Development of a High-Resolution Coupled Atmosphere-Ocean-Land General Circulation Model for Climate System Studies

Project Representative

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The mission of this project is to develop advanced climate models which have a capability to explore new areas of the climate simulation study by fully utilizing the Earth Simulator. The project started at the beginning of the Earth Simulator operation. In this project, three models have been developed: a CCSR/NIES/FRCGC atmosphere-ocean-land coupled model, a cloud-resolving atmospheric general circulation model, and an eddy resolving ocean general circulation model. In fiscal year 2006, new physical schemes associated with planetary boundary layer and cumulus convection were introduced to the CCSR/NIES/FRCGC model and it was confirmed that vertical profiles of cloud water has greatly been improved in a single column experiment with the new schemes. As for the second model, a sensitivity study of planetary boundary layer schemes for the turbulent transport on the cloud organization was carried out and we found that it affects strongly the cloud organization. In addition, a perpetual July experiment showed that rainfall rate of the model agreed well with fine scale structures of observation. Regarding the third model, we have completed to develop an eddy resolving model. The sea surface temperature distribution simulated by the eddy resolving model reflects the ocean eddy activity realistically.

Keywords: atmosphere-ocean-land coupled model, global cloud resolving model, global eddy resolving model

1. Background

We have combined former several Earth-Simulator research projects in which three climate-simulation models have been developed: a CCSR/NIES/FRCGC atmosphere-ocean-land coupled model, a global cloud resolving model, and a eddy resolving model. These projects are based on the medium-range (5-year) plan of the Japan Agency of Marine-Earth Science and Technology. By conducting these projects, we will finally achieve a state-of-art earth environmental model, exploring a new research field of climate simulation.

Studies with the two models are compensatory for the realization of a high-performance earth system model. That is, the first model is applicable for a long-term climate simulation with physical parameters revised through the straightforward simulation of climate system by the second model. By contrast, the experience with the low resolution model helps the realization of the next-generation earth system model.

2. Development of the CCSR/NIES/FRCGC coupled model

We have improved various physical parameterizations of the model associated with radiation, cumulus convection, cloud, and atmospheric lower boundary layer, for reproduction and prediction of the actual climate system. Model sensitivity experiments and analyses of model outputs were also carried out for a wide rage of climate system studies in the future.

Among the above studies, improvements of three dimensional distribution of water vapor and cloud water in climate models are very important subjects for both the reproducibility of present climate and evaluation of climate sensitivity. Therefore, we focused on representations of stratocumulus-topped planetary boundary layer over low sea surface temperatures (SSTs) and stratocumulus-topped trade cumuli over moderate SSTs. It has been recognized that it is difficult for the current stage of general circulation models (GCMs) to simulate these phenomena realistically, which is considered to be causes of major biases in most of the atmosphere-ocean coupled GCMs with respect to SSTs and cloud radiative forcing.

A single column model is used to evaluate several physical schemes. The southeast Pacific ocean is chosen for the location of the simulations where SSTs gradually change from low values of coastal upwelling to moderate values westward. First, impact of an improved Mellor-Yamada scheme based on Nakanishi and Niino (2004) is examined over low SST area near the coast where stratocumulus-topped boundary layer is persistently formed. The result shows that location of boundary layer top and vertical distribution of water vapor are greatly improved by the incorporation of the new scheme (Fig. 1). Another experiment over moderate SST area to the west of the coast is carried out. It is known from ship observations that stratocumulus-topped trade cumli is persistently formed in this region. It is shown that the representation of the trade cumuli in our model is greatly improved through the incorporation of the improved Mellor-Yamada scheme, a new cloud diagnosis scheme based on Xu and Randall (1996) and a modified triggering mechanism of cumulus scheme.

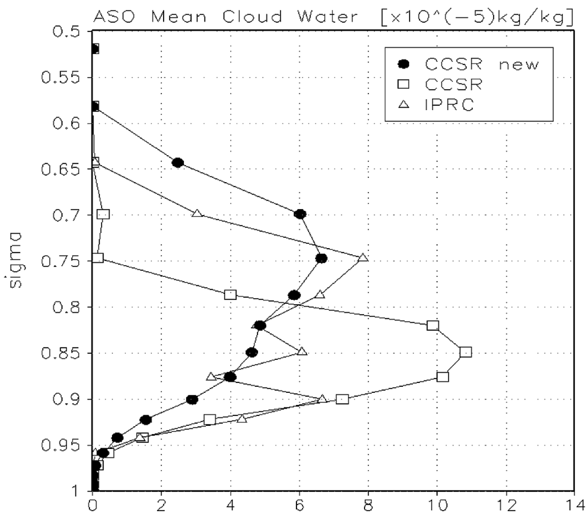

Fig. 1 The vertical distribution of cloud water (10^{-5} kg/kg) averaged from August to October in 1996. □: CCSR/NIES/FRCGC AGCM with the present parameterization, △: IPRC regional climate model, and ●: CCSR/NIES/FRCGC AGCM with the new parameterization. See text for detail.

3. Development of a global cloud resolving atmospheric model

We run NICAM (Nonhydrostatic ICosahedral Atmospheric Model) with a realistic land/sea distribution. Several "global cloud resolving" simulations with an explicit microphysics scheme were performed up to 3.5 km horizontal mesh intervals: short-term simulations for a week to month integration and long-term simulations for about 200-days integration to obtain a climate state. As a short-term simulation, starting with an initial condition of NCEP reanalysis data of 1st Apr. 2004, we integrated NICAM for a week with three different resolutions, 14 km, 7 km, and 3.5 km-mesh intervals. Interestingly, large-scale organization of cloud system is similar for three resolution cases and realistic development of typhoon (0401, Sudal) is captured. We also investigated the sensitivity study of planetary boundary layer scheme on the cloud organization by replacing the Mellor-Yamada level 2 moist closure, which considers the small scale atmospheric turbulence and clouds in a more adequate manner. As a result, we found that boundary layer process strongly controls cloud organization (Fig. 2). Furthermore, the diurnal cycle in the maritime continent in the tropics is drastically improved. These facts imply that the PBL scheme is very important as well as the cloud microphysics scheme in the development of the next generation global cloud resolving model.

Second, as a long-term simulation, we conducted a perpetual July experiment and examined climate sensitivity by increasing sea surface temperature (SST) by 2K. Figure 3 shows one-month average rainfall rate of 14km-mesh experiment. It was compared with one-month rainfall measured by

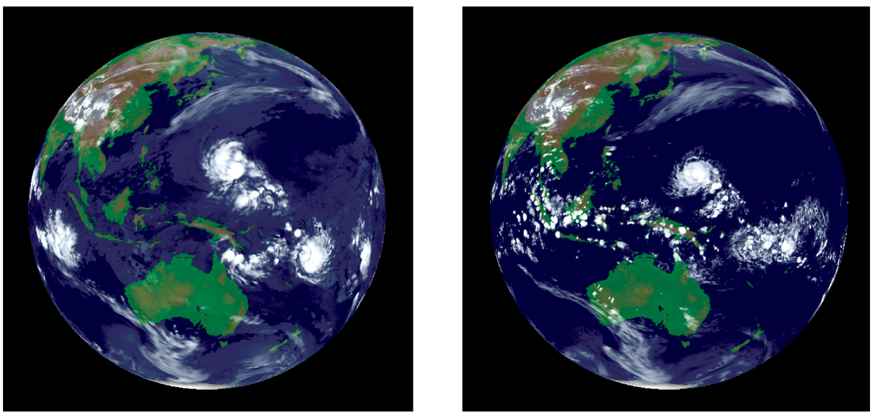

Fig. 2 Comparison of cloud organization. These figures indicate the OLR distribution at 4 day simulations. The left figure is the result from the old PBL scheme, while the right one is the results from the new PBL scheme. After the improvement of PBL scheme, the cloud organization well corresponds to the observation.

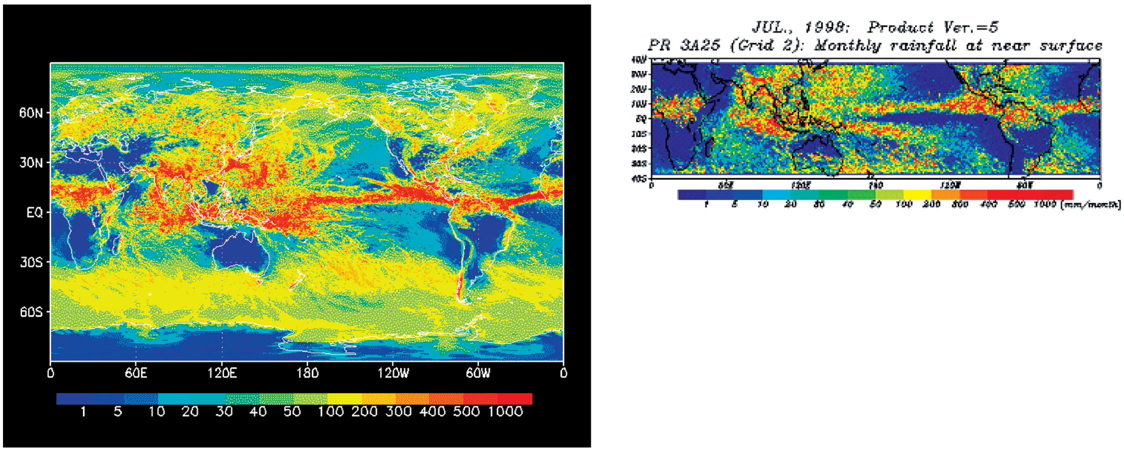

Fig. 3 Monthly mean rainfall of a perpetual July condition experiment by 14km-mesh NICAM (left) and that of TRMM PR (Precipitation Radar) data for Jul. 1998 (right: JAXA).

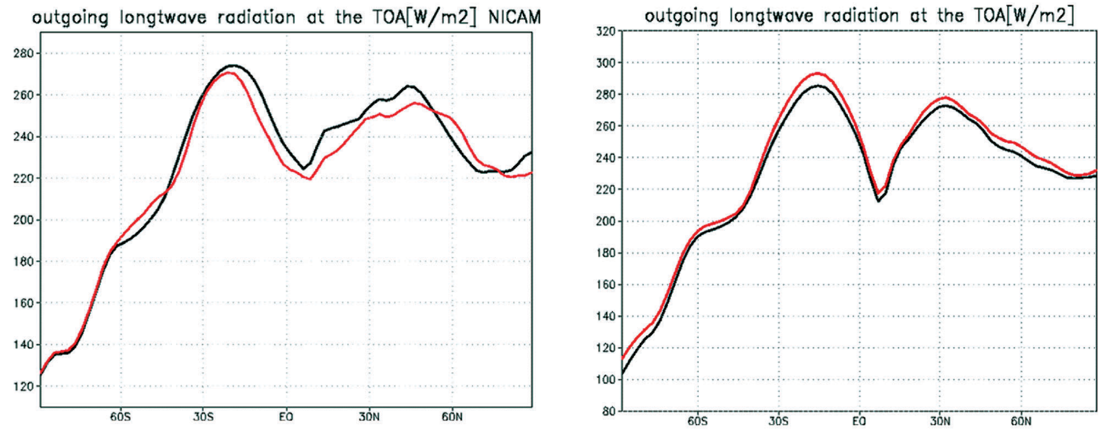

Fig. 4 Latitudinal distributions of zonal mean outgoing longwave radiation (OLR) of the control run (black) and warm condition run with 2K increased sea surface temperature (red). Left: 14km-mesh NICAM; right: CCSR/NIES/FRCGC AGCM, T42.

TRMM PR (Precipitation Radar; July 1998). Although the simulation is not directly comparable to the particular year of observation, the fine scale structure observation in the model is very similar to the observation especially over Pacific. From the climate sensitivity experiment, we obtained an interesting result (Fig. 4). According to NICAM results, outgoing longwave radiation at the top of the atmosphere (OLR) decreases around the tropics when SST increases, while OLR increases in the case of the CCSR/NIES/FRCGC atmospheric general circulation model using a cumulus parameterization with a spectral resolution of triangular truncation at wave number 42. The decrease in OLR of NICAM comes from the increase in upper layer clouds. We expect that cloud microphysics scheme affects cloud abundance, and believe that this result is not definitive. We are now investigating the robustness of sensitivity by changing microphysics and boundary layer schemes.

In the next year, we will start the full-scale research of predictability in the tropical region by using NICAM. The main targets are the Madden-Julian Oscillation (MJO) and cyclogenesis of tropical cyclones. Especially, MJO simulation by the global cloud resolving model is one of the most exciting challenges, by which we can expect not only the assessment of MJO as the natural hazard but also investigation of its mechanism and influence on the global scale dynamics.

4. Development of a global eddy resolving ocean model

An ocean general circulation model (OGCM) which can resolve mesoscale eddies in the global oceans is being developed. The OGCM employs a cubic grid so that it has a quasi-homogeneous grid on the sphere. This year, two important improvements, implementation of a mixed layer model and partial bottom cell, were completed and then the OGCM became applicable to realistic ocean simulations.We have performed a 15 km-mesh, eddy-permitting global simulation. Figure 5 shows the sea surface temperature of the simulation. The model realistically reproduces the wind-driven circulation as well as the global thermohaline circulation. The model captures eddy behaviors in the tropics and

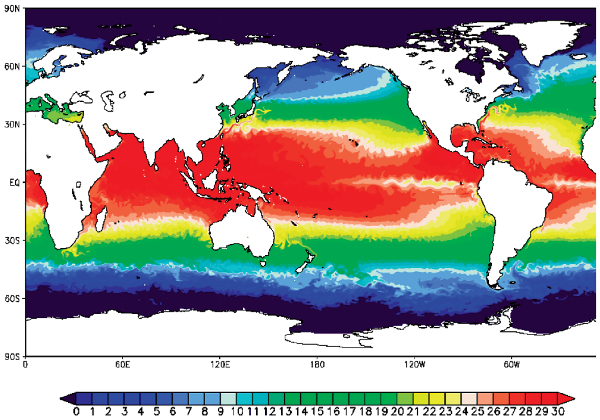

Fig. 5 Sea surface temperature [˚C] of the 15km-mesh cubic grid OGCM.

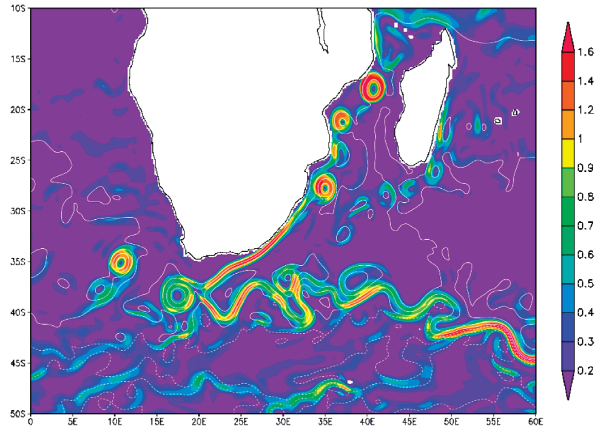

Fig. 6 Sea surface velocity [m/s] around the Agulhas Current.

in the western-boundary-current regions as well as other regions. We are now focusing on the Agulhas Current, which flows along the south-eastern coast of Africa. The Agulhas Current transports water mass from the Indian Ocean to the Atlantic and controls the return of North Atlantic Deep Water (NADW) to its forming region; hence it plays an important role in the global ocean circulation. Various eddies, for example, the Agulhas Rings, are observed in this region and our model captures eddies of the current system realistically (Fig. 6). The Agulhas rings are shed near the southern tip of Africa, and then move into the Atlantic. Other eddies, such as eddies in the Mozambique Channel, are also reproduced. With the model, we will study the role of eddies in the global ocean circulation and will improve accuracy of the climate change prediction.

気候システム研究のための
高精度大気・海洋・陸面結合大循環モデルの開発

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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変動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実施されている。プロジェクトでは、CCSR/NIES/FRCGC大気海洋陸面結合モデル、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。今年度は、CCSR/NIES/FRCGC大気海洋陸面結合モデルの大気境界層と対流スキームについて新しい物理スキームを導入し、これらを鉛直一次元モデルに適用することで観測に近い雲水の鉛直プロフィールが得られることを確認した。全球雲解像大循環モデルについては、更新した境界層スキームの感度実験を実行し、境界層スキームが雲の組織化に大きく関連していることを示すことができた。また7月の降水分布の計算結果が観測と微細な構造まで良く一致していることが示された。全球渦解像大循環モデルについては、開発が完了し、モデルで再現された海面温度分布は全球の渦の活動を良く再現している。

キーワード：大気海洋陸面結合モデル, 全球雲解像モデル, 全球渦解像モデル