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 arena of climate simulation study by fully utilizing the Earth Simulator. This project started at the beginning of the Earth Simulator operation and 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 2007, new schemes for planetary boundary layer and cumulus convection were applied to the CCSR/NIES/FRCGC model under a realistic condition. Thanks to the new schemes, the dry biases in the lower atmosphere reduced significantly and we obtained reasonable climate sensitivity in an experiment for global warming projection. For the global cloud resolving model, we have successfully simulated a Madden-Julian Oscillation event. We also performed the climate sensitivity test. A new boundary scheme is implemented to improve the expression of shallow clouds. For the eddy resolving ocean model, we performed eddy resolving ocean simulations in the Southern Ocean and the Agulhas Current region to investigate interactions between eddy and ocean circulation. In the Brazil-Malvinas Current confluence region in the Southern Ocean, low potential vorticity (PV) water of Malvinas Current is injected into relatively high PV water of Brazil Current by the eddy-induced velocity. In the Agulhas Current region, it is shown that eddies play important roles to transport water from Indian Ocean to Atlantic Ocean.

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 NICAM, and an eddy resolving ocean general circulation 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 simulations. Studies with these three 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 simulations by the second and third models.

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

We have had model experiments for improvement of physical parameterizations associated with radiation, cumulus convection, cloud, and atmospheric lower boundary layer, for reproduction and prediction of the actual climate system. Moreover, we have had comparison studies in order to find some missing features in the parameterizations adopted in MIROC against a cloud-resolving model, NICAM. Model sensitivity experiments and analyses of model outputs were also carried out for a wide rage of climate system studies including paleoclimate issues.

For the sake of realistic reproduction of three-dimensional distribution of water vapor and cloud water in climate models, an improved version of Mellor-Yamada scheme based on Nakanishi and Niino (2004) has been implemented in MIROC. Major differences of this scheme from the past scheme are improved treatment of mixing length and pressure correlation terms, updated closure constants based on LES results and higher level in the hierarchy of the scheme. Notable improvements were seen in vertical distribution of water vapor and cloud water in the lower troposphere (Fig. 1). Large dry biases around 850hPa are almost eliminated with this scheme. Low level clouds tend to be lift up making the result closer to observations. We also confirmed that the global warming projection under doubling CO_2 by MIROC with the new closure scheme reproduced a reasonable size of climate sensitivity in comparison with that with the previous scheme.

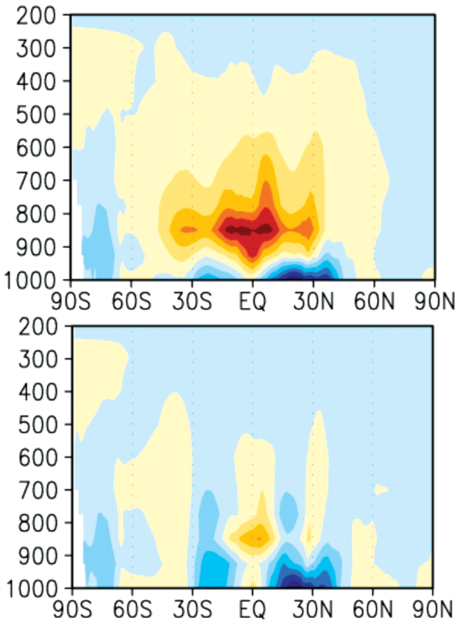

Fig. 1 Zonally averaged annual mean specific humidity biases [g/kg] for old (upper) and new (lower) schemes, compared with ERA40.

A version of MIROC AGCM with a high vertical resolution (T213L256) and without gravity wave parameterizations successfully simulated large-scale quasi-biennual and semi-annual oscillations (QBO and SAO, respectively) with realistic amplitudes in the equatorial atmosphere (Fig. 2). In this experiment, gravity waves are represented explicitly in the model outputs. Currently we have investigated the mechanism in QBO particularly in terms of roles of gravity waves exited by cumulus convection in the tropics.

3. Development of the global cloud resolving atmospheric model: NICAM

It is known that the conventional AGCMs cannot well reproduce Madden-Julian Oscillation. Since the global cloud resolving model NICAM is expected to reproduce it owing to explicit representation of convections, we have tried to simulate a Madden-Julian Oscillation event by NICAM. The simulation was successfully performed with 3.5 km and 7 km resolution; large scale cloud cluster is maintained and eastward propagates with a realistic phase speed. Furthermore, the detail structure in the cloud cluster is in good agreement with the observation. Figure 3 shows the result from this experiment, which gives the comparison between simulation result and satellite data. The simulation captures the eastward propagation of large scale cloud cluster and disturbances in the cloud cluster with relatively fast speed. We found that the propagation of disturbance with 5 days period plays an important role for eastward propagation of MJO over the maritime continent. We are now continuing to investigate the period of MJO and the realization of tropical cyclone associated with MJO by extending the simulation time of 3–5 months.

Second, we performed the climate sensitivity experiment

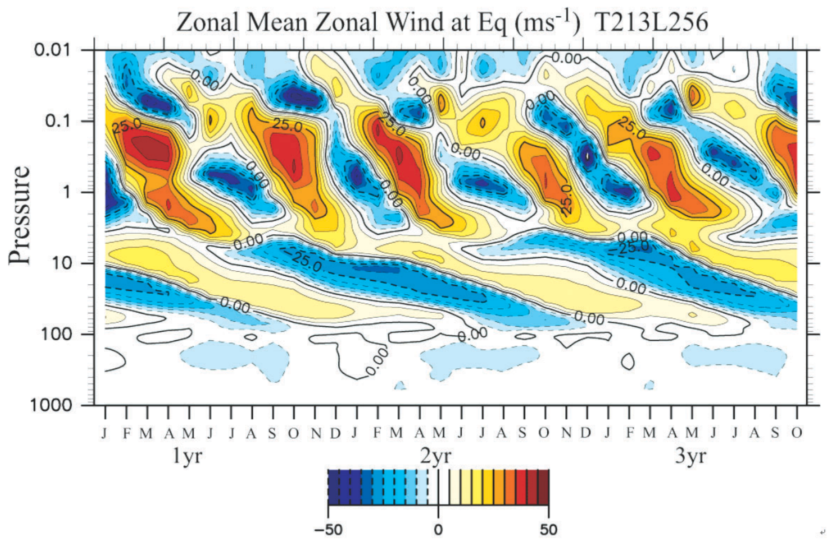

Fig. 2 Time-height section of zonally averaged zonal wind at equator.

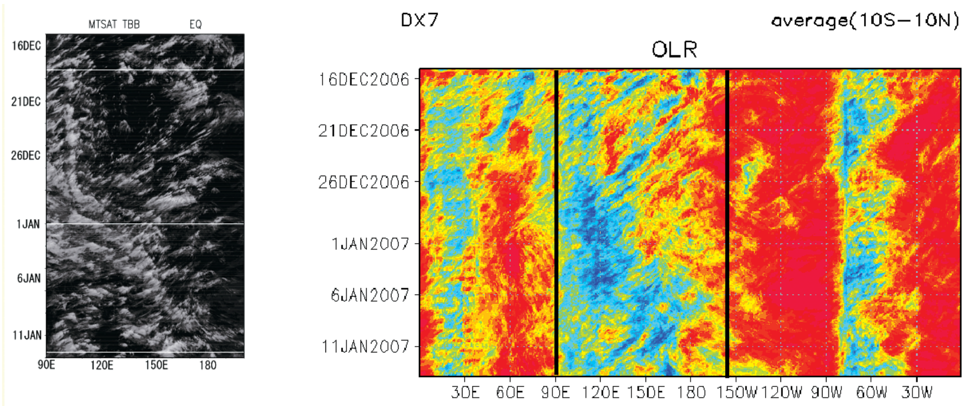

Fig. 3 The Madden-Julian Oscillation experiment by global cloud resolving model NICAM. Right figure: the Hovmoller diagram (10N-10S) of OLR by one month integration of 7km mesh model. The simulation starts from 15th December 2006. Left : the Hovmoller diagram of TBB on the equator by MTSAT-1R.

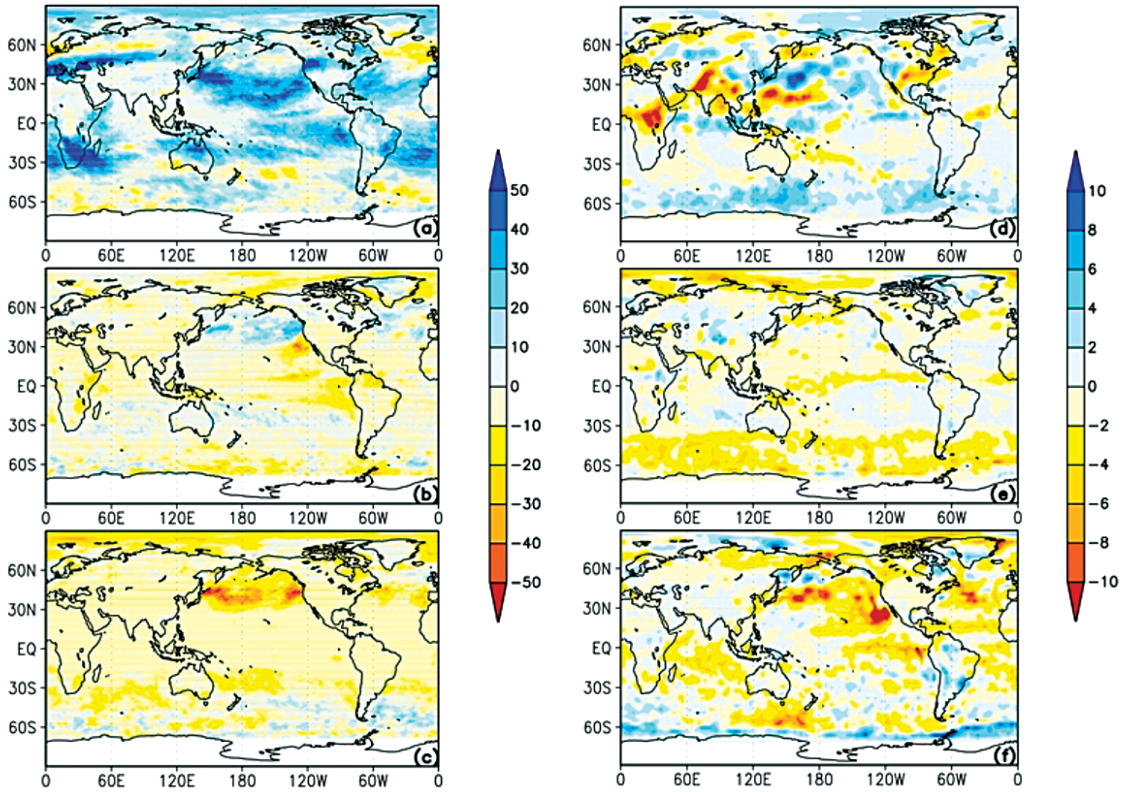

Fig. 4 Difference of clouds classified by the ISCCP simulator between the control experiment and the +2K experiment. Panels (a), (b) and (c) are high, middle and low clouds for NICAM. Panels (d), (e) and (f) are those for MIROC.

by using the global cloud resolving model, which was the first attempt over the world. As the experimental setup, the perpetual July condition was given and a couple of run (control run with the present SST and the perturbed run with SST + 2K) was conducted. As a result, the high-thin cloud dramatically increases in SST + 2K run (Fig. 4). This change is not seen in the results from the usual GCMs, which have been reported in IPCC AR4. Since the high-thin cloud has large greenhouse effect, its increase gives the positive feedback against the global warming and enhances the climate sensitivity. Now, we are conducting some sensitivity tests from the viewpoint of physical process and investigating the robustness of this result.

Third, we improved the boundary layer scheme. From the analysis of recent climate model, the offshore clouds in California and Peru coasts, which are widely distributed on the ocean, play an important role for climate sensitivity. Since the horizontal resolution in NICAM is several km, such clouds should be expressed implicitly. For this purpose, we implemented Nakanishi and Niino scheme, which

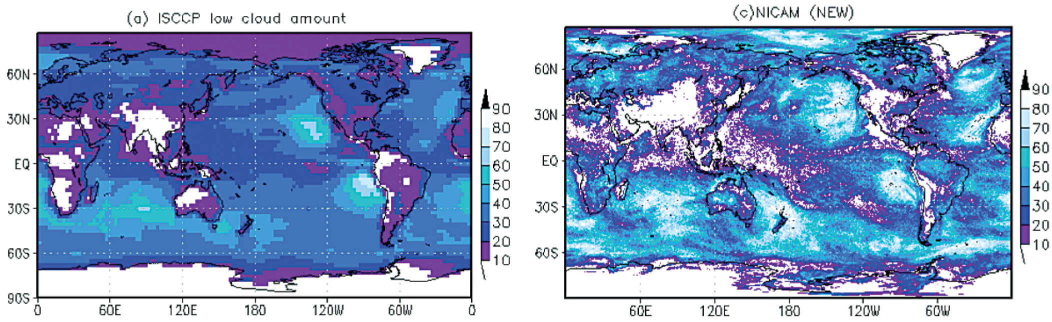

Fig. 5 Right: cloud amount of shallow clouds by NICAM. Left: observational cloud amount by ISCCP.

was employed in the recent MIROC model, into NICAM. Figure 5 shows the comparison of cloud amount in the lower atmosphere between the NICAM result and ISCCP data. As shown in Fig. 5, we can obtain the realistic shallow clouds near the California and Peru coast, which appear in the observation. This result suggests that the global cloud resolving model can well express not only the deep clouds but also shallow clouds. We will continue the improvement of physical process, especially, cloud microphysics and boundary layer scheme.

4. Development of the eddy resolving ocean model

We perform eddy resolving ocean simulations in the Southern Ocean and the Agulhas Current region to investigate interactions between eddy and ocean circulation.

In the Southern Ocean, an eddy resolving simulation with about 10 km horizontal grid size is performed. The model is integrated 53 years and output data of the last three years are used to evaluate effect of mesoscale eddies. Figure 6 shows the three-year averaged potential vorticity (PV) on σ_0 = 27.1 layer in the Atlantic Ocean. The PV is conserved as long as no influence from the sea surface or mixing with water of different PV occurs. This figure shows that low PV water in the southeast Pacific is fed into Malvinas Current through Drake Passage and merged with low PV water generated in the north of Burdwood Bank. At the Brazil-Malvinas Current confluence, the merged low PV water encounters Brazil Current, the PV value of which is relatively high due to the influence of Agulhas region. The difference of the PV values between these two currents appears to cause mixing of PV and this PV mixing generates an eddy-induced velocity which advects low PV water into high PV water region. The distribution of PV shows that the low PV water is advected downward into Brazil Current by the eddy-induced velocity.

In the Agulhas Current region, we perform eddy permitting simulations using both 15 and 40 km horizontal grid size. In order to study effect of eddies to mass transport in this region, artificial passive tracer is released in the south-western Indian ocean. The tracer is advected by the Agulhas Current and then flows into the South Atlantic Ocean. Figure 7 shows tracer distribution on σ_0 = 27.1 surface layer. It is shown that water from the Indian Ocean is trapped by the Agulhas Rings. This feature cannot be reproduced in the coarse resolution simulation of 40 km horizontal gird size simulation.

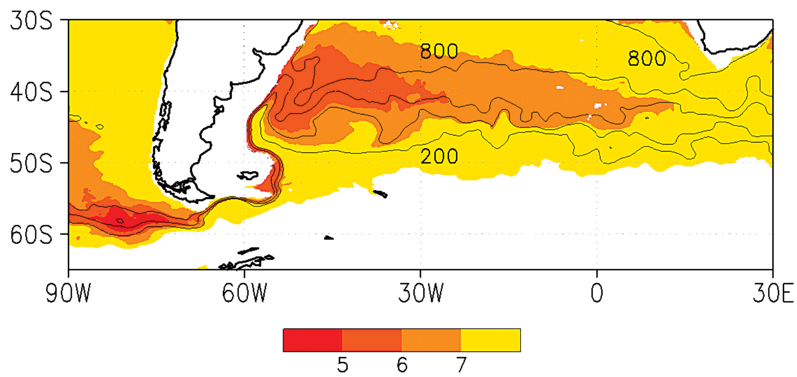

Fig. 6 Potential vorticity on the σ_0 = 27.1 layer (unit: 10^{-11} m^{-1} s^{-1}). The black lines are time-mean depths of 200, 400, 600, and 800 meters from south to north.

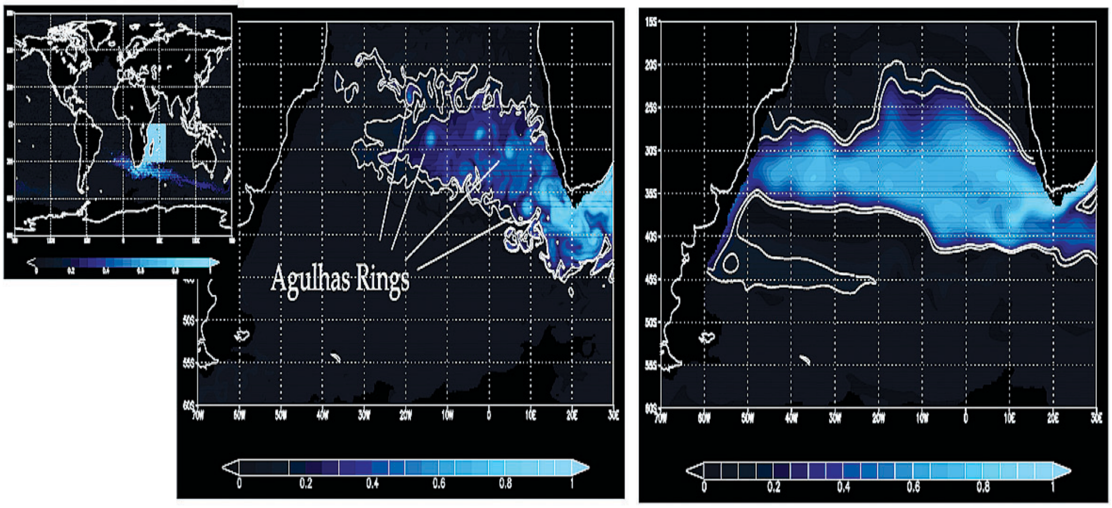

Fig. 7 Passive tracer density on σ_0 = 27.1 isopycnal surface after 7 years integration.
Left panel: result of 15 km simulation. Right panel: 40 km simulation.
Contour indicates tracer density 0.1 and 0.2.

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

プロジェクト責任者

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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新しい大気境界層と対流スキームを現実的な条件のもとで試験した。新しいスキームを採用したことで、大気下層の乾燥バイアスが劇的に低減され、また温暖化実験に適用したところ、これまで高めだった気候感度が平均的なモデルの水準にまで低下した。加えて、鉛直に256の層を配置した大気モデルで、従来の重力波抵抗パラメタリゼーションをとりはずして、重力波をモデルの中で陽に取り扱う実験を行った。従来モデルでの再現が困難であった、成層圏での準二年周期変動（QBO）と半年周期変動（SAO）の再現に成功した。モデルの出力を用いてQBOの発生メカニズムの調査を開始した。また全球雲解像大気大循環モデルについては、このモデルを用いて初めてMJOの再現実験に取り組んだ。その結果、大規模積乱雲群の組織化の維持、ゆっくりとした東進、内部構造まで観測に見られるような現象との一致が見られた。また、海洋大陸上、特にニューギニア島を超えてMJOに伴う雲集団が東進するには、東からの約5日周期の擾乱の伝播が重要な役割を果たしていることがわかった。また、全球雲解像モデルを現実海陸分布のもとでの7月条件に固定した長時間積分を行い、気候場を得るとともに、気候感度を調べるためにSSTを2度だけ昇温させた実験を行った。その結果、温暖化条件では、上層での薄い雲が増え、雲放射強制力の依存性が従来型のモデルと逆になるという結果を得た。現在、この結果を、物理過程に対する依存性の観点から解析を進め、結果がどれだけ普遍的なものか、またどのようなパラメータに依存するのかを明らかしつつある。今年度のモデルの改良は、境界層スキームについて行った。境界層過程として、共生プロジェクトで開発された最新のNakanishi and Niinoスキームを組み込んで、下層雲の表現の向上に取り組んだ。これにより観測に見られるようなカルフォルニア沖やペルー沖の下層雲が良好に再現される結果を得ることができた。最後に、全球渦解像大循環モデルについては、中規模渦と海洋循環の相互作用を調べる為に、渦解像シミュレーションを南大洋とアガラス海流領域で実施した。その結果、南大洋のブラジル・マルビナス合流域では、渦位混合によって、マルビナス海流の低渦位水が、比較的高渦位水のブラジル海流中に渦速度の輸送によって注入されていることが示された。またアガラス海流領域では、渦がインド洋から大西洋に海水を輸送していることが示された。

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