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

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The mission of this project is to develop advanced climate models which have a capability to explore new arenas of climate simulations by fully utilizing the Earth Simulator. The project started at the beginning of the Earth Simulator operation. The project consists of three model developments: an integrated earth system model, a cloud-resolving atmospheric general circulation model, and an eddy resolving ocean general circulation model developments. The achievement of the year on the first model is that global warming experiments by using the developed coupled carbon cycle – climate change model was performed and it was shown that interactions between climate and carbon cycle act to enhance atmospheric CO2 concentration, resulting in a positive feedback for global warming. On the second model, a 3.5 km-mesh global simulation on an aqua planet setup was performed and the results were compared with satellite observation data. The simulation captured a hierarchical structure of cloud system very well. On the third model, an eddy resolving world ocean simulation was successfully performed by implementing biharmonic horizontal diffusion and biharmonic Smagorinsky-like viscosity. The mesoscale eddies of world ocean were reproduced realistically. The eddy resolving simulation in the Southern Ocean also performed and calculated distribution of thickness diffusivity which represents the interaction between mesoscale eddies and ocean circulation.

Keywords: earth system model, carbon cycle, global cloud resolving model, global eddy resolving model

1. Development of an integrated earth system model

1.1 Development of a coupled carbon cycle – climate change model

1.1.1 Terrestrial carbon cycle model

Carbon cycle dynamics and CO2 release through land use changes during the 20th century was investigated using our coupled climate - terrestrial carbon cycle model. The results showed that net primary production (NPP) and heterotrophic respiration (HR) had been gradually increasing throughout the century. On the other hand, net ecosystem production (NEP: NPP-HR) had been almost always positive, meaning that the terrestrial biosphere had been a sink for atmospheric CO2. When the CO2 release through land use changes (LUCefflux) is taken into consideration, however, the net carbon uptake by (NEP-LUCefflux) often becomes negative. LUCefflux is large in South-East Asia and Southern America, and amounts to 49.2 PgC for the total of the 20th century. It can be said that LUCefflux is a significant component of the global carbon cycle.

NEP and LUCefflux averaged for 1980-1989 are +0.52 and –0.56 Pg C yr^{-1}, respectively, being much smaller in absolute values than the figures calculated based on inventory data (+2.40, –2.00 Pg C yr^{-1}; Houghton, 2003). The simulated budgets for NEP and LUCefflux may not be totally unrealistic considering the model reproduces well the observed time evolution of global mean atmospheric CO2 concentration.

1.1.2 Carbon Cycle Embedded in an Atmosphere-Ocean Coupled GCM

In the last FY (2004), we conducted a preliminary global warming experiment with our coupled atmosphere - ocean - carbon cycle model. The experiment was carried out for demonstrative purpose without a careful parameter tuning. In this FY (2005), a more credible experiment was re-performed with a careful parameter tuning (especially for the terrestrial carbon cycle model). A result of the re-experiment, with which the extent of the feedback between climate and carbon cycle is investigated, is shown in Fig. 1. The figure reveals that interactions between climate and carbon cycle act to enhance atmospheric CO2 concentration, resulting in a positive feedback for

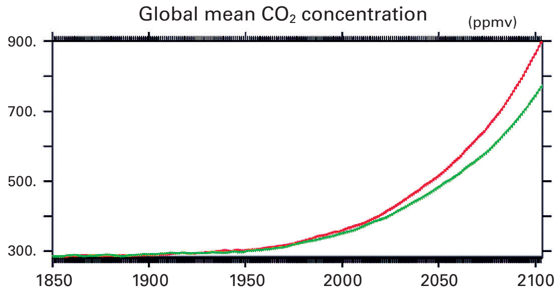

Fig. 1 Time evolution of atmospheric CO2 concentration obtained by providing CO2 emission data as model input. The red line shows the case where interactions between climate and carbon cycle are considered, and the green line not. Units are ppmv.

global warming. The main cause for the positive feedback is enhancement of the degradation of soil organic carbon due to warmer temperature. The difference in atmospheric CO2 concentration at 2100 between the two runs in Fig. 1 is 130 ppmv, corresponding to about 1°C, which is a significant difference for global warming projection. Sensitivity experiments with different sets of parameters are being carried out to check the rigidity of the present results, which are likely to be reflected in the next IPCC report (AR4) to be published in 2007.

1.2 Development of a coupled atmospheric composition - climate change model

Our integrated earth system is now equipped with the atmospheric chemistry model CHASER and aerosol transport model SPRINTERS, and the current status of the model is summarized by Kawamiya et al. (2005). Extension of CHASER to include stratospheric chemistry and to couple with the terrestrial ecosystem model Sim-CYCLE has been embarked. On the other had, analysis on some CHASER-only experiments were conducted, including those to project future atmospheric composition under SRES scenario and those under a model intercomparison project for atmospheric chemistry aimed at IPCC Forth Assesment Report. Analysis for the latter has been conducted involving scientists from across the world, who made comparisons on impacts of tropospheric and stratospheric ozone variation on global radiation budget. It was revealed that radiative forcing due to stratospheric ozone variation is highly model dependant (Fig. 2), indicating that the next focus should be on how one models stratospheric ozone chemistry.

This sub-theme also includes activity to improve NICAM (Non-hydrostatic icosahedral atmospheric model). In this FY, efforts are directed to incorporate SPRINTARS in NICAM.

1.3 Development of a cryospheric climate system model

Experiments with our ice sheet model were performed to investigate how Greenland ice sheet would respond to global warming, and to what extent the response would impact on sea level rise. The model was forced with data obtained from the global warming experiments conducted under the framework of Kyousei 1a (PI: A. Sumi). The results showed that sea level rise due to ice sheet melting is in the range of 5–8 cm at 2100, and 50–100 cm on a millennial time scale. It turned out that the ice sheet can only reach an equilibrium state on a time scale of 10,000 years, with a contribution of 2–4 m to sea level rise. Furthermore, an experiment was conducted under climate conditions with a quadrupled CO2 concentration. Under this climate the modeled ice sheet totally disappeared after a 3,000-year integration, resulting in a contribution of 6m to sea level rise. The coding for the fully coupled climate - ice sheet model has been completed as stated in the implementation plan for FY2005.

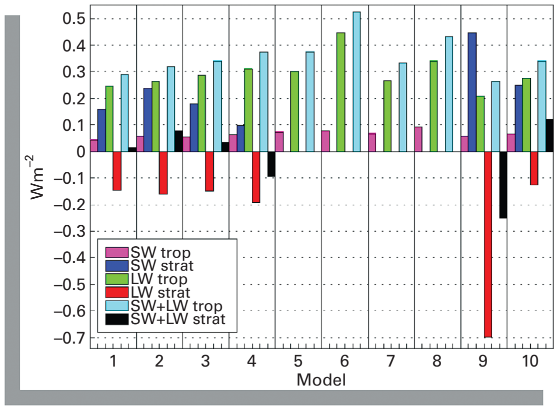

Fig. 2 Stratospheric and tropospheric radiative forcing computed by models participating in the model intercomparison project for atmospheric chemistry aimed at IPCC-AR4 (Gauss et al, 2005). Model #4 represents results from CHASER.

1.4 Improvement of the physical climate system model

The model top of our integrated earth system model was extended from the former 30 km with 20 layers to 80 km with 80 layers. The extension necessitated re-tuning work to, e.g., adjust the radiation budget at the top of the atmosphere, which has been accomplished by tuning of the large scale condensation parameterization. Further tuning work is, however, necessary because the extended model yields distributions of surface temperature, aerosol, and outputs form the terrestrial ecosystem model (Sim-CYCLE) worse than the former version with 20 layers. Tuning on stratospheric circulation was conducted in parallel with the tropospheric tuning, and was finished with a satisfactory match with observed fields. As for code optimization required to run the model with so many layers and chemical tracers, the model code was modified to utilize intra-node parallelization technique so that the atmospheric component can be run with more nodes (max. 32 nodes) than the current 2 nodes.

2. Development of a global cloud resolving atmospheric model

We have performed a 3.5 km-mesh global simulation on an aqua planet setup using a global cloud resolving model, NICAM. The simulation captures a hierarchical structure of cloud systems: deep convective towers, meso-scale system, cloud clusters, super cloud clusters, and global scale convectively coupled Kelvin waves. The statistics of cloud/rain properties are directly compared with high-resolution satellite data such as TRMM PR and GMS data. We are now conducting global cloud resolving simulations with land-sea distribution and realistic topography. Preliminary results with 14 km-mesh experiment show that typhoons are realistically simulated over the western Pacific (Fig. 3). With this approach, we will argue cyclogenesis of typhoons, intraseasonal variability of cloud systems in the tropics, and climate sensitivity without ambiguity of cumulus parameterization.

3. Development of a global eddy resolving ocean model

An advanced ocean model which can resolve mesoscale eddies in global ocean is being developed. This model makes it possible to simulate global ocean circulation without mesoscale eddy parameterizations. A coarse-resolution simulation of 1000 year time integration was performed last year using this developed ocean model and it was confirmed that the calculated results agreed well with conventional model results. The biharmonic horizontal diffusion and biharmonic Smagorinsky-like viscosity were implemented this year and a high resolution simulation was performed. Figure 4 shows the simulated sea-surface temperature distribution. This high resolution simulation reproduced mesoscale eddies of world ocean realistically.

In parallel, roles of mesoscale eddies in ocean circulation is studied by using an ocean model developed by Tokyo University. The calculation area is limited to the Southern Ocean, which is one of the highest eddy active regions in the world. The thickness diffusivity distribution, which represents the interaction between mesoscale eddies and large scale ocean circulation, has been estimated (Fig. 5.). It is shown that the diffusivity decreases sharply from the sea surface and has a constant of approximately 300 m^2s^{-1} value under 600 m depth. The Labrador Sea is another area where mesoscale eddies may play an important role. An eddy resolving simulation with about 5 km mesh size is now being carried out to study interaction between the deep-convection and mesoscale eddies.

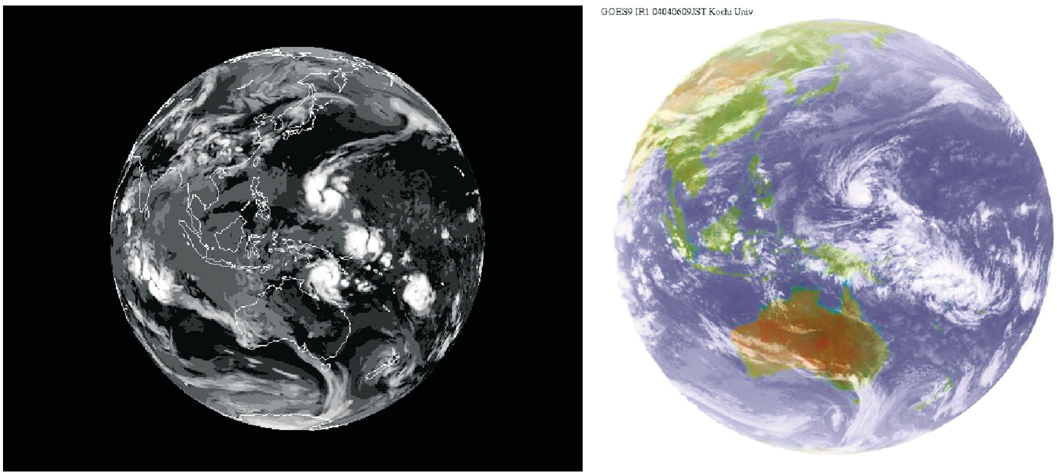

Fig. 3 Global view of OLR simulated by 14km-mesh NICAM (left) and GMS/GOES-9 TBB image (right, http://weather.is.kochi-u.ac.jp/) at Apr. 6, 2004, 00UTC. NICAM simulation is started from Apr. 1, 00UTC.

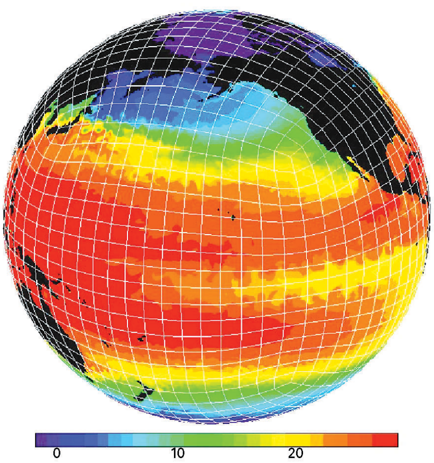

Fig. 4 The calculated sea-surface-temperature (unit: Celsius) using the developed ocean model.

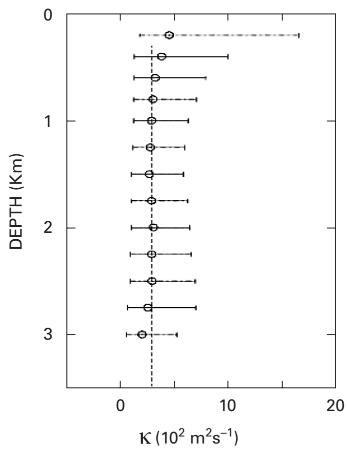

Fig. 5 The depth dependency of the thickness diffusivity. The averaged value under 600 m depth is about 300 m^2s^{-1}.

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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このプロジェクトは地球シミュレータを最大限に活用して気候シミュレーションの新たな領域を開拓する先進的な気候モデルを開発することであり、地球シミュレータの運用開始時から継続している。このプロジェクトでは、統合地球システムモデル、全球雲解像大気大循環モデル、全球渦解像海洋大循環モデルの三つのモデルを開発している。今年度の成果としては、統合地球システムモデルでは開発した気候・炭素循環結合モデルを使って温暖化実験を行い、気候と炭素循環の相互作用は大気中の二酸化炭酸を増加させることを明らかにした。つまり温暖化に正のフィードバックがあることになる。全球雲解像大循環モデルについては、3.5kmメッシュ水惑星全球雲解像計算を実行し、衛星データと比較してモデルが熱帯域の積雲の階層構造をよく捉えている事がわかった。また陸海地形を導入したモデルの開発も終了し初歩的な実験も開始した。全球渦解像大循環モデルについては、高解像度計算に必要なスキームを導入して全球渦解像長時間積分を実行した。また南大洋領域モデルで渦解像計算を実行し中規模渦と海洋循環の相互作用を表す量である層厚拡散係数の詳細な空間分布を求めた。

キーワード：地球システム・モデル, 炭素循環, 全球雲解像モデル, 全球渦解像モデル