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 preliminary results of global warming experiments with our ocean-only carbon cycle model, the current development status of our coupled carbon cycle – climate model, code optimization of the atmospheric chemistry model, evaluation of transport processes of our atmospheric GCM, and improvements of the core climate model.

Keywords: Earth system, Carbon cycle, Atmospheric Chemistry, Stratosphere

1. Introduction

Frontier Research System for Global Change (FRSGC) launched in FY2002 a project to develop an integrated earth system model 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 CO2 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.

After this introductory section, we show in section 2 preliminary results of global warming experiments with our ocean-only carbon cycle model and the current development status of our coupled carbon cycle – climate model. Section 3 contains code optimization of the atmospheric chemistry model and evaluation of transport processes of our atmospheric GCM. Finally, efforts to improve the core climate model are presented in section 4.

2. Development of an oceanic carbon cycle model

Precedent to the inclusion of the carbon cycle to our coupled climate model, preliminary experiments for future uptake of CO2 by the ocean are carried out using an ocean-only model with carbon cycle processes. The model's horizontal resolution is 1 deg. by 1 deg., and it has 54 vertical levels. The model is forced with and without the effect of global warming using results from a coupled climate model. The CO2 concentration is increased in both cases by 1%/year after 1990. The focus is on the differences in time evolution of the uptake between the two cases, which turn out to be small (Fig. 1). The present result is not something that attracts many people's attention in that it only confirms the result of past experiments reported in the IPCC Third Assessment Report, but it is meaningful for the project in that it assures that the model shows a plausible behavior.

Following the experiment with the ocean-only model,

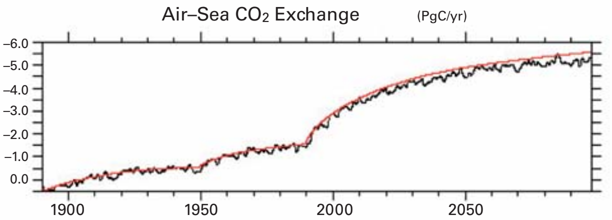

Fig. 1 Model projection of future CO2 uptake by the ocean under CO2 increase of 1%/year after 1990. The red line represents the result where the model is forced without the effect of global warming, and the black line with it.

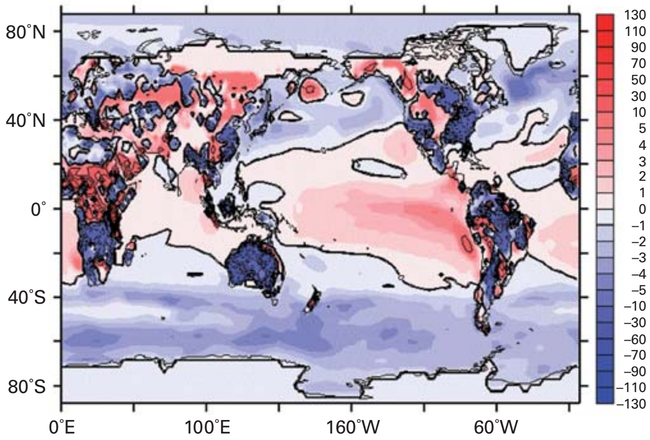

Fig. 2 Annual mean CO2 exchange at the land and sea surface obtained by the model. Units are molC m^{-2} $year^{-1}$. Red shows areas where CO2 is released to the atmosphere, while blue shows areas where CO2 is removed from the atmosphere. Note that the model spin-up is still insufficient and the result here is far from equilibrium.

we have embarked on the incorporation of oceanic and terrestrial carbon cycle processes into our coupled climate model. A prototype of a coupled carbon cycle climate model is now completed (Fig. 2). Parameter tuning, code tidying, and sufficient spin-up etc. will be further conducted to prepare for the "Coupled Carbon Cycle – Climate Model Intercomparison Project (C4MIP)" and contribution to the IPCC Forth Assessment Report.

3. Development of a coupled chemistry-aerosol-climate model

In this fiscal year, the subgroup "coupled atmospheric composition-climate model"have started developing a chemistry-aerosol coupled climate model on the ES using a global chemical model CHASER (Sudo et al., 2002) and aerosol model SPRINTARS (Takemura et al., 2000) which are both based on the CCSR/NIES (the Center for Climate System Research/ National Institute for Environmental Studies) atmospheric GCM (AGCM) version 5.7b.

3.1. Optimization of the coupled chemistry-climate model CHASER on the ES

Since the chemistry component in CHASER, including 53 chemical species and 140 photochemical reactions in its present configuration, requires much computational time relative to the default AGCM, optimization of the CHASER code is our critical issue in view of our planed long-term simulations on the ES. This fiscal year, we have tuned the CHASER code to reduce the total CPU time cost on the ES, prior to coupling the aerosol component of SPRINTARS with CHASER. To optimize CHASER we mainly use list-vector method for conditional vector operations (such as "IF" blocks) in the chemistry component; list-vector is also used in the physics component of the CCSR/NIES AGCM5.7b. Fig. 3 compares the CPU time required for one-year integration with the optimized CHASER code and original one. Significant reduction in CPU time is found for the chemical reaction processes and cloud-related processes: wet deposition and nitrogen oxides (NOx) production by lightning in convective clouds. Owing to our tuning, the total CPU time required for the all processes in CHASER (including dynamics and physics) decreases by 35% on the ES. With the new code, one-year CHASER simulation (with T42L32) requires CPU time of 73 hours on the ES L-system (4 nodes: 32 PE). The averaged vector operation ratio and length are 97.8% and 175, respectively. Further optimization of CHASER on the ES will be achieved by using microtask for computation of the chemistry component.

3.2. Evaluation of transport processes in the CCSR/NIES AGCM

Tracer transport is one of the most important processes in a chemistry/aerosol model. This fiscal year, we have evaluated the transport process (especially in the stratosphere) in the CCSR/NIES AGCM using passive tracers. We calculate distribution of age of air, a good measure of cross-tropopause and stratospheric transport, and evaluate it with the observation derived age distribution. The observed age

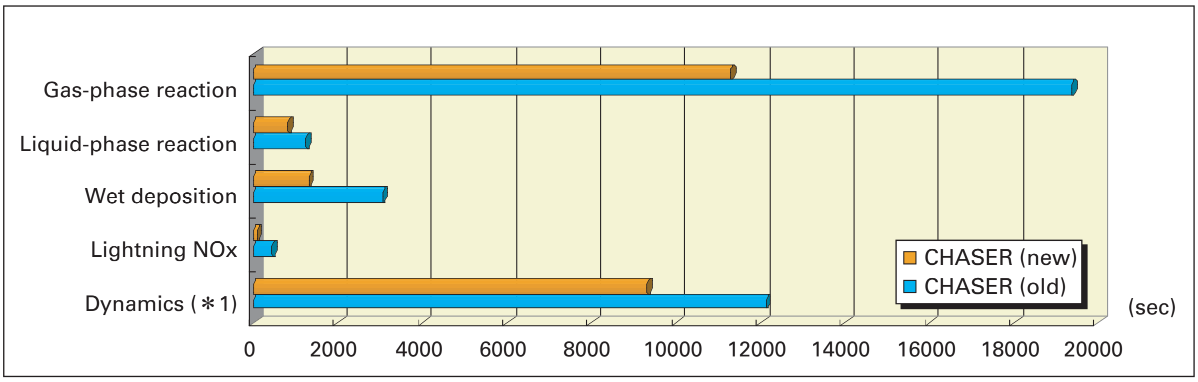

Fig. 3 Reduction in CPU time (sec) required for one-year integration of the CHASER model (with T42L32) by adopting the list-vector method in the new code (red). Shown are CPU time only for chemistry-related processes in CHASER. *1: Reduction in "Dynamics" comes mainly from tuning vectorization of the tracer transport process in the CCSR/NIES AGCM5.7b.

of air is well reproduced by the model in the tropics, but is underestimated in the extra-tropics (Fig. 4). Transport associated with the stratosphere-troposphere exchange will be further evaluated in the next fiscal year.

4. Improvement of the physical climate system model

This sub-group aims at improvement of an AGCM used as a basic component of the integrated earth system model. 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 80 km).

There has been a shortcoming in the previous version of the AGCM. Temperatures near the tropopause had a large cooling bias by about 10 K, so that distribution of moisture and clouds was quite unrealistic. In order to look for causes of such biases, Mini-Project for Physical Process Intercomparison (MIPPI) was conducted as a cooperative effort with Japan Meteorological Agency (JMA) and UK Hadley Center. As a result, it was found that radiative heating rate near the tropopause was significantly underestimated in the previous version of our radiative transfer code "mstrn-8" (Nakajiama et al. 1995).

Very recently, a new version of radiation code "mstrn-X" was released by CCSR radiation group (Sekiguchi 2004), in which following improvements were made; 1) an update of HITRAN database for atmospheric absorption, 2) a replace of a program calculating continuum absorption (from LOWTRAN7 to MT_CKD_1), 3) a substantial increase of bands for calculations of atmospheric absorption, 4) a change in optimization method for a selection of integration points. The cooling biases near the tropopause and in the lower stratosphere almost disappear when the new radiation code is used.

Other efforts performed in this fiscal year are implementation of a non-orographic gravity wave drag parameterization and estimation of gravity wave source distribution by using a very high resolution version of the AGCM. The non-orographic gravity wave drag parameterization is required for a better simulation of the middle atmosphere, because it represents effects of unresolved waves which accelerate / decelerate large-scale wind fields. A "Doppler-spread" parameterization proposed by Hines (1997) is employed, because it has been well tested by various modeling groups.

Fig. 5 shows global distribution of horizontal RMS winds associated with small-scale (horizontal wave length: 250–1250 km) gravity waves, which are simulated by a T213L250 AGCM. The RMS winds and propagation directions are derived using a hodgraphic method around 70 hPa, and averaged over January. Arrows show amplitudes of wind fluctuation in 8 azimuths at their locations. Red contour lines show monthly mean precipitation. Fig. 5 illustrates realistic characteristics of gravity waves; 1) large wind variances and a dominance of westward propagation over storm tracks, and some localized maxima over mountainous regions in mid latitudes of winter hemisphere, 2) broad maxima corresponding to large-scale precipitation patterns in the tropics and mid latitudes of summer hemisphere, which reflect importance of source distribution, 3) minima in high latitudes of both hemispheres. By use of this source information with the Hines parameterization, realistic circulations in the tropics are realized with a middle resolution version (T42L78) of the model (not shown).

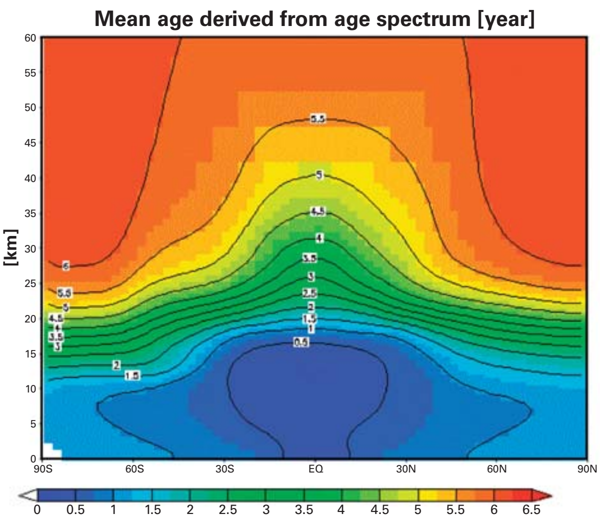

Fig. 4 Zonal mean distribution of age (years) of air estimated by the CCSR/NIES AGCM.

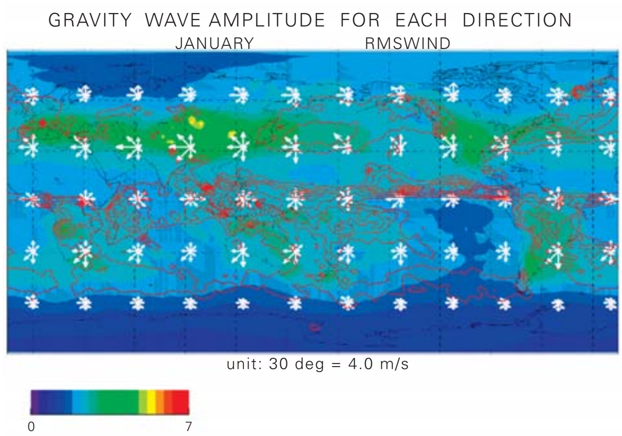

Fig. 5 Global distribution of RMS winds for small-scale gravity waves (colors) at 70 hPa in January. Arrows: amplitudes of wind fluctuation in 8 directions at their locations. Contours: monthly mean precipitation. The contour interval is 3 mm day^{-1}.