Future Climate Change Projection using a High-Resolution Coupled Ocean-Atmosphere Climate Model

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A high-resolution atmosphere-ocean coupled model has been developed in order to improve a global warming simulation. Based on preliminary experiments, an atmospheric component is T106 global spectral model with 56 levels and an ocean component is 1/4 degree by 1/6 degree grid point model with 46 levels. A land surface model (MATSIRO) and a river model are incorporated. 10 nodes are allocated to the atmospheric component and 76 nodes are allocated to the oceanic component.

Corresponding to the increase in horizontal and vertical resolution, subroutines for physical processes are reexamined. Various options have been examined and final specification was decided. Coupling between atmosphere component and ocean component is done through MPMD (Multiple Program and Multiple Data) algorithm.

In order to improve the computational efficiency of the atmospheric model, following actions were taken; (1) parallelization by using 40PE, (2) list-vectorization in physical processes, (3) improvement in tracer advection, (4) improvement of expansion of spherical harmonics, (5) Increase of PE from 40PE to 80PE, (6) optimization of Legendre transformation. Due to these efforts, computational speed becomes 77 times faster than that in a serial computation.

The vectorization efficiency of the atmospheric component, the ocean component, and the coupled model is 98.1, 99.2 and 98.0%, respectively. Performance of computational speed is 1.3 GFLOPS/PE (16%), 2.6 GFLOPS/PE (33%), and 1.9 GFLOPS/PE (20%), respectively. Actual sustained speed of the coupled model is 1.3 TFLOPS, which is 20% of the maximum speed.

The coupled model has been run for 7 years and results are examined.

Keywords: Coupled ocean-atmosphere climate model, Global warming, Climate change projection, IPCC

1. Introduction

Climate change associated with the global warming is one of the most important social concerns today. There exist huge demands for more accurate and reliable information for the future climate change. For example, we are frequently asked whether severe storm is increased or not. However, the present climate model is not sufficient for answering these requests, mainly because our knowledge about climate system is insufficient. However we don't make a maximum use of our present knowledge, because our computational capability is limited.

Based on the Earth Simulator, a project for developing a high-resolution atmosphere-ocean coupled model has been started jointly by CCSR (Center for Climate System Research, University of Tokyo), NIES (National Institute of Environmental Studies) and FRSGC (Frontier Research System for Global Change). The reason why we need a high-resolution climate model is because we need finer scale information of climate change in temporal and spatial scale to provide more reliable climate scenarios to the society.

2. How to define a resolution?

Although high resolution is desirable, what extent of resolution is necessary? It is obvious that finer resolution is desirable, but as computational capability of the Earth Simulator is limited, we have to choose a certain resolution. We have to compromise many factors such as computation capability, data volume and model performance. In order to decide the model resolution, several preliminary experiments were conducted. Kawatani and Takahashi (2003) run the T106L60 AGCM to simulate the Baiu front. He succeeded in simulating the mean profile of the Baiu front as well as disturbances in it. Kimoto (2002) examined the frequency distribution of daily precipitation of T42 and T106, and observation over 5.0 x 5.0 box (top), 2.5 x 2.5 box (middle) and 1.0 x 1.0 box.

It is clearly shown that the light rain is more frequent in T42 simulation than the observation. On the other hand, frequency in the heavy rainfall becomes larger in T106. It is concluded that T106 simulation represents well the observed distribution.

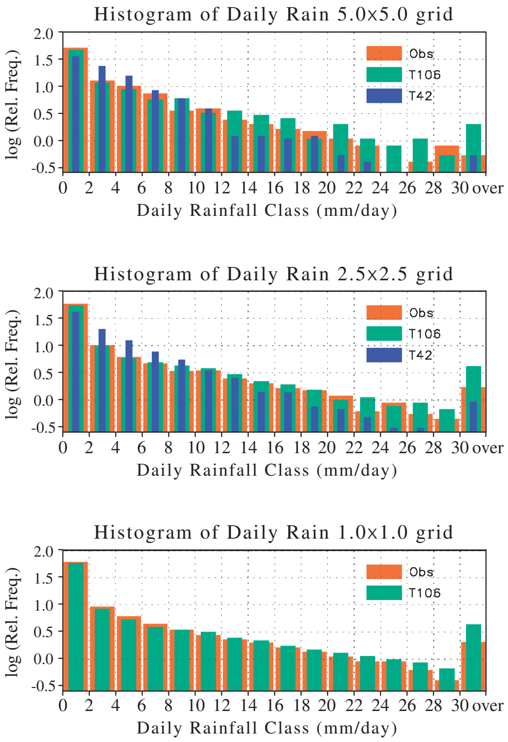

Fig. 1 Histogram of Rainfall simulation and observation around Japan. (top) 5° x 5° grid, (middle) 2.5° x 2.5° grid, and (bottom) 1° x 1° grid.

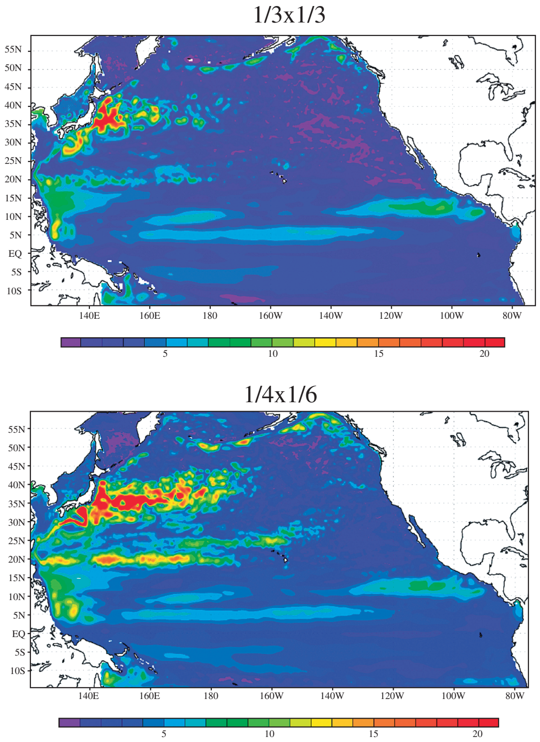

Fig. 2 Variability of ocean surface simulated by 1/3 x 1/3 model (uppert) and 1/4 x 1/6 model (lower). Variability associated with the Kuroshio extension is well represented in the 1/4 x 1/6 model.

For the ocean component, many experiments have been conducted over the North Western Pacific region. For example, variability of sea surface height over the North-eastern Pacific region of simulations with different resolutions is examined. In Fig.2, the results by 1/3 x 1/3 model and 1/4 x 1/6 model are shown. Compared with the observation of TOPEX-Poseidon (not shown), the simulation with 1/6 x 1/4 model represents well the nature.

Beside this comparison, various aspects are examined such as the separation of the Kuroshio from Japan Island. Then, we concluded that 1/4 x 1/6 resolution is enough.

Based on these preliminary experiments, we have determined the following formulation of the high-resolution climate model;

(1) Atmospheric component; ①T106 spectral dynamical core with 56 sigma levels, ②grid advection for tracer transport, ③k-distribution DOM/Adding radiation with maximum-random cloud overlapping, ④direct and indirect aerosol effect, ⑤prognostic Arakawa-Schubert cumulus convection scheme, ⑥Meller-Yamada level 2 + non-local PBL, ⑦topography induced gravity drag.

(2) Oceanic component; ①grid ocean model with free surface (hybrid sigma-z model), ②rotated lat.-lon. grid (poles are in Greenland and Antarctic), ③48 vertical levels with 8 sigma levels near surface, ④UTOPIA/QUICKEST advection scheme, ⑤Smagorinsky horizontal viscosity, ⑥isopycnal diffusion, ⑦surface Boundary layer, ⑧bottom boundary layer, ⑨convective adjustment.

Besides atmospheric and oceanic components, the land surface model (MATSIRO) and the river model are coupled. Coupling of atmospheric component and oceanic component is done through MPMD (Multiple Programming and Multiple Data).

3. Improvement of Computational efficiency

In order to optimize the codes for the parallel-vector architecture, intensive efforts have been conducted. First, parallelization was done by using MPI technique. Atmospheric component is divided into 80 along latitudinal circle and ocean component is divided into 608 regions (2 in longitudinal direction and 304 in latitudinal direction). The improvement of computational speed in the atmospheric model is shown in Table 1. In atmosphere, gird advection scheme is applied for tracer advection. Efficiency of grid advection is considered.

Intensive efforts have been paid in order to improve a computational performance of models. As an example, a result of speed-up in the AGCM is shown in Table.1. Here,

Table 1 Speed-up of CPU time of AGCM by changing a version (Explanation of V0-V8) is given in the text.)

	V01	V02	V03	V04	V05	V06	V07	V08
CPU(s)	57,707	2,171	1,962	1,585	1,048	884	835	749

Table 2 Summary of Computational aspect of AGCM, OGCM and Coupled model.

	Number of PE	Vectorization Ratio (%)	Averaged Vector length	MFLOPS/PE
AGCM	80	98.1	159	1300
OGCM	608	99.2	236	2620
Coupled Model	688	98.0	225	1590

V01 denotes a serial run by using 1PE. V02 is a result of parallelization of 40PE. In V03, list-vectors are introduced in the physical processes. In V04, spherical harmonics expansion is improved, and 80PE is used in V05. Communication is improved in V06. In V07, further tuning is done in Legendre transformation and "All to All" communication is coded by MPI-2. Based on these recoding, about 77 times sped up is achieved.

Based on intensive effort of our team, acceptable performance is achieved and computational performance of model is shown in Table 2. Its elapse time for one-month simulation is about 2000 second and it is concluded that it is feasible to integrate 100 years in one month.

4. Results

When horizontal and vertical resolution is increased, physical processes are also developed in accordance with resolution increase. This process takes a long time and huge effort. In order to determine a specification of model physics, many numerical experiments have been conducted so far.

Even though the Earth Simulator has excellent capability, it still takes a lot of time to run a high-resolution climate model. In order to improve our climate model and understand the physics of the climate system, convenient model is necessary. We developed a medium resolution climate model (T42L20 AGCM +1x1.4 OGCM). In this medium resolution climate model, we could run it for 100 years in a stable manner without flux correction.

We could run the high-resolution climate model for 7 years because the Earth Simulator is so crowded and we could not obtain a suitable CPU time. The 7-year averaged SST is shown in Fig.3 (right). Compared with the observed SST (left in Fig.3), it is noted that warm water pool in the western tropical Pacific is cooler than the observed one, but general correspondence is not so bad.

Annual mean observed rainfall is shown in Fig.4 (left) and the 7 year averaged rainfall simulated by the high resolution coupled model is given in Fig.4 (right). There are good and bad aspects. For example, the Baiu front is well simulated. On the other hand, the SPCZ is poorly simulated, and the double ITCZ features are emphasized. However, it should be noted that these results are based on the first 7 year simulation. We will examine these results and improve the model performance in the next year.

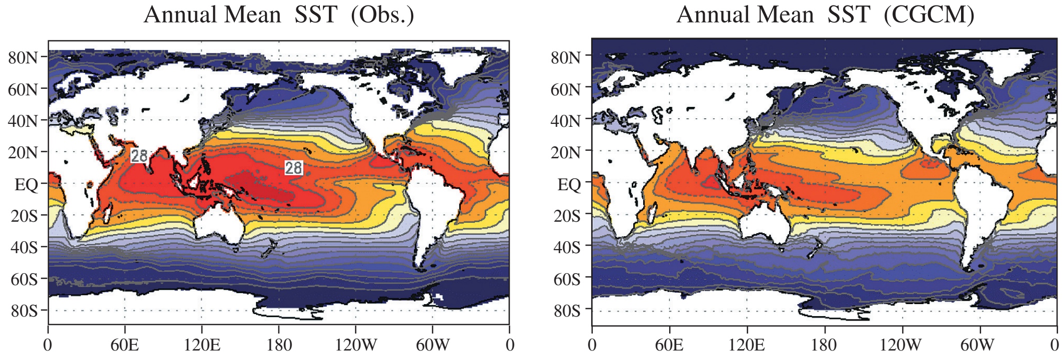
Annual Mean SST (Obs.)
Annual Mean SST (CGCM)

Fig. 3 Annual mean Sea Surface Temperature (left) and the 7 year averaged SST by the high resolution Coupled Model (right).

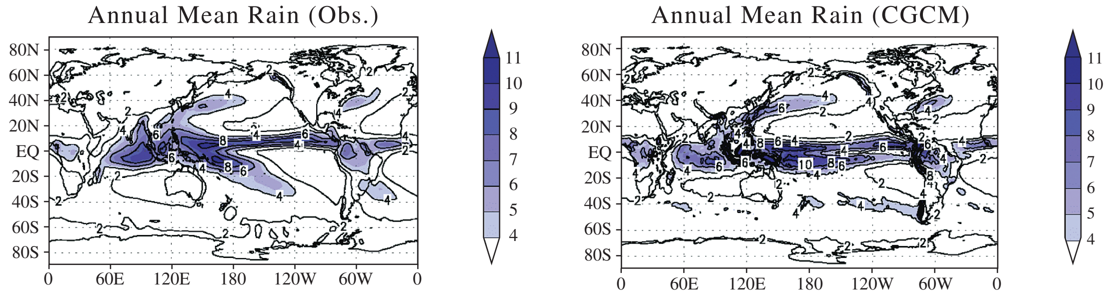
Annual Mean Rain (Obs.)
Annual Mean Rain (CGCM)

Fig. 4 (Left) Annual mean observed rainfall and (right) the annual mean rainfall simulated by the Coupled model.

高分解能大気海洋モデルを用いた地球温暖化予測に関する研究

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1. 目的

現有の、CCSR／NIES気候モデルを基礎として、高分解能の大気海洋結合モデルを開発し、IPCC／SRES排出シナリオに基づいて地球温暖化予測実験を行う。そのため、

(1) 新しい結合モデルを開発する。

(2) 非静力学熱帯大気モデルを開発し、対流のパラメタリゼーションの改良をはかる。

(3) ハドレーセンターの気候モデルと比較検討し、気候モデルの改良を図る。

の項目について、地球シミュレータを用いて、研究を行った。

2. モデルの詳細

新たに開発する大気海洋結合モデルは、大気が、水平解像度約120km(T106)、鉛直56層、海洋が、経度方向に1/4度、緯度方向1/6度格子の鉛直46層モデルである。このため、大気は、10ノード、海洋は、76ノードを使用し、MPMD(マルチプルプログラム、マルチプルデータ)形式の並列計算を採用する。

3. 平成14年度の研究成果

①大気海洋結合モデルについては、大気モデルの開発(並列化、ベクトル化)を行った。分解能を向上させたために、物理過程をすべて見直し、パラメータの再決定などのチューニングを行なった。現在、version 1のモデルとして、おおよその仕様は完成した。海洋モデルは、当初は自然な極座標を用いる予定であったが、極での計算不安定を避けるために、極を回転させることにした。この変更に伴い全球上での表現が変化するために、性能のチェック、それから、パラメータの調整などをおこなった。現在、一応の試験は終了し、性能は満足できるものと考えている。大気と海洋を結合させるcouplerは、大気の格子と海洋の格子が、回転のためにズレてくるので、大気海洋間で、降水やフラックスの抜けがないように注意をしながら開発を行った。

②計算効率を上げるために、さまざまな努力が行われた。例えば、大気モデルでは、並列化を導入したり、移流のところを改良したり、Legendre　変換のところを改良したり、通信部分の改良をはかるなどを行った。その結果、最初の1PEの場合に比べ、80PEを用いた場合には、おおよそ70倍程度の加速が得られた。

③さまざまなプログラムの改良の結果、大気部分は、80PE、平均ベクトル長が159、1PEあたりの計算速度は、1,300MFLOPS、海洋部分は、608PE、平均ベクトル長が236、1PEあたりの計算速度は、2,620MFLOPS、結合モデルでは、それぞれ、688、225、1,590MFLOPSとなった。この結果、1ヶ月の結合モデルの積分が、実行時間で2000秒で可能となった。これらの結果により、予定した1ヶ月で100年積分が可能となった。

④現在、結合モデルの時間積分を行い性能を調査している段階である。計算速度の目標は、1ヶ月で100年の時間積分が可能ということであるが、一応、目標とする計算速度は達成している。しかしながら、計算機の混雑のために、2ヶ月で7年の積分しか可能とならず、開発に支障が出てきている。

キーワード：大気海洋結合気候モデル、地球温暖化、気候変化見通し、IPCC