Super-High-Resolution Climate Simulations with an Atmospheric General Circulation Model

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We have developed an extremely efficient atmospheric general circulation model (AGCM) on the Earth Simulator (ES). The AGCM, called AFES, achieved 26.58 Tflops or 64.9% of the peak performance with the full configuration of the ES. This performance was recognized as the fastest computation in the world at Super Computing 2002, and AFES won Gordon Bell Award for Peak Performance. We employed hybrid programming, balancing internode parallelization (MPI), intranode parallelization (microtasking) and vector processing.

With AFES on the ES, we carried out three meso-scale resolving global simulations, targeting wintertime cyclogenesis, Baiu (Meiyu) frontal zone and typhoon genesis. To the best of our knowledge, these ultra-high resolution simulations were performed first in the history of computational meteorology. Preliminary results suggest feasibility of the global meso-scale resolving simulations. We now plan to study weather-climate variability induced by interactions with large-scale field and meso-scale phenomena by ultra-high resolution simulations during the next fiscal year.

Keywords: Earth Simulator, atmospheric general circulation model, meso-scale resolving global simulation, high performance computing

1. Tuning of computational efficiency of AFES on the Earth Simulator

AFES (Atmospheric general circulation model [AGCM] for the Earth Simulator [ES]) was adopted from an AGCM jointly developed by the Center for Climate Change Research, the University of Tokyo, and the Japanese National Institute for Environmental Studies. It was, however, totally rewritten from scratch and programmed to run extremely efficiently on the ES. AFES achieved 26.58 Tflops or 64.9 % of the peak performance with the full configuration of the ES. This speed was recognized as the fastest computation at Super Computing 2002, Baltimore, MD, USA, November, 2002, and AFES won Gordon Bell Award for Peak Performance.

AFES is very scalable as shown in Fig. 1. The strategies we took for optimizing AFES for the ES are summarized as follows.

1) In order to obtain the best computational efficiency on the ES, AFES was programmed to utilize three-tier parallelization available on the ES. For internode parallelization for the distributed memory architecture, MPI (Message Passing Interface) was used. For intranode parallelization for shared memory architecture, microtasking, which is a kind of thread programming, was used. In other words, hybrid programming was employed. Finally vector parallelization within each processor was efficiently used. The three-tier parallelization was optimally balanced for extreme efficiency.
2) AFES's dynamical core employs the spectral transform method that uses the Legendre transform (LT) extensively. The amount of computations of the LT increases with the third power of M, where M is the truncation total wavenumber. Therefore, the LT was especially optimized for the vector processing. Accordingly, the actual elapsed time of the LT is only 50 to 60 % even at the ultra-high T1279 resolution that is very close to the limit of the hydrostatic approximation used in AFES. It is much smaller than what would be expected from the third power law of M. The reason for this high efficiency is that the LT is very suitable for vector computing and has extremely high scalability at this ultra-high resolution.
3) The ES has high-speed interconnection network (IN). It is a full crossbar switch, and its speed is 12.3 GB/s x 2 (theoretical). In order to utilize this fast communication, MPI_PUT and MPI_WIN_FENCE, that are one-way communication facility of MPI-2, are used. Also Global Memory (GM), that is a new facility of the ES, was efficiently used. GM communicates data between nodes without memory copy to the system buffer and improves internode communication for the distributed memory system dramatically.

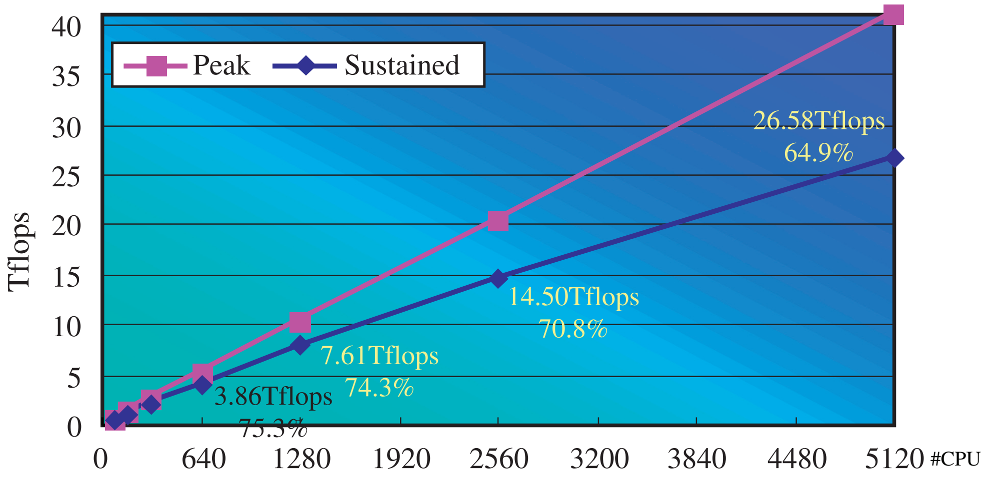

Fig. 1 AFES's scalability at the T1279L96 resolution. The abscissa indicates the number of CPUs of the ES, and the ordinate indicates the computational speed. The pink line indicates the theoretical peak performance.

The above optimizations are mainly for ultra-high resolution simulations. We have also investigated the computational performance of AFES with a little lower resolution. It was found that the computational efficiency decreases as resolution decreases. However, we have obtained valuable information about the guidelines for further optimizations of AFES. Also we have obtained the information on allocation of computer resource for various resolutions.

2. Ultra-high resolution simulations

With the extremely efficient AFES on the ES, three meso-scale resolving global simulations with the T1279L96 resolution were performed, targeting wintertime cyclogenesis, Baiu (Meiyu) frontal zone and typhoon genesis. To the best of our knowledge, the resolution of these global simulations is highest in the history of computational meteorology. There are interaction between large-scale field and meso-scale phenomena, and high impact weather events are results of downstream developments of Rossby wave propagations, which are truly global phenomena. These topics can be studied only by meso-scale resolving global simulations.

Fig. 2 shows a snapshot of global precipitation field from one of our simulations. It may look like a synthesized picture from artificial satellites. It shows both large-scale field, such as the intertropical convergence zone and mid-latitude cyclone activities, and meso-scale phenomena, such as typhoons to the south of Japan and fronts associated with cyclones. Even though Fig. 2 gives a merely quick look at the simulation, it clearly suggests that the feasibility of ultra-high resolution simulations for studies on inter-scale interactions. Fig. 3 shows an enlarged picture of Fig. 2 over the Japan area. While vigorous verification against the observations is yet to be done, the figure shows meso-scale structures such as an eye of one of typhoons. Fig. 3 also confirms the feasibility of these ultra-high resolution simulations.

It was found that the higher the resolution, the more organized precipitation pattern from sensitivity simulations on the resolution. The more organized precipitation pattern in higher resolution simulations look more realistic although rigorous verifications has yet to be done. It was also found that conventional physical parameterizations, which had been developed mainly for much coarser resolution AGCMs, did not break down, and ultra-high resolution simulations seemed satisfactory. However, we plan to explore possible improvement in physical parameterizations further in the near future.

3. Sensitivity to resolution

Simulation may not improve automatically with resolution. In some cases, a higher resolution simulation can be worse than a lower resolution simulation if model parameters are highly tuned at the lower resolution. We investigated how precipitation field changes with the resolution. The purpose of these simulations is to obtain the guideline for tuning model parameters for higher resolution.

Fig. 4. shows comparisons of latitudinal distributions of zonal mean JJA (June-July-August) precipitation when (a) horizontal and (b) vertical resolutions are changed. The black curve is the observation (CMAP: CPC Merged Analysis of Precipitation). The resolution increases from red to blue, to green. It is seen that higher horizontal resolution may not significantly improve the latitudinal distribution of precipitation (Fig. 4a) while the higher vertical resolution seems to improve the intensity of tropical precipitation (Fig. 4b). However, this improvement is accompanied by deterioration in excess mid-latitude precipitation. It suggests that rather sophisticated parameter tuning and/or improvement in physical parameterization is necessary to improve precipitation intensity and pattern overall.

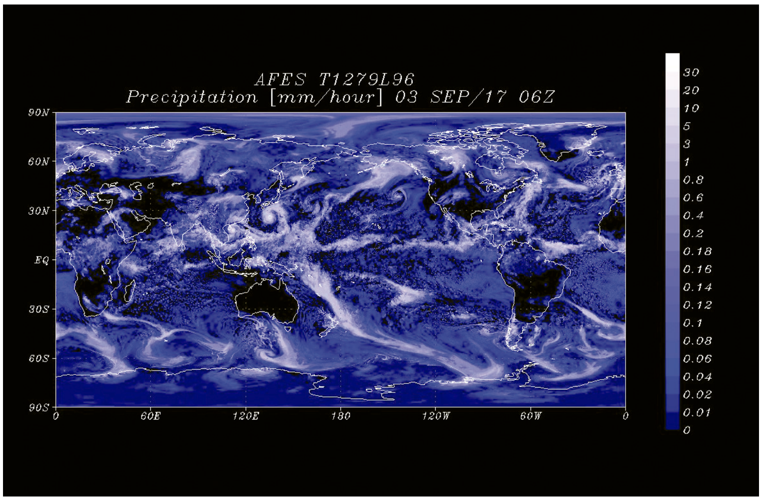

Fig. 2 A snapshot of global precipitation field from one of meso-scale resolving global simulations.

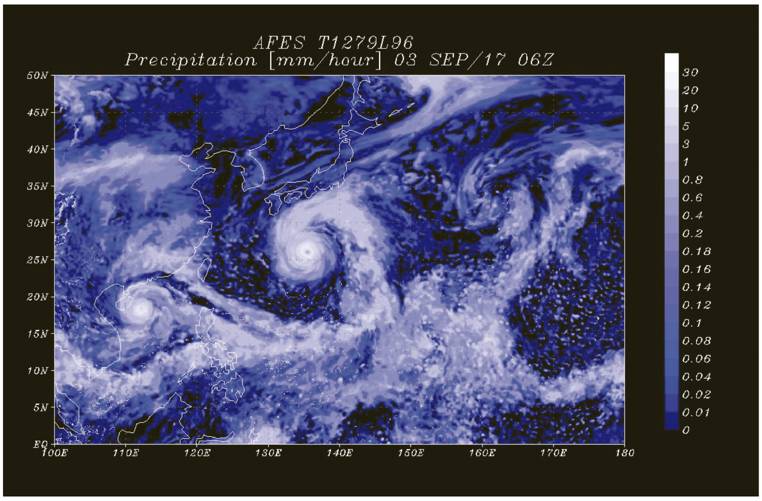

Fig. 3 An enlarged figure of Fig. 2 over the Japan area.

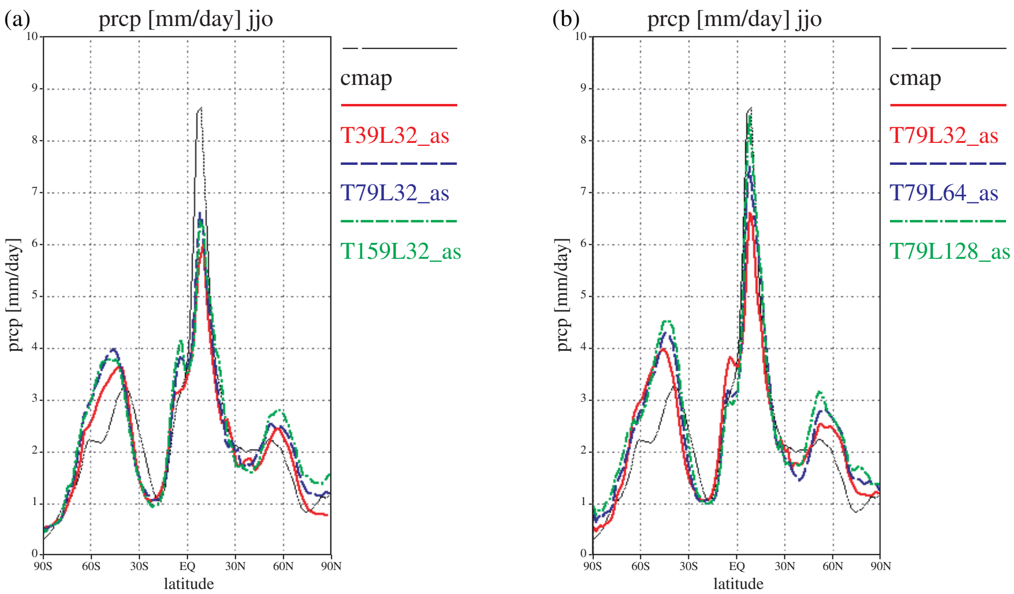

Fig. 4 Latitudinal distribution of zonal mean June-July-August precipitation. Sensitivities on (a) horizontal resolution and (b) vertical resolution. The black curve is the observation (CMAP). The resolution increases from red to blue, to green.

We are now using a simplified version of Arakawa-Schubert scheme. We have been experimenting with Emanuel scheme also. Preliminary results suggest that there are some improved aspects with the latter scheme.

4. Concluding remarks

We have developed an extremely efficient AGCM on the ES. The AGCM, called AFES, has demonstrated not only the high computational performance on the ES but also feasibility of meso-scale resolving global simulations. We plan to use AFES on the ES to study weather-climate variability induced by interactions between large-scale field and meso-scale phenomena. The planned simulations are expected to contribute not only to science by a better understanding of the weather-climate system but also to society by providing basis for better weather and climate forecasts.

大気大循環モデルを用いた超高解像度気候シミュレーション

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地球シミュレータ(ES)で高効率に走る大気大循環モデル(AGCM)を開発した。AFESと名付けられたそのAGCMは、ES全ノードを用いて26.58テラフロップス、ピーク・パフォーマンス比64.9%を達成した。この実行速度によりSC2002においてゴードン・ベル賞を受賞した。AFESにはハイブリッド・プログラミングが用いられ、ノード間並列(MPI)、ノード内並列(マイクロタスキング)とベクトル演算のバランスが上手く取られている。

AFESをES上で実行し、冬季の低気圧、梅雨前線、台風をターゲットとした三つのメソ・スケール解像全球シミュレーションを行った。これほどの超高解像度全球シミュレーションは、計算気象学史上初のものである。その結果を踏まえ、来年度には、この超高解像度シミュレーションにより大規模場と中規模現象の相互作用から励起される気象・気候変動の研究に着手する予定である。

キーワード：地球シミュレータ、大気大循環モデル、メソ・スケール解像全球シミュレーション、ハイ・パフォーマンス・コンピューティング