Development of an Integrated Earth System Model for Prediction of Global Environmental Changes

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The project aims at development of an integrated earth system model, where biological and chemical processes important for the global environment are allowed to interact with climate changes. The model is developed by adding individual component models to atmospheric and oceanic general circulation models (GCMs). The component models include ones for terrestrial and oceanic carbon cycle, one for atmospheric chemistry. Improvement of the GCMs necessary for the incorporation of these component models is also covered by the project plan. At the moment, development of the oceanic carbon cycle model and effort to improve the atmospheric GCM are advanced compared to other activities of the project in terms of the usage of the Earth Simulator. A preliminary experiment from the oceanic carbon cycle model shows a reasonable agreement with satellite measurements for surface chlorophyll, an indicator of phytoplankton abundance. The model is currently run using 80PEs with the vector and parallel operation ratios being 97.4% and 99.7%, respectively. Increase of the number of PEs is planned to enable an integration of a few thousands of years required to achieve the full equilibrium of the ocean carbon cycle model. Effort to improve the atmospheric GCM demonstrates that vertical resolution is the key to eliminate the cold bias near the tropopause in the GCM adopted, using 80PEs with typical vector and parallel operation ratios of 99.0% and 99.1%, respectively.

Keywords: Earth system, Carbon cycle, Cold bias, Tropopause

1. Introduction

Frontier Research System for Global Change (FRSGC) launched this FY a project to develop an integrated earth system model that operates on the Earth Simulator, in collaboration with the Center for Climate System Research of the University of Tokyo, National Institute of Environmental Studies and some other universities. The model incorporates various processes that influence the global environment as realistically as possible including chemical and biological processes such as uptake of CO_2 by biota and ozone hole formation. The project consists of four sub-projects, that is, "development of a coupled carbon cycle -climate change model", "development of a coupled atmospheric composition- climate change model", "development of a cryospheric climate system model" and "improvement of the physical climate system model". At FRSGC, we already have component models that correspond to the first three sub-projects above, and it is planned that in the first three years we introduce the component models to an already existing coupled atmosphere-ocean GCM (CGCM). As the forth sub-project, the CGCM will be improved with an emphasis on the representation of the middle atmosphere. Priority is currently on the development of the carbon cycle model. It is hoped that the integrated earth system model will be useful not only for scientific investigations on interactions between sub-systems of the climate system, but also for decision-making regarding the global change, by providing a scientific basis on the projection of, e.g., future concentration of atmospheric CO_2. In this report, we will show some preliminary reports from two subgroups, the carbon cycle subgroup and the physical model improvement subgroup, which are relatively advanced regarding the usage of the Earth Simulator compared to other subgroups.

2. Preliminary results from the ocean component model of the carbon cycle subgroup

For the pelagic ecosystem model required for modeling the oceanic carbon cycle, we adopt the model with four compartments, developed by Oschlies and Garcon (1999). This simple model is appropriate for our purpose because the integrated earth system model we aim at incorporates a lot of other parameters that are often poorly constrained. Given such a situation, it would be unwise to add even more uncertainties to the integrated model by adopting a pelagic ecosystem model with a more complicated structure that might help improving quantitative agreement between the model and observations. The model by Oschlies and Garcon (1999) has already been incorporated in the ocean general circulation model developed by the Center for Climate System Research, University of Tokyo. The model has a horizontal resolution of 1 deg. x 1 deg. and has 54 vertical levels. Preliminary results from the combined model after five years of integration are displayed in Figs.1,2.

The model reproduces the general pattern of chlorophyll distribution obtained by satellite measurements such as elevated concentrations in the subpolar gyres (Figs.1a,b). Noticeable differences include, on the other hand, the model's overestimate in the equatorial Pacific. Figs.2a,b depict annual air-sea CO_2 exchange from the model and observations, respectively. Overestimate of CO_2 release from the ocean is conspicuous in the equatorial Pacific, partly because the integration period here (five years) is much shorter than the time required for total carbonate to reach the equilibrium (a few thousands of years). The result here shows that we already have a tool to investigate the oceanic carbon cycle with explicit representation of pelagic ecosystems if we further integrate the model for a few thousands of years, which would take an impractically long time without the Earth Simulator.

The oceanic GCM has been run with 80PEs using MPI. Its vector and parallel operation ratios are 97.4% and 99.7%, respectively. The ocean general circulation model used is common with that used by the Category 1 of the Kyousei project (representative: A.Sumi, Univ. of Tokyo), with which our project collaborates closely regarding technical issues of model development including the code optimization needed for running the model on the Earth Simulator. It is planned to run the model for ~2000 years using more PEs (~300PEs) , which would require about two months even with such a large number of PEs to achieve the full equilibrium state for all the variables in the ocean carbon cycle model.

3. Improvement of the physical climate system model -Background and Plans-

This subgroup aims mainly at improvement of an atmospheric GCM (AGCM) used as a basic component of the integrated model. The AGCM is based on the CCSR/NIES (the Center for Climate System Research / National Institute for

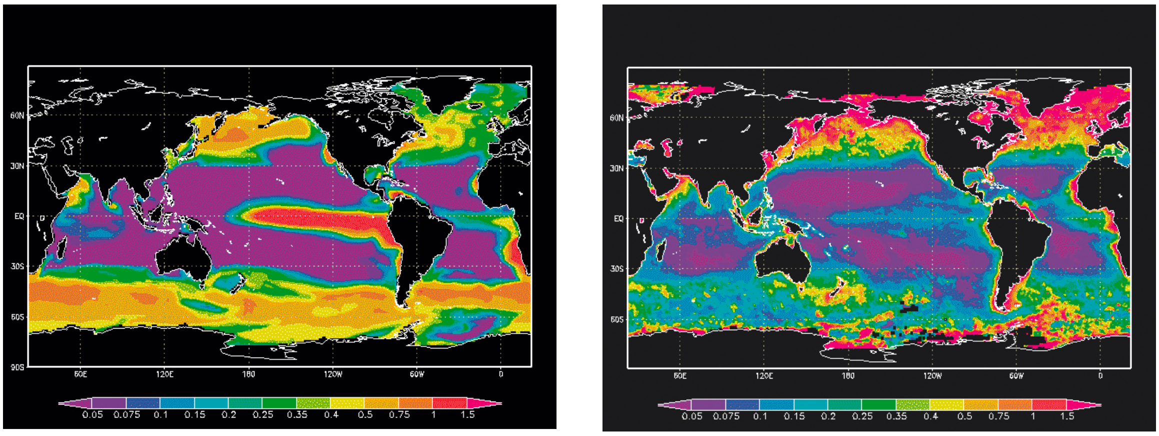

Fig. 1 Annual mean chlorophyll obtained by the model (a) and satellite measurements with CZCS (b). Units are mgChl/m^3.

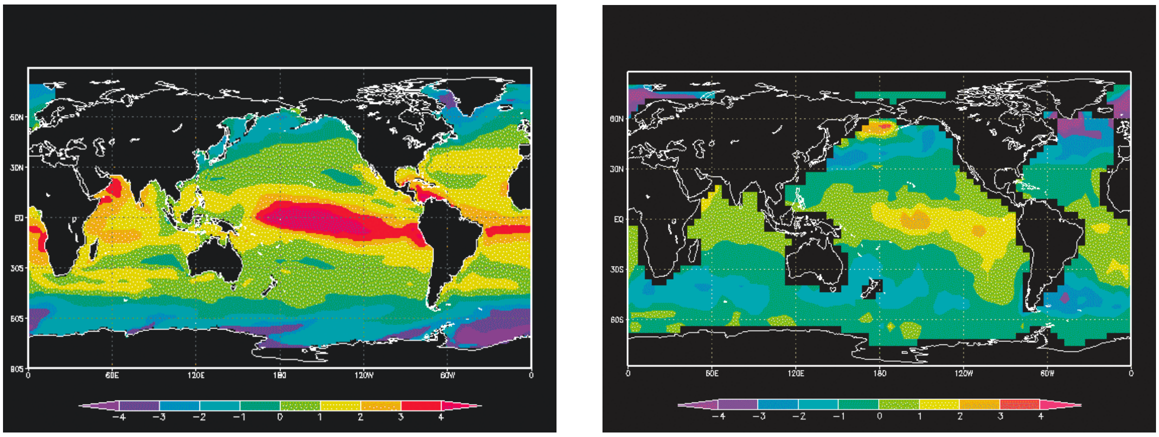

Fig. 2 Annual air-sea exchange of CO_2 obtained by the model (a) and observations (Takahashi et al., 1999; b). Positive values mean fluxes from the ocean to the atmosphere, and vice versa. Units are molC/m^2/yr.

Environmental Studies) AGCM version 5.7b, which has been developed for the IPCC assessments, i.e., the main objective of the Category 1 of the Kyousei Project (representative: A.Sumi, Univ. of Tokyo). In order to predict long-term changes in chemical composition, e.g., stratospheric ozone, the model has been extended to include the middle atmosphere (up to about 80km).

There are some shortcomings in current version of the AGCM. In particular, improvement of moisture, cloud and temperature fields near the tropopause is very important. That region is too moistened and too cold compared with observations. It may cause serious problems. For example, clouds and water vapor near the tropopause have a strong radiative forcing, which may reduce outgoing longwave radiation and resultant warmer temperatures in the troposphere. In addition, too much water vapor in the lower stratosphere may bring about too frequent occurrence of polar stratospheric clouds resulting in severe Arctic and Antarctic ozone depletion.

It is generally considered that such problems are caused by poor representation of radiative transfer and internal gravity waves from the upper troposphere to the middle atmosphere. Because accuracy of radiative transfer and representation of small-scale gravity waves are strongly dependent on vertical resolution of the AGCM, a series of experiments with various vertical resolutions are required. In order to investigate sensitivity of resultant temperature and moisture fields to the vertical resolution, several vertical resolutions ranging from 100m to 1500m have been tested on the Earth Simulator. Period of time integration is 10 years, and last 3 years are averaged and analyzed.

Fig. 3 shows sensitivity of the simulated temperature field (represented as 'bias' by subtracting observed one) to the vertical resolution. Although horizontal resolution used in this experiment is relatively low (T21), the simulated temperature field near the tropopause becomes more realistic as vertical resolution getting higher.

It is concluded that the cold temperature biases near the tropopause (300-50 hPa) are significantly improved by using of higher vertical resolution. Only the Earth Simulator can make this kind of research possible, because finer vertical resolution as well as finer horizontal resolution experiments with long-term integration require huge computational resources.

The improvements of the AGCM are continued cooperating with the Category 1 of the Kyousei Project (representative: A.Sumi, Univ. of Tokyo). As for the optimization of the AGCM, its typical vector and parallel operation ratios are 99.0% and 99.1%, respectively. It is parallelized with 80PEs using MPI. In order to perform further parallelization, microtasking is being planned. To provide an idea about the current computational performance, it needs about 9 elapsed hours per model year with resolution of T106 (320x160 grids) L40 (40 layers), although it depends on maximum wind speed (~180m/s if the middle atmosphere is included) in the model due to the CFL condition.

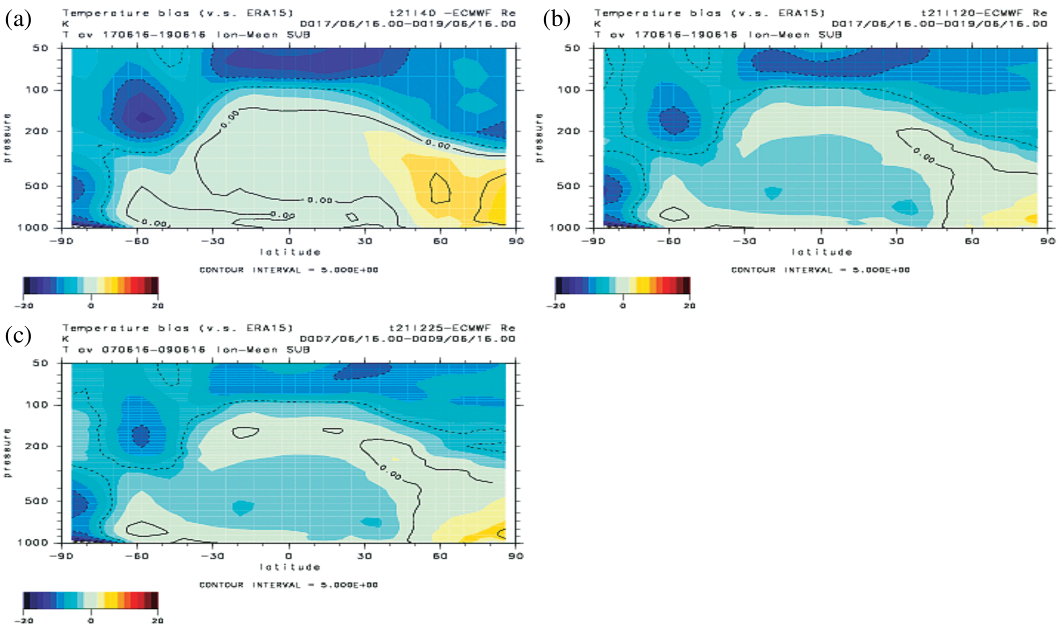

Fig. 3 Zonal mean temperature bias in June for vertical resolution of (a) 1500m, (b) 500m and (c) 200m. Reference temperature is ERA15. The contour interval is 5 K.

地球環境変化予測のための地球システム統合モデルの開発

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本プロジェクトでは、地球環境形成に重要な生物学的・化学的過程と気候変動との相互作用を取り扱える地球システム統合モデルの開発を目指している。モデル開発は大気および海洋の大循環モデル（General Circulation Model, GCM）に個々のコンポーネントモデルを付加していく形で行われ、付加されるコンポーネントモデルとしては、陸域および海洋の炭素循環モデル、大気化学モデルがある。またこれらコンポーネントモデルをGCMに組み込む際に必要になり得るGCMそのものの改良もプロジェクトの視野に入っている。地球シミュレータの使用という観点においては現在のところ、海洋炭素循環モデルの開発と大気GCMの改良とがプロジェクト内の他の活動に比べて進んでいる。海洋炭素循環モデルによる予備的実験においては、表層クロロフィル（植物プランクトンの指標）に関してモデル結果が衛星観測と比較的よい一致を見せることが示された。モデルのベクトル化率は97.4%、並立化率は99.7%であり、現在のところ80PEを使用している。モデルが完全な平衡状態に到達するのには2000年にわたる積分期間が必要であり、その実現のためさらに使用PE数を増やす予定である。また大気GCMを改良していく過程において、対流圏界面付近での低温バイアスの除去には鉛直解像度が鍵となることが示された。大気GCMの使用PE数は80であり、典型的なベクトル化率、並列化率はそれぞれ90.0%、99.1%である。

キーワード：地球システム、炭素循環、低温バイアス、対流圏界面