Development of High-resolution Atmosphere Ocean Coupled Model and Global Warming Prediction

Group Representative

Koki Maruyama Director, Environmental Science Department, Abiko Research Laboratory, Central Research Institute of Electric Power Industry

Authors

Koki Maruyama [*1] · Yoshikatsu Yoshida [*1] · Junichi Tsutsui [*1] · Norikazu Nakashiki [*1]
Jong-Hwan Yoon [*2]

*1 Central Research Institute of Electric Power Industry

*2 Research Institute for Applied Mechanics, Kyushu University

We have been conducting a research project to develop high-resolution climate models for global warming studies. The models are based on the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM), and a limited-area ocean model of Kyushu University. We modified these programs to achieve higher parallel efficiency and vector optimization on the Earth Simulator (ES). The code optimization resulted in great improvement in computing performance for large-scale applications.

Numerical experiments with the atmosphere component of the CCSM were conducted to study climate sensitivity to horizontal resolution in the range of 300 km to 40 km. Although higher resolution models tend to generate less cloud amount and overestimated precipitation, such systematic biases can be reduced to some extent by parameter tuning in physical processes. Experimental ensemble climate simulation was also conducted, and different characteristics of tropical cyclone variability depending on basins were suggested.

Numerical experiments with the ocean component of the CCSM were conducted with a horizontal resolution of 1/10 degree. This "eddy-resolving" resolution allows the model to realistically simulate the path of western boundary current such as Kuroshio. Sensitivity experiments on horizontal mixing processes indicated that simulated current can be improved by adjusting viscosity and diffusivity. The limited area ocean model was applied for the Pacific Ocean with a resolution of 1/6 degree. This model has an advantage of simulating regional-scale circulation quantitatively, and new insights were provided regarding the Ryukyu Current.

Keywords: parallelization, ensemble climate simulation, tropical cyclone, eddy-resolving ocean model, Kuroshio Current

1. Preparation of optimized climate model software

As a first step to develop our high-resolution atmosphere/ocean/land/sea ice coupled model used for global warming projections, an atmosphere component model, the NCAR Community Climate Model (CCM3), and an ocean component model, the Los Alamos National Laboratory (LANL) Parallel Ocean Program (POP), were optimized for the ES in terms of vector and parallel computing efficiency. Timing of these programs on the ES was made and post-processing tools were also prepared.

(1) Optimization of the atmosphere model code

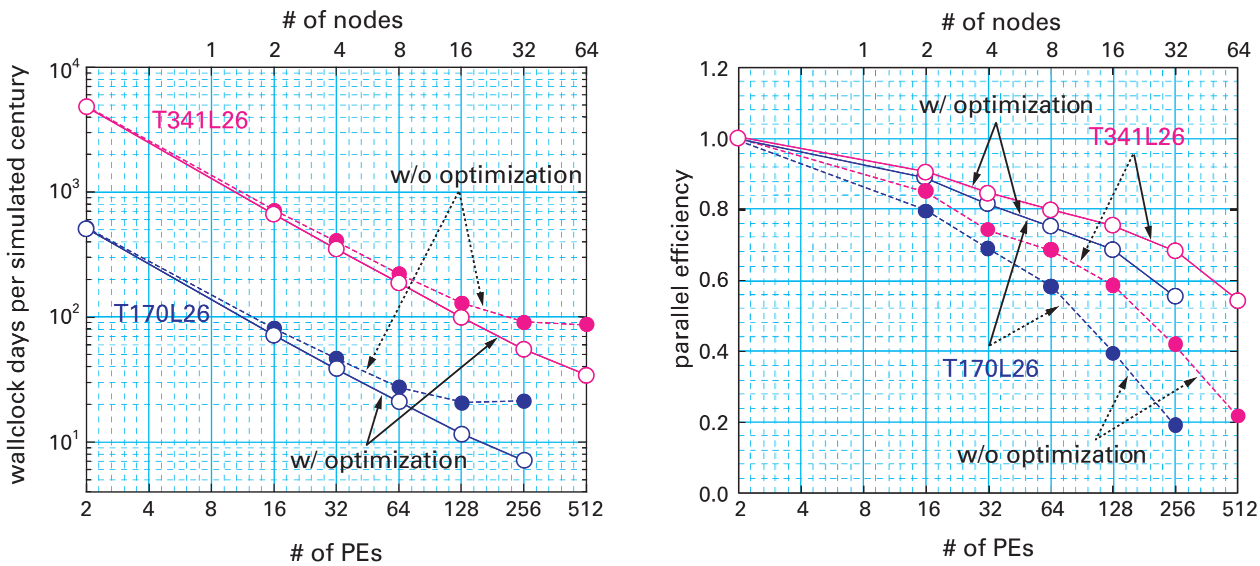
The formulation of the CCM3 employs a horizontal spectral transform method and a vertical finite difference method with a semi-implicit, leapfrog time integration scheme and a complete set of physical parameterizations. The CCM3 is a parallel program, assuming shared-memory parallel vector machines (CRAY or NEC) or scalar massively parallel processors as a target platform. One of the most important features of the ES, from the hardware point of view, is that hundreds of shared-memory nodes are connected by single-stage crossbar network. Each shared-memory node consists of 8 vector processors that are tightly connected via 16 GB main memory. To efficiently utilize such architecture of the ES, our optimized version of CCM3 code incorporates the hybrid MPI/multi-thread parallelism. The MPI and "microtask" are employed, respectively, for the internode communication and multi-threading within each node. Our hybrid implementation still employs one-dimensional domain decomposition. In other words, a latitude line or a Fourier wave number is a minimal unit of parallel computing. With this parallel decomposition strategy, we are able to have enough granularity even for multi-threading, so startup cost for multi-threading is negligibly small. In addition, we employ a quasi-cyclic allocation of Fourier wave numbers to MPI processes, to improve load balancing in spectral space. Furthermore, to reduce communication overheads for MPI, we employ non-blocking communication functions of MPI-1, one-sided communication functions of MPI-2, and the butterfly type communication for all-gather type collective communication. The distributed/parallel output capability is also implemented in our optimized version of CCM3 code.

The timing of the CCM3 code was made at T170L26 and T341L26 resolutions on the ES (see Fig. 1). With the above optimizations in terms of parallelization, the CCM3 code becomes much more scalable on the ES. At T341L26 resolution, the optimized code sustained about 700 Gflop/s and one simulated century can run in about five weeks on 64 nodes of the ES.

(2) Optimization of the ocean model code

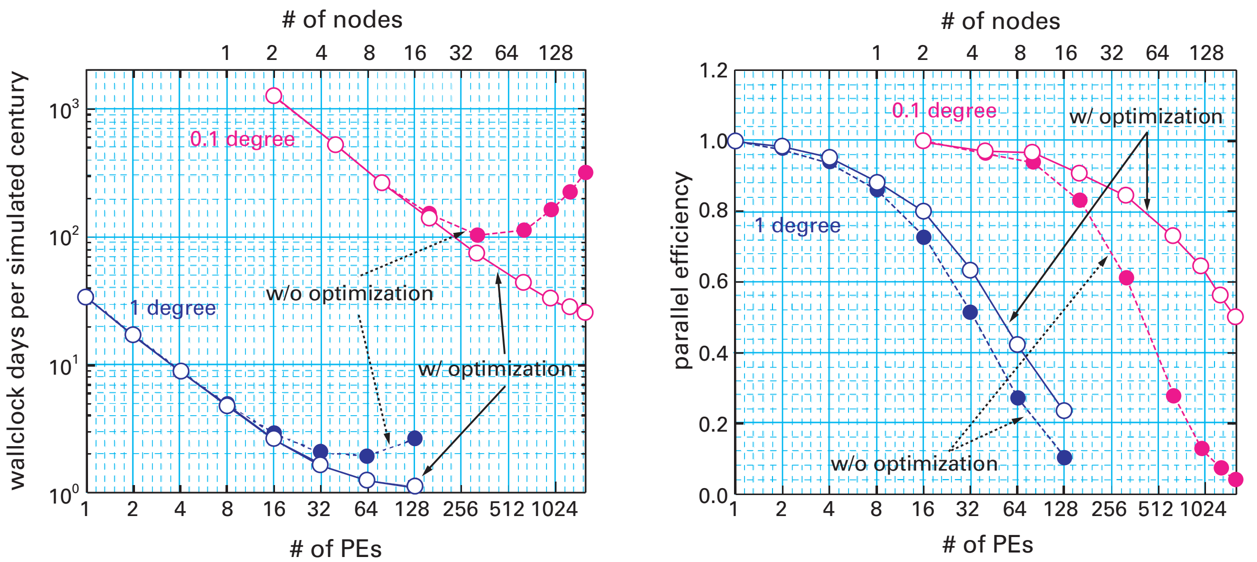
The POP is a parallel ocean program assuming scalar massively parallel processors as a target platform. That is why we had to do some vector optimization at first to use the POP code on the ES. Then, we made parallel optimization for the POP code.

In terms of the scalability of the POP code on the ES, we had a severe performance problem: there was a scalability wall around 30 or 60 nodes (see Fig. 2). Beyond this wall, wall-clock time got longer when we used more nodes. Through detailed analysis of cost distribution in the POP code, we found that a performance bottleneck was a global



(a) wall-clock time (b) parallel efficiency

Fig. 1 Parallel computing performance of CCM3 on the Earth Simulator.



(a) wall-clock time (b) parallel efficiency

Fig. 2 Parallel computing performance of POP code on the Earth Simulator.

reduction in the conjugate gradient solver for the barotropic mode. The global reduction in the POP code was originally implemented with "MPI_allreduce" in the MPI library of the ES. This MPI_allreduce is able to run much efficiently when the packet size is large enough, e.g., hundreds of kilobytes. However, when the packet size is small, say, less than tens of bytes, the MPI_allreduce is much more expensive than the case with much larger packets. Because of such buggy performance of the MPI_allrecude on the ES, we decided to develop a global reduction code. There are three stages in our implementation of the global reduction: the first stage is the local reduction within each node; the second is the global reduction over multiple nodes which is done by one representative process in each node; then, the final stage is a data scattering within each node, where all reductions and scattering are coded in the binary-tree manner. Furthermore, we made some modest optimizations like reduction of number of issuing communications and implementation of distributed parallel I/O capability in the POP code.

Timing of the POP code was made on the ES. The resolution was one degree (320x384x40 grid division) and 1/10 degree (3600x2400x40 grid division). Observed improvement in scalability with our parallel optimizations is significant in both cases, in particular, much significant at 1/10 degree resolution (see Fig. 2). In the one-degree case, one simulated century can run in 40 wall-clock hours on four nodes. In the 1/10 degree case, one simulated century can run in a month on 200 nodes. The sustained rate is about two or three Tflop/s although it strongly depends on choice of parameterizations.

2. Development of high-resolution atmosphere models

We investigated climate sensitivity of the optimized CCM3 to spatial resolution. Simulations with T170 and T341 codes in addition to the standard T42 code are compared regarding simulated climatology including globally averaged energy statistics. Also, two different vertical resolutions, 18-layer (standard) and 26-layer, are compared.

Global annual mean statistics show that the model with the higher horizontal resolutions tend to generate less cloud amount and overestimated precipitation. It can be speculated that clouds in higher-resolution models are formed by stronger updrafts with smaller horizontal areas and, as a result, likely to bring more precipitation amount. Although there are some tunable parameters to control cloud formation and precipitation, it is difficult to independently adjust each atmospheric process due to some nonlinear behavior or compensation among the processes. An experimental run with the T341 code resulted in global energy imbalance of about several watts per square-meters after some changes in cloud diagnostic parameters. Regarding typical characteristics of simulated climatology such as spatial distribution of precipitation, simulations with the higher resolution models are similar to that with the standard T42 model. Likewise, some of deficiencies in the standard model are left unchanged even in the higher resolution models, which implies that the representation of important physical processes are crucial to improve simulated climatology regardless of horizontal resolution. Presumably, as far as about T341 resolution, it is possible to obtain a reliable coupled climate model without significant changes in the framework of physical parameterizations used in a lower resolution model.

In addition to this sensitivity study, we conducted an ensemble climate simulation with a modified CCM3 to investigate interannual variability of tropical cyclone (TC) frequencies. The modification is an implementation of an inhibition mechanism for the deep convection scheme in the model, and allows the model to produce TC-like disturbances with a realistic frequency. Since the model shows a large interannual variability even with climatological sea surface temperature (SST) data as a boundary condition, an ensemble climate simulation is needed to reduce such model-inherent variations. We used a T42 resolution model in this fiscal year as a preliminary experiment.

The western North Pacific and the North Atlantic are both major TC basins, for which reliable TC records are available over a period of more than 50 years. Such long-term TC records show large variability with interannual and interdecadal time scales associated with naturally occurring climate changes, and the characteristics of the variability is different between the two basins. El Niño and Southern Oscillation (ENSO) is one of the contributory factors to affect the variability. In the North Atlantic, an anomalous increase in upper tropospheric westerlies during ENSO warm events inhibits TC activity by increased tropospheric vertical wind shear, and less anticyclonic upper level winds. In the western North Pacific, although the relationship between TC activity and ENSO is not as evident as in the North Atlantic in terms of the annual number of TC formations, ENSO events can modulate the location of formation area or seasonal activity. Considering this characteristic behavior of TCs in the two basins, we are investigating impacts of SST variations associated with ENSO on TC activity by numerical experiments.

Currently, we have completed seven climate simulations using observed SST from 1979 through 1989. Time integrations will be extended to the end of the 1990s. In the 1980s, two ENSO warm events occurred. Observed TC records show some responses to the events such as decreased frequencies during the periods. In the western North Pacific, it is remarkable that the observed response was delayed more than several months. Although the simulated interannual variations indicate some features of observed tendencies, the reproducibility in the western North Pacific is not as good as in the North Atlantic (see Fig. 3). In particular, the model shows scattering

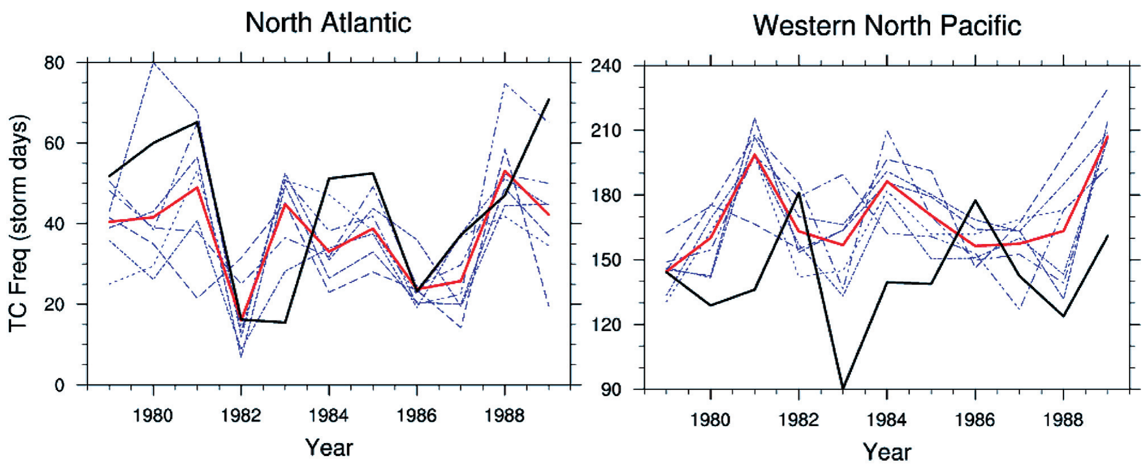


Fig. 3 Interannual variations of tropical cyclone (TC) frequencies in the North Atlantic (left) and the western North Pacific (right). TC frequencies are evaluated as total storm days in each basin. Blue, red, and black lines denote each simulation member, ensemble mean, and observation,respectively.

results among the ensemble members regarding the observed delayed response. This result implies that SST variations associated with ENSO affect TC activity rather directly in the North Atlantic, and that more climatological factors are indirectly involved in the TC activity in the western North Pacific.

3. Development of high-resolution ocean models

The high-resolution "eddy resolving" global ocean model was applied on the ES. The resolution of the model is 1/10 degree in horizontal and 40 levels in vertical, and the North Pole is shifted on the Hudson Bay to avoid the numerical singularity of the grid. The bi-harmonic mixing is adopted for the horizontal mixing of the momentum and tracer. The KPP scheme was used for the vertical mixing. The boundary conditions such as the heat and salt flux at the sea surface were estimated by the bulk formulation using daily NCEP (National Centers for Environmental Prediction) dataset (1990-2000). The model was integrated over 10 years with the time step of 220 per day.

The global surface flow pattern (Kuroshio, Gulf Stream, Equatorial Current and Circum Polar current, etc.) was reproduced well in comparison with the computational result with "eddy permitting" model (POP 1 degree model).

The left in Fig. 4 shows the snapshot of SST around Japan, illustrating a typical path of Kuroshio in the Pacific region, where Kuroshio flows at west off Nansei Island in the East China Sea, and separates at Inubosaki into the Kuroshio Extension. However, the unrealistic dipole eddy appears off Shikoku.

The top and bottom right in Fig. 4 indicate the volume transport around Japan. In Japan Sea, volume transport is calculated at Tsushima, Tsugaru and Soya straights. The volume transport changes with annual cycle, and its mean values well represent the observation (for example, Yanagi,

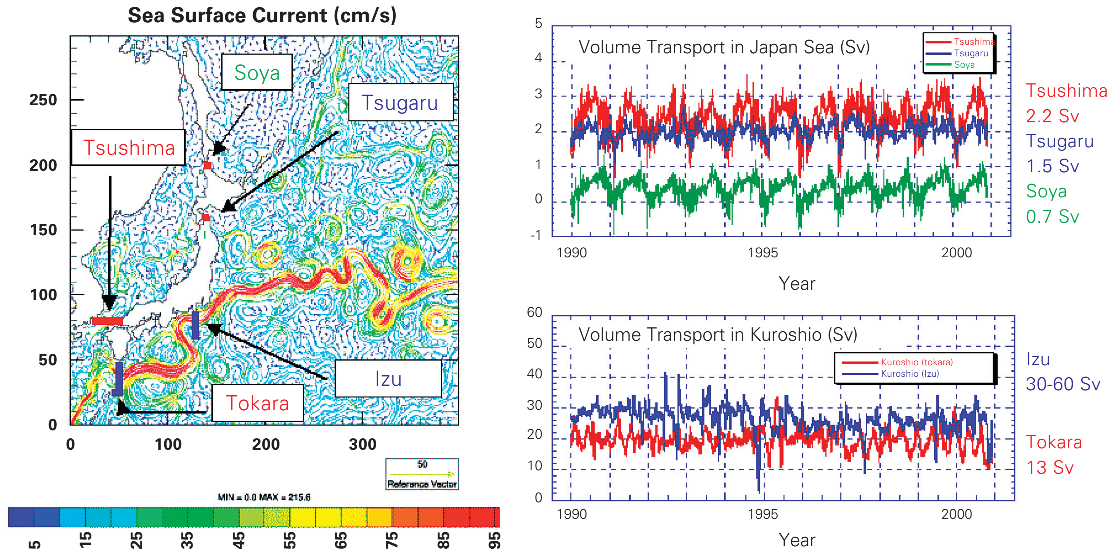


Fig. 4 Calculated flow around Japan using the POP with 1/10 degree resolution.
Left: Snapshot figure of sea surface temperature showing the path of Kuroshio clearly.
Right: Comparison between the calculated volume transport and the observational data.

2002). In Kuroshio region, however, the volume transport is underestimated at Izu section, which may be caused by the meandering of the Kuroshio path or re-circulation.

The sensitivity analysis on the horizontal mixing was carried out to improve the representation of the western boundary current such as Kuroshio and Gulf Stream more accurately. The viscosity and diffusivity of bi-harmonic mixing was reduced to 1/2 and 1/3. The monthly boundary sea surface condition using NCEP dataset was used for the 10 years integration. In 1/3 viscosity and diffusivity case, the path of the western boundary currents were improved; especially the dipole eddy off Shikoku was abating.

4. High resolution Pacific Ocean Circulation Model

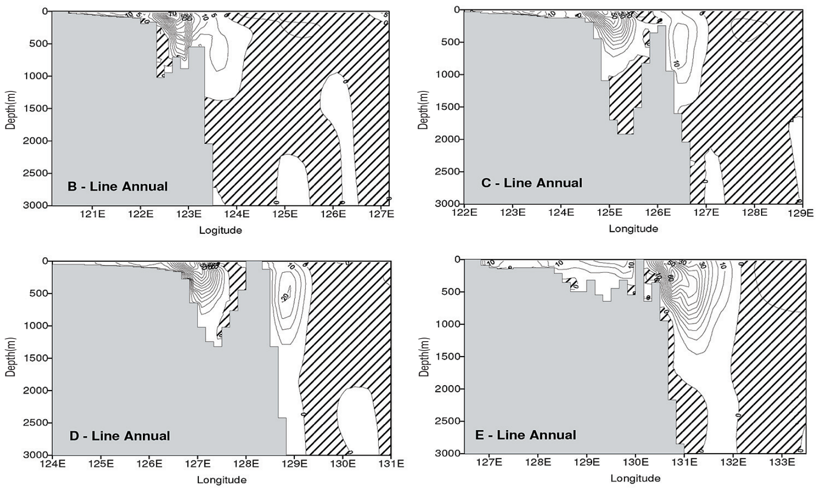
Limited area ocean models were applied for the Pacific Ocean with high resolution (1/6 degree and 1/12 degree), and ocean circulation and water mass distribution were investigated choosing appropriate parameterizations. The model is the RIAMOM developed by the Research Institute for Applied Mechanics (RIAM) group in Kyushu University with 75 vertical levels using 3D MSQUICK scheme for tracer advection. The model domain is the whole Pacific Ocean. In this fiscal year, we obtained results of the case of 1/6 degree horizontal resolution.

Although water masses such as North Pacific Intermediate Water (NPIW) and Antarctic Intermediate Water (AAIW) are poorly reproduced, simulated sea surface height is compared well with that observed by satellite altimeter. The circulation pattern of the northwest Pacific Ocean was reproduced with high accuracy providing new insights of the Kuroshio (the Ryukyu Current) flowing along the eastern side of Ryukyu Islands. The modeled northeastward Ryukyu Current with mean transport of about 20 Sv has a subsurface velocity maximum at 500～600 m depth with the volume transport increasing northeastward from Taiwan to the Tokara Strait. Those features are compared well with observed features (Ichikawa et al., 2003). The increment of the transport is supplied by the westward current between 23°N and 26°N. As shown in the vertical section of velocity in Fig. 5, the shallow strait east of Taiwan allows only the upper part of the Kuroshio to pass through, resulting in the formation of the subsurface velocity core of the Ryukyu Current. The core disappears after merging with the Kuroshio in the East China Sea at the Tokara Strait.

In addition, it was confirmed that the formation of the Subtropical Counter Current is closely related with Hawaii Island Chain. In the next year, we are going to do experiments using 1/12 degree model which were tested this year.

Acknowledgement

This study was performed under the Project for Sustainable Coexistence of Human, Nature and the Earth of the Ministry of Education, Culture, Sports, Science and Technology of the Japanese government.



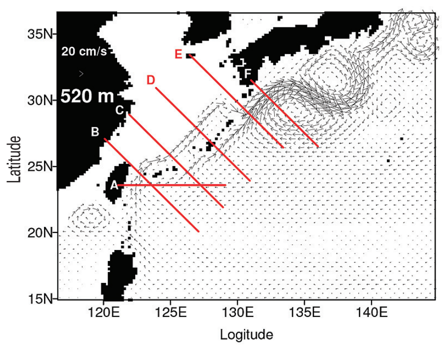


Fig. 5 Vertical sections of velocity (C.I.=5cm/s). Shaded areas indicate negative values. Subsurface maxima of northeastward velocity are found along the lines B, C.

大気海洋結合モデルの高解像度化

利用責任者
丸山 康樹 電力中央研究所 我孫子研究所 環境科学部長
著者
丸山 康樹*1・吉田 義勝*1・筒井 純一*1・仲敷 憲和*1・尹 宗煥*2
＊1 電力中央研究所
＊2 九州大学 応用力学研究所

全球海洋モデルPOPを対象に、通信方法などの改良を行い、計算性能の飛躍的な向上を図った。最適化したコードを用いて、高解像度(0.1°)の現状再現計算を行った。海表面での境界条件を日毎に与えて10年間積分を行い、黒潮等の良好な再現を確認した。日本周辺海流の定量的精度向上のため、粘性係数や拡散係数の調整計算を行った。

全球大気モデル CCM3に対して、MPIとマイクロタスクの併用、MPI通信の高速化などの改良を行い、地球シミュレータ用のコード最適化を行った。今後の高解像度大気・海洋結合モデルの開発を考慮して、降水や放射などの物理過程に対する解像度依存性を調査した。また、粗いモデル(T42)によるアンサンブル気候シミュレーション(メンバー7)をテスト計算し、海面水温と熱帯低気圧出現頻度の年々変動について、観測事実との類似性を見出した。

九州大学の太平洋海洋循環モデルRIAMOMを最適化した。1/6°モデルを用いて、60ノードを使用した並列計算により、30年の時間積分を行った。海表面変位は衛星による観測値とよく一致し、黒潮海流系で最も理解の遅れている南西諸島東側の流れ(琉球海流系)についての新しい知見を得た。

キーワード：並列化、アンサンブル気候予測、熱帯低気圧、渦解像海洋モデル、黒潮