# 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 a coupled atmosphere-ocean general circulation model. Here we report analysis on results from a global warming experiment with coupled climate - carbon cycle model, current status on development of the component models, and model tuning efforts for the fully integrated earth system model.

**Keywords**: Earth system, Carbon cycle, Atmospheric Chemistry, Cryosphere, Aerosol

## 1. Introduction

Frontier Research Center for Global Change (FRCGC) of JAMSTEC launched in FY 2002 a project to develop an integrated earth system model (ESM) that operates on the Earth Simulator. 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 the time of project embarkation, FRCGC already had component models that correspond to the first three sub-projects above, and we develop the ESM by incorporating the component models to an already existing coupled atmosphere-ocean GCM (CGCM), which corresponds to the fourth sub-project. In this last FY of the project, we have fairly completed the development and are nearly ready for an ESM-based global warming experiment, which will be one of the novelties of 5th Assessment Report of Intergovernmental Panel on Climate Change expected to be published around 2013. On the other hand, development of the component models is vigorously continued. Here we report current status of the component models and parameter tuning for the fully integrated ESM.

### 1.1 Development of a coupled carbon cycle - climate change model

#### 1.1.1 Terrestrial carbon cycle model

We developed a coupled climate-carbon cycle model composed of a process-based terrestrial carbon cycle model, Sim-CYCLE, and the CCSR/NIES/FRCGC atmospheric general circulation model. We used this model to examine the multi-temporal scale functions of terrestrial ecosystem carbon dynamics induced by human activities and natural processes and evaluated their contribution to fluctuations in the global carbon budget during the 20th century. Our results indicate that monthly to interannual variation in atmospheric $CO_2$ concentration anomalies (anomaly; a variation component calculated as the difference of original data to averaged seasonal and interannual changes) showed 1 to 2-year time lags behind anomalies in temperature, similarly as the observation by Keeling et al. The anomalies in heterotrophic respiration (HR) varied almost concurrently with temperature anomalies. The anomalies in net carbon balance (NCB) trace the time derivative of variation in $CO_2$ anomalies. The global atmospheric $CO_2$ growth rate were fluctuated with a 1- to 2-year time lag behind temperature fluctuations, through the activity of terrestrial component. The similarity of our results to observation indicates that this coupled model could simulate the global carbon dynamics very well. In this fiscal year, moreover, we improved some parts of the land surface scheme MATSIRO, and modified this coupled model to include SEIB-DGVM functions for more realistic future simulation.

1.1.2 Ocean biogeochemical model (carbon cycle component for the fully integrated ESM)

A global warming experiment has been performed using a coupled climate - carbon cycle model in order to examine climate - carbon cycle feedback. By the end of the twenty-first century, the warming leads to further $CO_2$ increase of 123 ppmv. The positive feedback can mainly be attributed to the soil carbon dynamics in land. According to the investigation on regional scales, Siberia is the primary area with an intense positive feedback (Fig. 1a), because the acceleration of microbial respiration due to warming causes a decrease in soil carbon. Amazonia also shows a positive feedback that result from the acceleration of microbial respiration, although Amazonian forest dieback does not occur in our model. On the other hand, some areas, Western and Central North America and South Australia, indicate a negative feedback, because the enhancement of litterfall balances the loss in soil carbon. The oceanic contribution to the feedback is much weaker than that in the land, but a positive feedback in the northern North Atlantic is as strong as those of Amazonia and Siberia of our model (Fig. 1b). In the northern North Atlantic, the reduction of $CO_2$ absorption is caused by stratification in the surface water. In addition, the $CO_2$ subduction is also reduced around there, because the stratification leads to not only the reduction of $CO_2$ absorption but also a decline of $CO_2$ transport by NADW following the weakening of its formation. Thus, the carbon cycles make the contributions to the climate - carbon cycle feedback through the totally different mechanism by region.

1.1.3 Dynamic vegetation model

Our project has developed a Dynamic Global Vegetation Model (DGVM) SEIB-DGVM. Among existing DGVMs, only SEIB-DGVM simulates local area interactions of individual trees within a spatial explicit virtual forest. This feature would improve reliability in predicting vegetation changes, and enables sensitivity experiments that have never been done by previous studies. Using SEIB-DGVM, we compared the simulated changes in vegetation cover between rapid and slow seed migration scenarios for the next 100-200 years. In both of the case, boreal forest moved to higher latitude, and temperate-deciduous trees invaded where boreal forest has been removed, resulting in dense and open forests for rapid and slow seed-migration scenario, respectively. This result indicates the importance of seed-migration for predicting the transient vegetation changes. In this fiscal year, we also conducted many improvements to adequately represent population dynamics in tropical-rain- forest.

1.2 Development of a coupled atmospheric composition - climate change model

1.2.1 Model for interaction between global warming and change in atmospheric composition

In order to contribute to the latest scientific assessment of stratospheric ozone depletion issued by WMO and UNEP, an experiment which is designed to reproduce the stratospheric ozone in the last 25 years have been performed in corporation with the National Institute for Environmental Studies. This experiment has done as a part of international project, Chemistry-Climate Model Validation Activity (CCMVal). Because our CCM has been improved in several aspects in recent years, the calculated seasonal march of total ozone showed a great improvement over that calculated with the previous version of CCM. We have performed a multivariable regression analysis to extract the signal in the calculated ozone in response to the change in solar activity. The analyzed solar signal in calculated ozone has a peak in the tropical lower stratosphere which is consistent with that extracted from the observed ozone data. More detailed analysis show that this peak in ozone solar signal is relevant to the change in the vertical advection of ozone. The upward motion of air in the tropical lower stratosphere is weakened under the strong solar activity, and then the reduced influx of

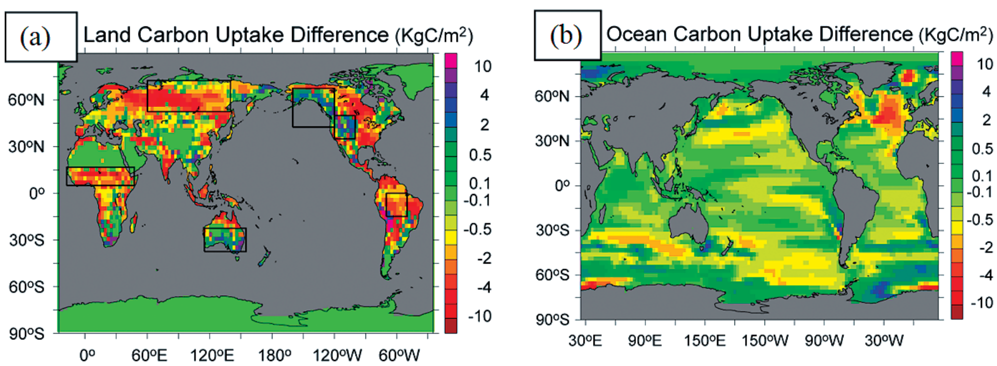


Fig. 1 Difference in accumulated $CO_2$ uptake flux (KgC m$^{-2}$) between coupled and uncoupled run for (a) land and (b) ocean. Red colors indicate regions where interactions between warming and carbon cycle lead to reduction of carbon storage, meaning the feedback is positive.

tropospheric ozone, which is in general smaller than stratospheric ozone, into the stratosphere makes a positive peak in ozone in the tropical lower stratosphere.

1.2.2 Accurate estimation of feedback between global warming and the cloud-aerosol-radiation system

We implemented an aerosol transport model SPRINTARS (Takemura et al., 2000, 2002, 2005) to a framework of global cloud resolving model (GCRM) NICAM. The physical and chemical processes of aerosol including emission, transport, deposition and chemical reactions are taken into account in this aerosol-coupled GCRM. The effect of aerosol on cloud microphysics is also incorporated into the model through a bulk parameterization, which includes an empirical relationship between aerosol and cloud particle numbers, and auto-conversion rate in warm rain formation as a function of cloud droplet number as well as cloud water content. The cloud microphysical and optical parameters such as effective particle radius and optical thickness are calculated in the model. We performed some test runs with coarse horizontal resolution of about 240km and obtained a global distribution of aerosol and cloud similar to original version of SPRINTARS coupled with CCSR/NIES/FRCGC AGCM. Global cloud resolving experiments were also conducted on Earth Simulator with horizontal resolution of 14km and 7km. Simulated results are compared with satellite remote sensing for several important parameters of aerosol and cloud, such as optical thickness of aerosol and cloud, Angstrom Exponent and cloud particle effective radius (Fig. 2). The simulated global feature was consistent with satellite observation. It was found that the cloud particle effective radii are simulated to have a detailed feature over equatorial region, similar to the satellite retrieval, which is difficult to be reproduced by conventional GCMs. Some coastal features in effective cloud particle radius are also found to be more realistic than those simulated by GCM.

1.3 Development of a cryospheric climate system model

It has been pointed out that there are systematic errors in numerical solutions for equilibrium ice-sheet thickness distribution under idealized conditions, as compared to analytic solutions. These errors are prominent around peripheries of an ice-sheet, and could amount to a few hundred meters making these errors non-negligible for certain problems. For example, ice-sheet response to global warming would start from the peripheries, demonstrating the need to their better reproduction. We therefore devised a numerical scheme that reduces the errors around the peripheries and applied it to an idealized case. The results are documented and will appear in Annals of Glaciology (Saito et al, 2007). This study shows that there can be an overestimate of a few hundred meters for ice-sheet thickness around peripheries, due purely to a numerical reason. Parameter sensitivity experiments have been also carried out regarding response of an ice-sheet toward global warming. They confirmed that, regardless of parameter values, there is a threshold temperature rise beyond which reduction in ice-sheet volume becomes considerably larger.

1.4 Improvement of the physical climate system model

Photochemical reaction processes for the stratosphereic chemistry associated with halogen species have been intro-

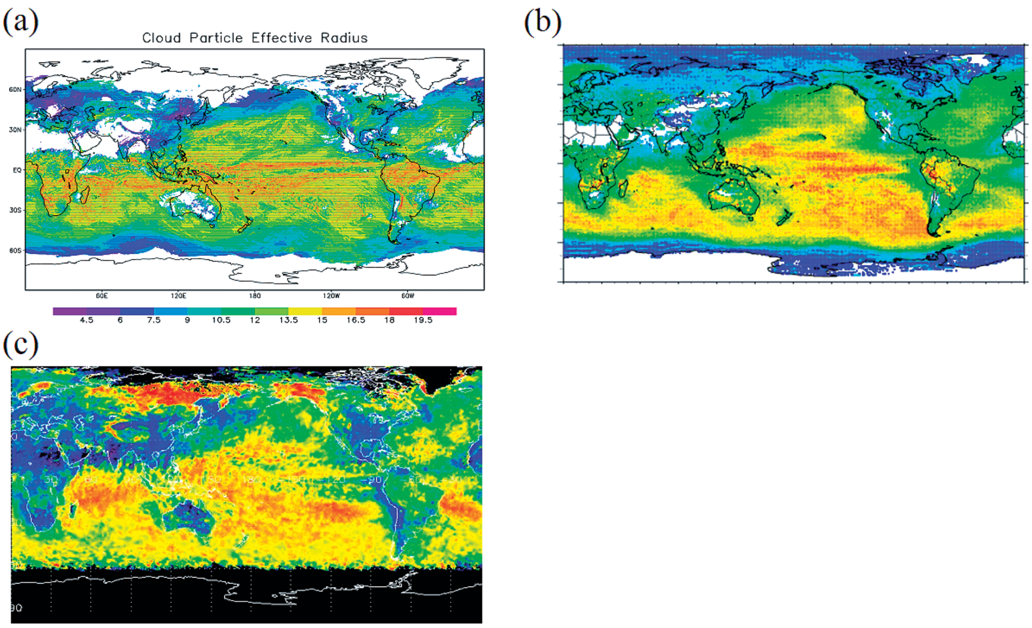


Fig. 2 Distribution of cloud particle effective radius in April obtained by (a) NICAM– SPRINTARS coupled model, (b) CCSR/NIES/FRCGC AGCM – SPRINTARS coupled model and (c) MODIS satellite observations (courtesy of T. Nakajima of Tokai University).

duced into the integrated earth system model. Distribution of storatospheric ozone is successfully simulated as well as thermal structure in the stratosphere and mesosphere. Reality of the present climate simulation in the troposphere has been improved by parameter tuning for clouds and aerosols. The parameter tuning for the simplified aerosol model SPRINTARS were performed to improve aerosol distribution. For example, dust generation had been underestimated in past results. It has been dramatically improved after the tuning (Fig. 3). The prescribed surface albedo over desserts has been increased, taking account for scattering effects due to dust particles. Ability of aerosols to form cloud condensation nuclei has been reconsidered in order to improve distribution of clouds and cloud radius. However, an essential problem has not been solved, that is, clouds over the land are much underestimated compared to those over ocean. An additional problem was found when we used the new radiation scheme mstrnX. Arctic sea ice decreased in the course of long-time integrations of the model. It was probably caused by an underestimation of summer time low-level clouds over the Arctic. These problems will be reconsidered after planned modifications for clouds and boundary layer parameterizations in near future.

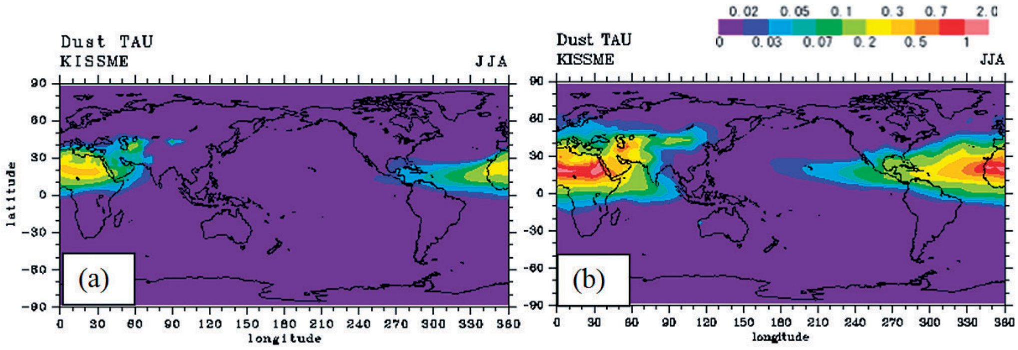


Fig. 3 Optical thickness for dust aerosols (a) before and (b) after the parameter tuning.

# 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。本報告書では、大気海洋結合炭素循環モデルによる温暖化予測実験の結果解析および各コンポーネントモデルの開発状況、全コンポーネントモデルを含む地球システム統合モデルのパラメータチューニングの進行状況について述べる。

キーワード：地球システム, 炭素循環, 大気化学, 雪氷圏, エアロゾル