Development of Super High Resolution Global and Regional Climate Models

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The purpose of the five-year project "Development of super high resolution global and regional climate models" is to develop a global climate model with a horizontal resolution of 20 km realistically simulating such phenomena as typhoons and Baiu front globally, and cloud resolving regional models with a horizontal resolution of a few km simulating meso-scale phenomena such as heavy rainfall and heavy snowfall. These models are utilized to investigate the effects of global warming on these phenomena through time-slice numerical experiments. The project consists of two subprojects: "Development of a global climate model with a horizontal resolution of 20 km" and "Development of non hydrostatic models (NHMs) with horizontal resolutions of several km"(hereafter referred to as subproject 1 and subproject 2, respectively). The subprojects 1 and 2 are lead by Akira Noda and Masanori Yoshizaki, respectively.

Keywords: global warming, global climate model, high resolution, typhoon, Baiu front, semi-Lagrangian scheme, cloud-resolving non-hydrostatic models (NHMs), heavy rainfall, heavy snowfall, snowband, Japan Sea polar-air mass convergence zone (JPCZ)

Subproject 1: Development of a global climate model with a horizontal resolution of 20 km

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Abstract

The objectives of subproject 1 for the fiscal year 2002 (FY2002) are to migrate and optimize a global model to the Earth Simulator (ES) and to conduct test runs simulating typhoons with the optimized global model of high efficiency and high resolution. The main results are as follows: FORTRAN programs for a global model were migrated and optimized to the ES. The horizontal resolution of the model was increased up to 20 km. The model performance was greatly improved by tuning vectorized routines, parallelization between nodes and automatic microtasking parellelization within each node. The introduction of a semi-Lagrangian scheme to the time integration routine brought a further speed-up. We conducted test runs simulating typhoons in the Pacific with the 20 km-mesh global model and compared with satellite observations. The results prove the feasibility of utilizing our high resolution global model to climate change study. Thus the subproject 1 has proceeded on schedule in FY2002.

Results

a. Migration of programs and optimization

Migration and optimization

We migrated programs of a global atmospheric general circulation model (the JMA-MRI unified model) jointly developed by the Meteorological Research Institute and the Japan Meteorological Agency, and optimized them on the ES. A successive optimization by tuning vectorized routines, parallelization between nodes, and automatic microtasking parellelization within each node lead to a reduction in CPU time (Fig. 1).

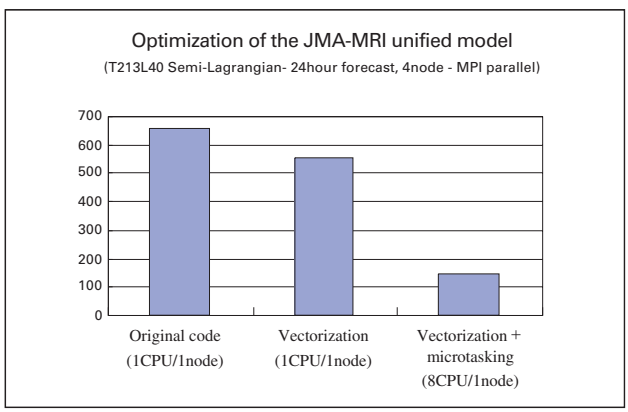

Fig. 1 Reduction in CPU time (unit: sec) required for 24-hour integration by optimizing the original code (left) by tuning vectorization (middle) and vectorization + microtasking (right) for an 60 km-mesh global model.

We achieved a vectorization rate of 98.4%. We scanned the FORTRAN programs thoroughly and optimized the source codes which were inappropriate for the auto-parallelization.

Computational efficiency (Semi-Lagrangian scheme)

We made an effort to speed up the time integration of the global model by replacing the conventional Eulerian scheme with a newly developed semi-Lagrangian scheme. The semi-Lagrangian scheme enables us to use a much longer time step and hence the less total number of time steps, which results in a large reduction in CPU time for calculating dynamical and physical processes. Figure 2 compares the efficiency of time integration between the conventional Eulerian scheme and the semi-Lagrangian scheme, showing that the latter can perform time integration more than twice faster than the former due to taking longer time steps.

b. Test runs with a 20 km-mesh global model

Toward high resolution

We increased the horizontal resolution of the optimized global model up to 20 km and conducted test runs simulating typhoons.

Test runs: simulation of typhoons with a 20 km-mesh global model

Since this project focuses on investigating the effects of global warming on climatology of Baiu front and typhoon, these phenomena should be simulated realistically by the model. We therefore firstly simulated typhoons as a forecast mode with observed initial conditions to see the model performance. Figure 3 compares the performance of simulating typhoons in the western Pacific between 60 km-mesh and 20 km-mesh models. The time integration started at 00Z on July 9, 2002. The cloud field of 24 hours after starting the integration is presented. The results from the 60 km-mesh model

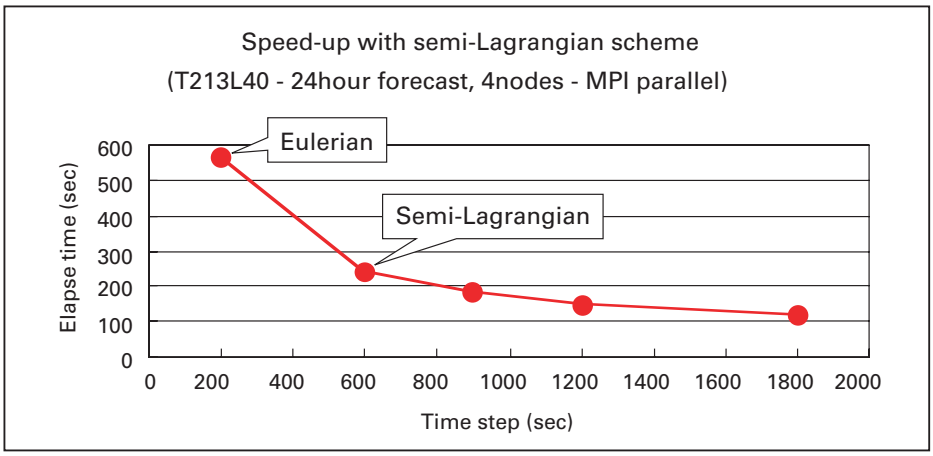

Fig. 2 An illustration of speed-up with semi-Lagrangian scheme for a 60 km-mesh, 40-level model. The ordinate is the elapse time for a 24-hour forecast with a 60 km-mesh model and the abscissa is the time step. Units are second.

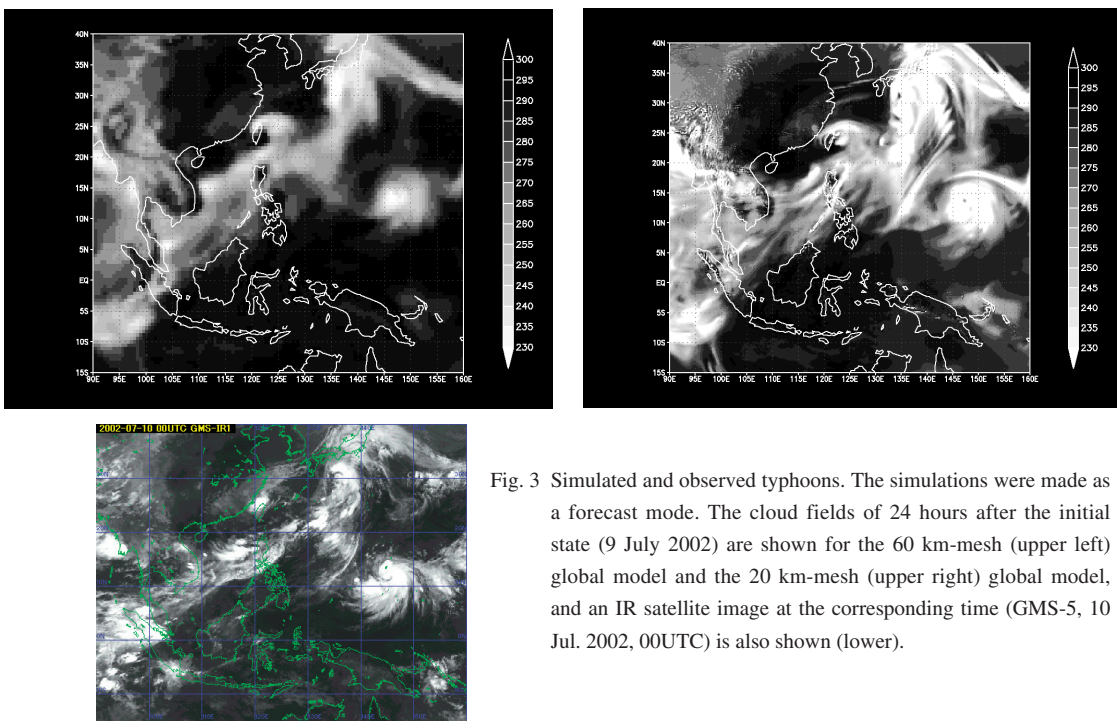

Fig. 3 Simulated and observed typhoons. The simulations were made as a forecast mode. The cloud fields of 24 hours after the initial state (9 July 2002) are shown for the 60 km-mesh (upper left) global model and the 20 km-mesh (upper right) global model, and an IR satellite image at the corresponding time (GMS-5, 10 Jul. 2002, 00UTC) is also shown (lower).

(left) and from the 20 km-mesh model are shown in the figure and an IR satellite image at the corresponding time is also shown for the sake of comparison. The eyes and spiral cloud bands of the three typhoons are well simulated in more detail by the 20 km-mesh model than by the 60 km-mesh model, suggesting that much improvement may be expected for simulating typhoons by using higher resolution models.

Subproject 2: Development of NHMs with the horizontal resolutions of several km

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Abstract

The objectives of subproject 2 for the fiscal year 2002 (FY2002) are to migrate and optimize cloud-resolving non-hydrostatic models (NHMs) to the Earth Simulator (ES) and to conduct preliminary runs simulating heavy rainfall and heavy snowfall with the optimized NHMs of very high resolutions. The main results are as follows: Migration of programs, optimization, and increase of resolution of the NHMs for the ES were performed. We improved the calculation efficiency by tuning parallelization between nodes, and vectorization of programs, and adaptation for automatic micro-tasking parellelization on 1 node. Further, we conducted preliminary runs simulating heavy rainfall in the Baiu season and heavy snowfall over the Sea of Japan, by using the NHMs with fine horizontal resolutions. Compared with previous studies, very fine structures were well simulated. Thus the subproject 2 has proceeded on schedule in FY2002.

Results

a. Migration of programs and optimization

Migration of programs and optimization

First, we made basic configurations to run NHMs on the ES.

Second, programs of NHMs, which were originally designed to run on the vector-type super-computers with several processors, were written by using Fortran 90 and MPI (programs to communicate data among nodes) partly local to the Hitachi machines. On the other hand, the ES are NEC SX parellel-type computers with the vectorization. So we optimized the NHM programs for the ES, and confirmed that they achieved good performances on it.

Third, the ES has 8 processors in one node, and auto-pararellelization can be applicable by the compiler. It was shown that the real performance using the original programs was 2.5 Gflops, when one processor was used (Peak: 8 Gflops). So we optimized the source codes which were inappropriate for the auto-parallelization. As a result, the vectorization and auto-parallelization were greatly improved.

However, we need to improve the programs further to get a higher calculation efficiency. Now we continue the optimization of the NHMs in cooperation with specialists of super-computers and ES staffs.

Efficiency of calculation

We examined the calculation efficiency of the NHMs on the ES. The three-dimensional calculation domain used for it had 1000x1000 grid points in the horizontal direction and 38 levels in the vertical direction. The node numbers were used up to 64, which was permitted to use by the ES center on January 2003. 97.6% and 99.91% efficiencies were attained for the vectorization and parellelization, respectively. In Fig. 4, the scalability is shown as a function of node number. The real scalability increased with the increase in the node number, reaching 70% of the peak at the 64 nodes. Thus the present NHMs are well parallelized and the resources of the ES are well utilized.

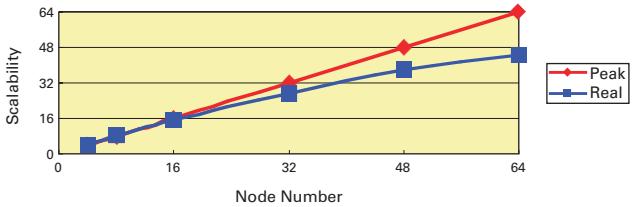

Fig. 4 Acceleration rate (Scalability) of an NHM as a function of node number. Calculation domain size is $1000 \times 1000 \times 38$ with horizontal grid size dx=dy=2 km. The NHM is vectorized and auto-parallelized on the ES. The scalabilities are computed at 1000 time steps.

b. Test runs by the NHMs simulations

Toward high resolution/wide-range of NHMs

In order to simulate heavy rainfall or heavy snowfall in the wide-range areas by using the cloud-resolving models, we increased the horizontal resolution of the NHMs to several km, and also to expand the model domain. In this fiscal year, we made such procedures, and conducted test runs for snowbands over the Sea of Japan by utilizing the NHMs, which were optimized on the ES.

Numerical simulation of snowbands observed over the Sea of Japan in winter.

A high-resolution wide-range simulation of cloud bands associated with the Japan Sea polar-air mass convergence zone (JPCZ) in winter was performed using the NHM with 1km horizontal resolution and 1000×1000 km calculation domain on the ES (Fig. 5).

During winter monsoon season, broad cloud bands extending southeastward from the base of the Korean Peninsula sometimes bring heavy snowfalls to the Sea of Japan-side coastal regions of Japan Islands. These cloud bands form over the low-level convergence zone between two cold airflows with different property. The case studied is a typical broad cloud bands that developed over the Sea of

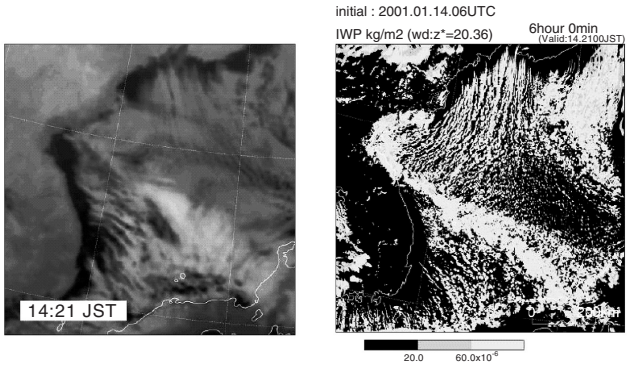

Fig. 5 Left: Cloud distribution of the GMS image. Right: Distribution of vertical integrated ice water path, simulated by the 1 km-NHM.

Japan on 14 January 2001.

In the present study, the NHM has a horizontal grid size of 1 km with 1000 $\times$1000 grid points (1 km-NHM). The vertical grid with a terrain-following coordinate contains 38 levels with a variable grid interval of 40 m near the surface and 1090 m at the top of the domain. The model top is 20.36 km. The time step interval is 5 seconds. The 1 km-NHM is one-way nested within the NHM with a 5 km grid forecast (5 km-NHM). The initial and boundary conditions for the 5 km-NHM are provided from output produced by Regional Spectral Model (RSM). The RSM with a horizontal grid size of about 20 km is a hydrostatic model used operationally in JMA.

The 1 km-NHM successfully reproduced cloud bands associated with the JPCZ extending southeastward from the base of the Korean Peninsula to the San-in and Hokuriku district over the Sea of Japan. Several cloud streets were also calculated around cloud bands. The JPCZ formed between warmer west-northwesterly flow from Korea Peninsula and colder north-northwesterly flow from Primorskii in the lower level. A strong horizontal convergence line and an updraft line were situated at the southwestern edge of the JPCZ. Deep convective clouds with the height of about 4 km formed along the line. Ice and snow particles blown off from the convective clouds were advected by the southwesterly flow and formed anvil-like stratiform clouds extending northeastward. These two types of clouds formed the cloud bands. These model-simulated features almost agreed with those of the observation using by a meteorological satellite, meteorological radars and an instrumented aircraft.

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高精度・高分解能気候モデルの開発

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本プロジェクト「高精度・高分解能気候モデルの開発（5年計画）」の研究目標は、地球温暖化が台風、集中豪雨・豪雪等の中小規模現象に及ぼす影響を調べるために、台風等を世界規模で再現する20 kmメッシュの全球気候モデルと、集中豪雨・豪雪等を広域で再現する数kmメッシュの雲解像大気モデルを開発することである。また、開発したモデルを用いて、地球温暖化が台風、集中豪雨等に与える影響を温暖化数値実験により調べることを目標にしている。

平成14年度の目標は、モデルの地球シミュレータへの最適化、計算スキームの高速化、高分解能化、及び高分解能化したモデルを用いた中小規模現象のシミュレーション・テストランである。平成14年度の成果は以下のとおりである。

地球シミュレータへのプログラムの移植、最適化、高分解能化、広域化を実施した。プログラムのベクトル化チューニング、さらにノード内自動並列化のチューニング、ノード間並列チューニングによる最適化によって、モデルの計算性能を向上させることができた。また、モデルの計算スキームにセミラグランジュ法を導入し、計算の高速化を図ることが出来た。さらに、モデルの空間分解能を高め、これを用いて台風、集中豪雨、豪雪のシミュレーションのテストランを実施した。これまでの分解能のモデルに比べ、より詳細に現象が再現できる可能性が得られた。このように、平成14年度は、ほぼ計画通り進捗した。これにより、次年度以降の本格的なモデル開発への準備が整ったと評価している。

キーワード：地球温暖化、全球気候モデル、雲解像非静力モデル、セミラグランジュ法、台風、梅雨前線、
集中豪雨･豪雪、雪バンド、日本海寒気団収束帯