of long wave emission flux toward the sky in 3D radiation (full S-to-S) and three-dimensional distribution of net longwave radiative flux into the surfaces, respectively. Because sky factor in the alley put in the building is small, long wave emission to

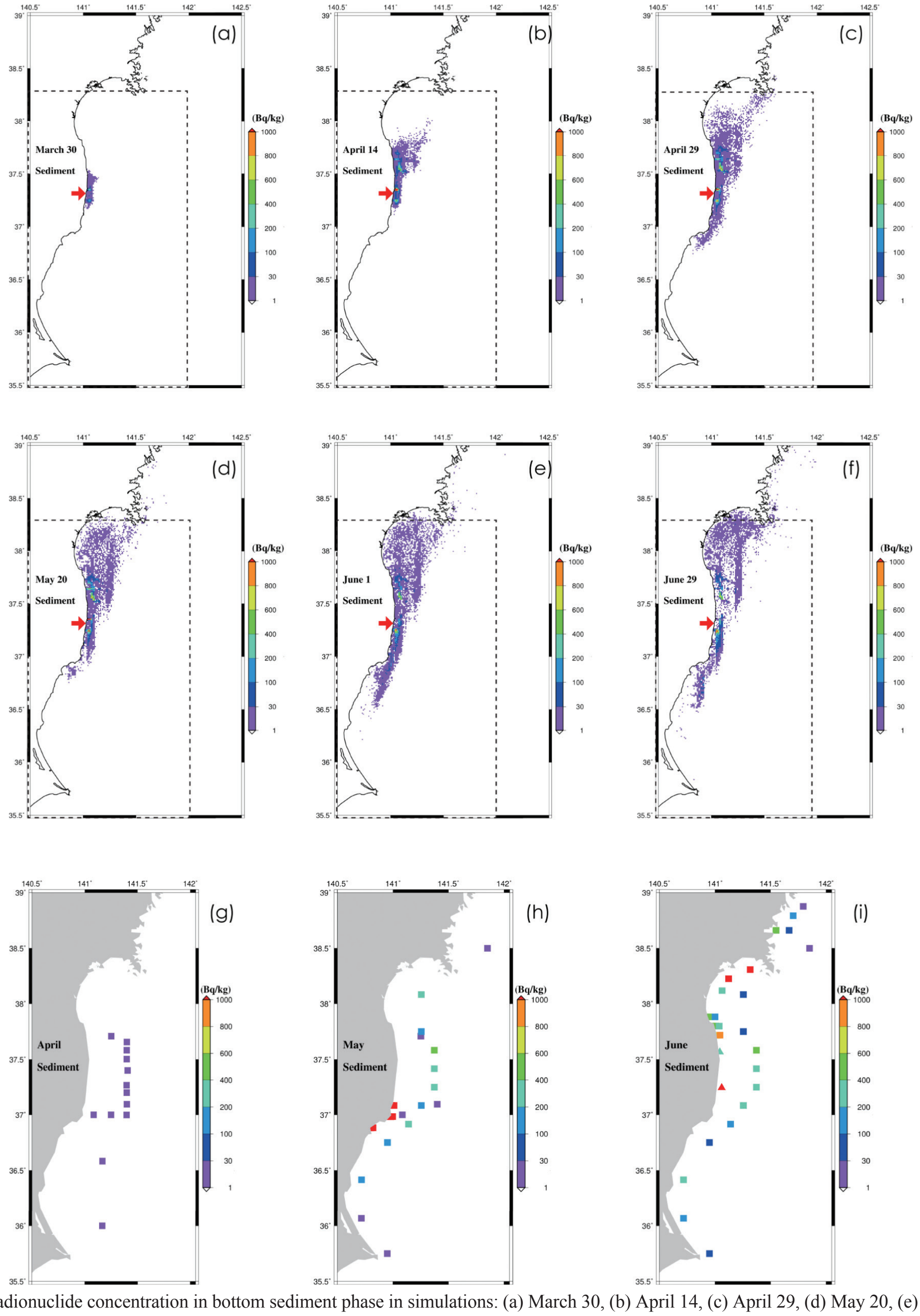

Fig. 6 (a-f) Radionuclide concentration in bottom sediment phase in simulations: (a) March 30, (b) April 14, (c) April 29, (d) May 20, (e) June 1, and (f) June 29, 2011. (g-i) Monthly averages of observed radionuclide concentration in bottom sediments: (g) April, (h) May, and (i) June, 2011[7].

the sky is weak in Fig. 7. In Fig. 8, the net long wave emission flux shows negative value, on the other hand, there is the point indicating positive value in the alley put in the buildings. These results show that radiative cooling is restrained by buildings and that is one of the factor of heat storage in boundary layer.

6. MSSG as a regional climate model

For the first step of seamless simulation to consider an adaptation strategy for climate variability, regional climate model was constructed using MSSG model to simulate urban climate over Kanto plain. Significant uncertainty in the atmospheric model is known to be cloud microphysics, and sensitivity of the urban climate to microphysics is examined. The simulation results with 4 km horizontal resolution show that two-moment microphysics improves trends of intense precipitation compared to one-moment scheme (Fig. 9). Further sensitivity study for horizontal resolution which was used with 4 km in these trial simulations is required for intense rainfall with inaccurate.

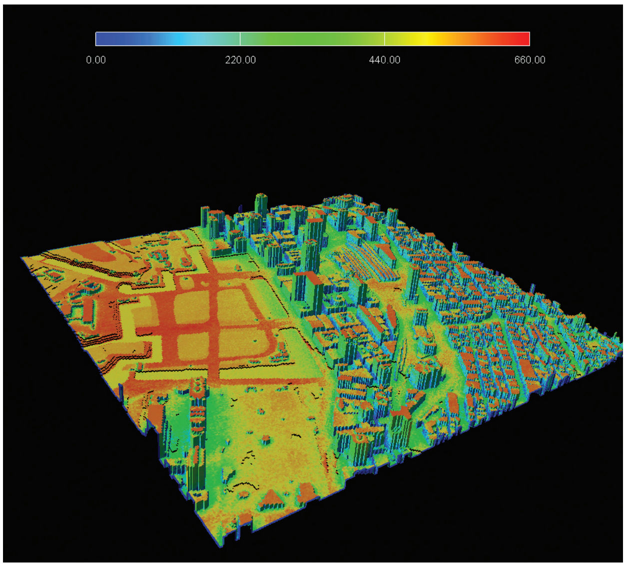

Fig. 7 Three-dimensional distribution of longwave radiative flux [W/m^2] toward the sky.

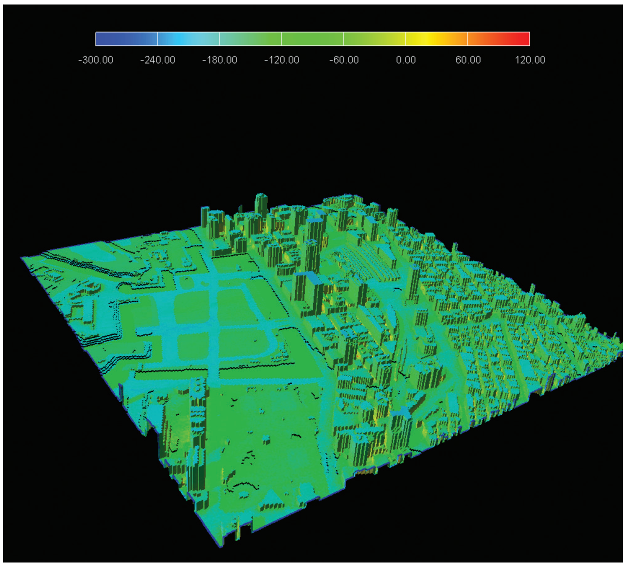

Fig. 8 Three-dimensional distribution of net longwave radiative flux [W/m^2] into the surfaces.

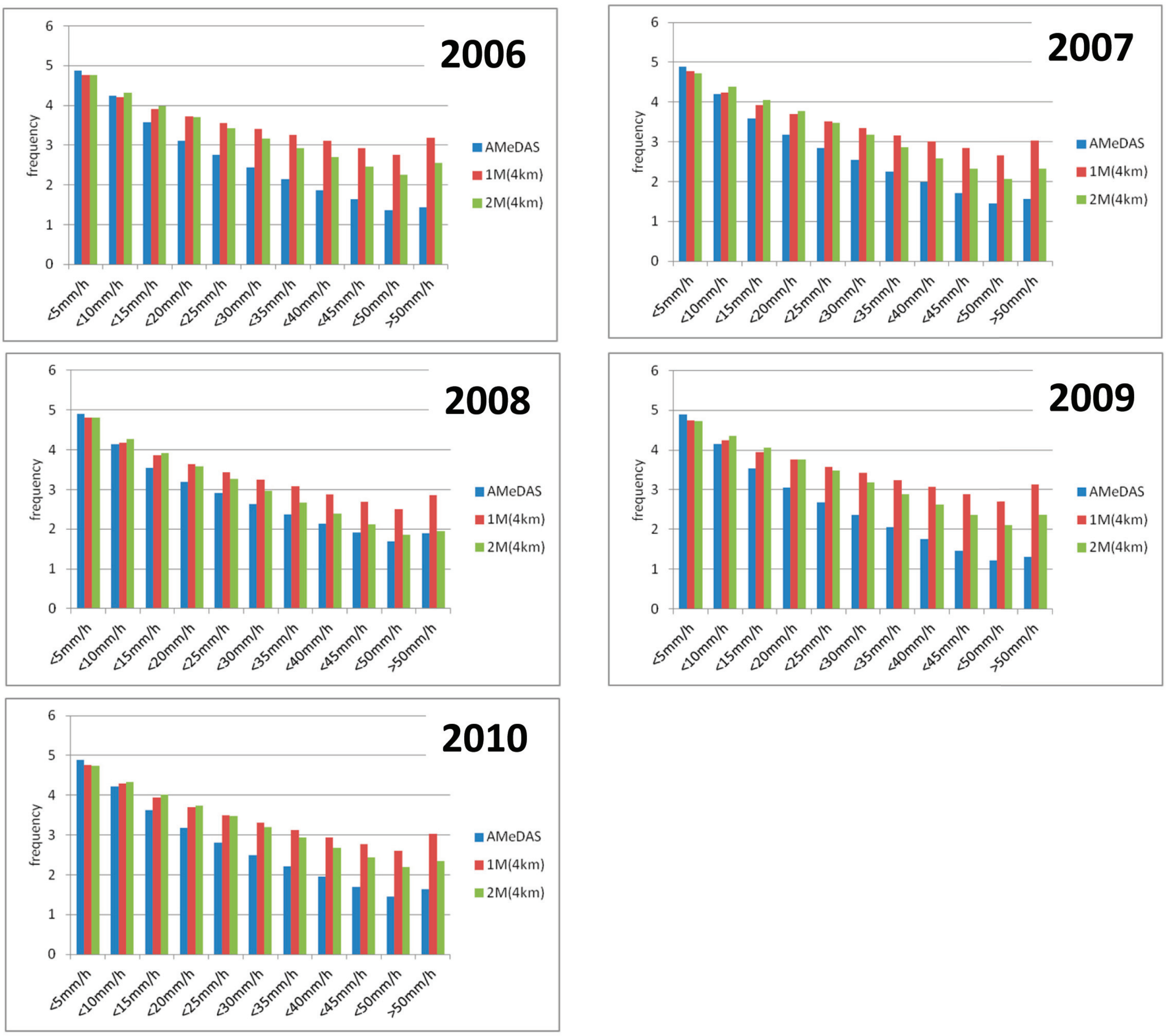

Fig. 9 Frequency of precipitation [mm/h] form simulations in each summer during 2006-2010.

7. Future work

In this report, we introduced improvements of physical performance of MSSG to performing seamless simulation. In near future, we are planning to validate physical performance of realistic multi-scale multi-physics phenomena such as MJO and El Nino and Indian Ocean Dipole by longer integration with further high resolution. In the simulations, climate impact in urban area due to those climate variability will be investigated.

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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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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. Aiming to seamless simulation, cloud micro-physics from the both view points of the accuracy of advection computation and high computational performance and oceanic part downscaling were improved and those results are summarized. In addition, three dimensional radiation scheme was developed and its impact was shown. The trial simulation for investigate regional climate variability was performed and its result was presented in this report.

気候変動現象による都市域の気象・気候への影響を同定するためのシームレスシミュレーションを可能とするという最終目標のために、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）にそれぞれに対して、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要素モデル開発に注力した。

MSSG-A においては、モデルの物理的性能を左右する雲微物理モデルにおける高精度の計算手法を開発し、WENO スキームで雲の熱力学的エネルギーが数値拡散なく移流され、その効果はサブグリッドスケール混合よりも大きいことを示し、高精度移流スキームの有効性を明らかにした。また、従来の方法では膨大な計算機資源が必要なため無視されてきた流体を介した粒子間相互作用（Hydrodynamic Interaction, HI）を効率よく考慮できる手法 BiSM（the binary-based superposition method）を開発した。また、液滴のサイズによる散乱強度、散乱方向の差異を考慮することにより、目視観察と同様の明暗を再現した結果、積雲の濃淡が積雲対流のスケールだけでなく、より小さなスケールでも存在しており、実際の雲と同様の濃度変動が再現できることを示した（図 1）。

MSSG-O においては、Noh-Kim スキームの改良と検証行い、拡散が強く、表層が数値的に不安定である問題を解決し、正確な長期積分を可能とした。加えて、世界的にも数が少ない海水と海底土の間でおきる物質循環モデルへ拡張し、ダウンスケーリングシミュレーションを実施し、福島沖での拡散過程を再現することに成功した。また、マルチプロセス領域モデルとして河川・海洋の相互作用導入した地上水流モデルを開発し、降水データから河川流出をシミュレーション可能にした（図 2）。

都市気象と気候変動のマルチスケール関連性を明らかにすることを目的に、まず、都市域の特性を再現する 3 次元放射計算スキームを導入した。熱輸送解析を行った結果、都市域の蓄熱過程を考慮するためには 3 次元放射過程を考慮する必要性が明らかとなった。さらに、関東域の領域気候モデルの構築を行い、最もモデルの不確実性が強いと考えられる雲微物理スキームのインパクトを調べた結果、2 モーメントスキームが降水強度分布でよりよい結果を示すことがわかった。また、構築したモデルは定量的に関東域の降水および地表面温度を再現できることが分かった。

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

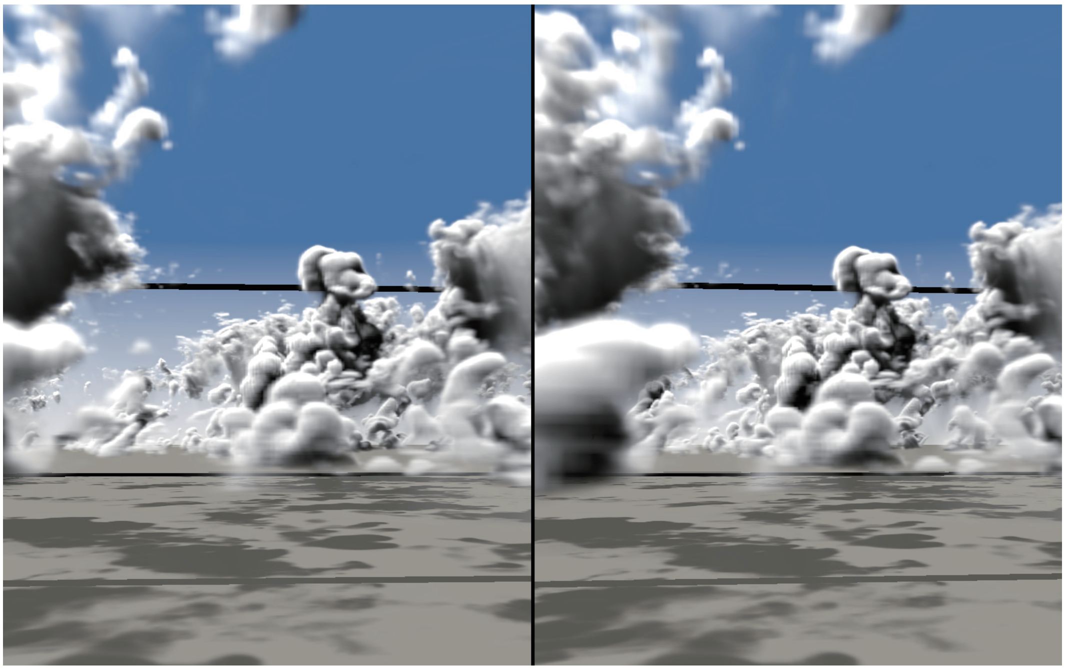

図 1　ステレオグラム（立体視画像）で示した積雲の 3 次元分布。左右の図はそれぞれ右目と左目から見た角度に対応しており、交差法による立体視として積雲の分布を把握することができる。「第 26 回数値流体シンポジウム　ベスト CFD グラフィックスアワード　最優秀賞」を受賞。

図 2　地上水流モデルによる関東域の事例降雨後の地表水の厚さ分布