韓國海岸海洋工學發表論文集 (2003)
第 14券, pp. 18-27

Development of high-resolution atmosphere ocean coupled model and global warming projection with Earth Simulator -A whole research plan and result in FY2002-

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1. What is problem?

The goal of the UN Framework Convention on Climate Change (UNFCCC) is to stabilize atmospheric CO2 concentration for preventing global warming in future. However, there are many unknown factors regarding stabilization of CO2 concentration. What level of concentration should be appropriate to prevent global warming? When should we stop the increase of CO2 concentration? What kind of countermeasures of reducing CO2 emission will be available for CO2 stabilization?

In the middle of 1990's, the Central Research Institute of Electric Power Industry (CRIEPI) in Japan and the Electric Power Research Institute (EPRI) in USA and others started the global warming research project ACACIA (ACACIA home page) with National Center of Atmospheric Research (NCAR) in order to obtain good understanding about the goal of stabilization. However, the ACACIA project has just finished in 2000 after achievement of its own goal.

Fig.1 shows one of the results obtained in the ACACIA project, which shows the global warming predictions by the NCAR first generation fully coupled climate model CSM-1 (ACACIA home page; Maruyama et al., 2000). In this case, two scenarios for the 21st century were assumed; (1) "Business As Usual" future, in which atmospheric CO2 concentrations double from today's levels to about 710ppm in the year 2100. And (2) "CO2 Stabilization " future, in which CO2 emissions are reduced in order to eventually stabilize CO2 concentrations at 550ppm, roughly twice the pre-industrial level (280ppm). In Fig.1, we recognize the difference of global mean temperature increase between two scenarios is just only about 0.5 degree at the year 2100.

Fig.1 may suggest that effect of CO2 stabilization for prevention of global warming might be eventually small. However, there still remain many scientific problems in the coupled model, CSM-1. For example, the overall warming over 1870–1998 for the model agrees well with observations, but the model result differs markedly from the observations between 1930 and 1970. In addition, we have little scientific information about change of extreme climate events such as tropical cyclones through results by CSM-1. Therefore, NCAR has developed the second version of coupled model CCSM-2 (Community Climate System Model version 2) to overcome shortcomings of the first version of CSM-1. NCAR expects that CCSM-2 will produce improved simulations of the mean climate and climate variability (NCAR home page).

2. Research Plan for five years

2.1 Objectives

In this research project, we will develop high-resolution atmosphere/ocean coupled models and carry out global warming projections with the Earth

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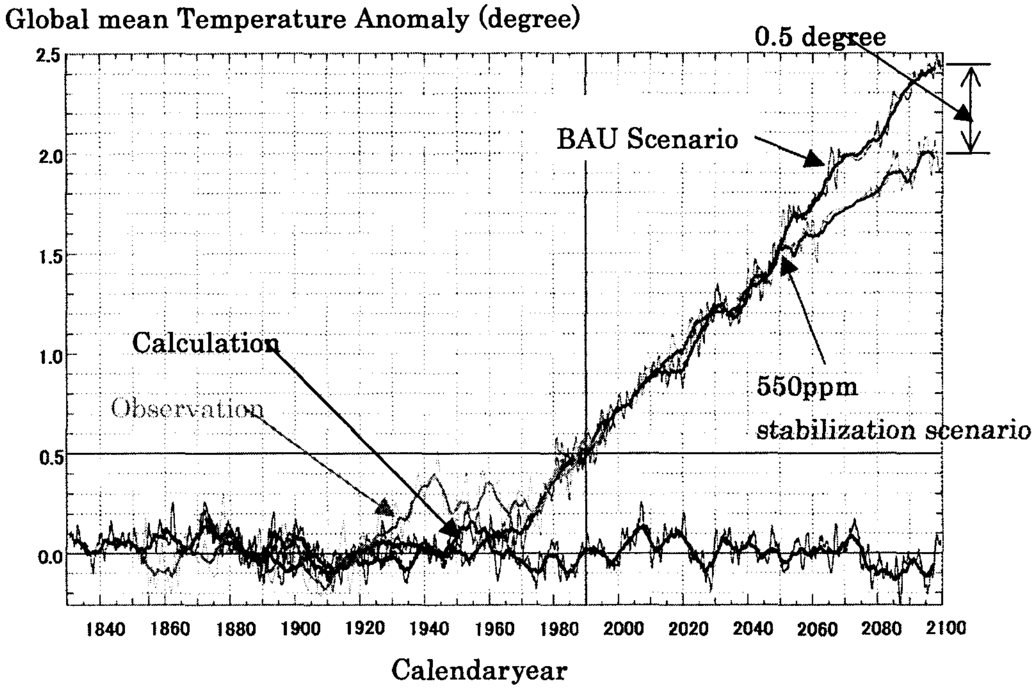


Fig.1. Estimation of effectiveness of CO2 stabilization scenario for prevention of global warming with the coupled model CSM-1(ACACIA project, 1998).

Simulator (ES) (Earth Simulator Center home page) based on the NCAR second generation coupled model, CCSM-2. We will develop high-resolution coupled models through optimization of codes for the Earth Simulator.

We will apply the previous IPCC/SRES emission scenarios and carry out global warming projections using the ES for comparison of the results described in the IPCC third assessment report (TAR) in 2001. In addition to the IPCC/SRES scenarios (IPCC home page), we will consider the stabilization scenarios of atmospheric CO2 concentration since Kyoto Protocol to prevent global warming in future. We will make up obtained scientific results into papers and reports, which are supposed to be referred in the IPCC forth assessment report (4AR) published in 2007.

2.2 Models

Based on the NCAR coupled model, CCSM-2, we will develop high-resolution atmosphere/ocean coupled models. For the ocean component of the coupled model, we will increase the horizontal resolution in the range of 100 km to 10 km to simulate the present state of the global ocean well, for example, meandering of the Kuroshio current and the Gulf stream. For the atmosphere component, we will increase the horizontal resolution in the range of 150 km to 40 km and improve performance regarding natural variability, tropical cyclones, and orography-induced phenomena. After adequate numerical tests on the ES, we will develop coupled models consisting of the high-resolution component models and carry out global warming projections.

2.3 Schedule

The research schedule for five years is shown in Table 1. There are four research subjects. We will study optimization of codes for the ES regarding software engineering and develop post-processing tools for large amount of data obtained from the high-resolution models. For the first three-year period from FY2002 to FY2004, we will conduct ensemble global warming projections using the optimized coupled model code with a moderate resolution, about 110 km and 100 km for the atmosphere and the ocean components, respectively. For the second two-year period from FY2005 to FY2006, we will challenge to develop the very high-resolution coupled model, about 40 km and 10 km for the atmosphere and the ocean components, respectively, and carry out global warming predictions in an ordinary single-prediction on the ES.

2.4 Organization

CRIEPI is responsible for contract of research project with one of Japanese Ministry, that is, the Ministry of Education, Culture, Sports, Science and Technology, called MEXT hereafter. CRIEPI organizes an international research consortium to carry out the MEXT project as shown in Fig. 2. CRIEPI, Kyushu University, NCAR and he Los Alamos National Laborary (LANL) are the participants of the research consortium. In odder to consult the research consortium through check and review of plan and result of the project, CRIEPI organizes a MEXT high resolution steering committee, called HSC hereafter, and the HSC will be held a couple of times in a year.

Table 1. Research schedule

Research Subjects	FY2002	FY2003	FY2004	FY2005	FY2006
1. Optimization of model codes for Earth Simulator	a)optimization of model components	b)optimization of coupled model including coupler c)development of post processing tools			
2. Development of high resolution atmosphere	a)T85-T341(150-40km) global atmosphere model				
3. Development of high resolution ocean models	a) 0.1 degree(10km) ocean model b)high resolution Pacific ocean model(1/12~1/36 degree)				
4. Global warming prediction with coupled	a) investigation of CO_2 emission scenario	b) global warming prediction with moderate		c)projection with very high resolution	

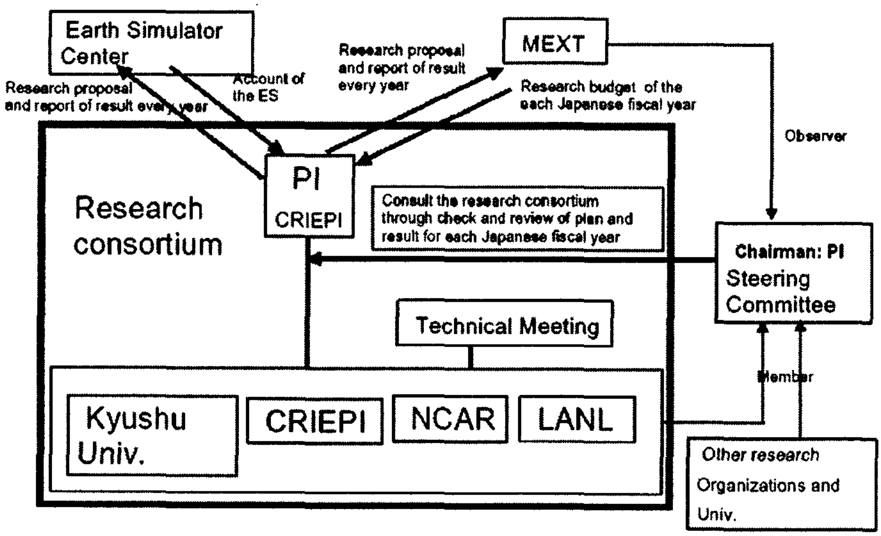


Fig. 2. International research consortium.

3. Research results in the FY2002

3.1 Development of optimized climate model codes

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 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 developed (Yoshida, 2003; Yoshida and Kitabata, 2003; Jones et al., submitted).

3.1.1 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 640 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. 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 as shown in Fig. 3. 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.

3.1.2 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 as shown in Fig. 4. 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 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.

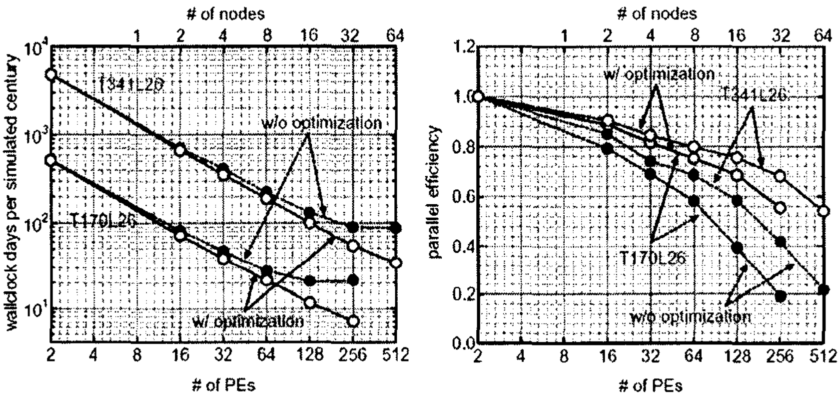
Timing of the POP code was made on the ES. The resolution was one degree (320x384x40 grid division) and 1/10 degree (3600x2400x40 grid division). Observed improvement in scalability with our parallel optimizations is significant in both cases, in particular, much significant at 1/10 degree resolution as shown in Fig. 4. 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.

3.2 Development of high - resolution atmosphere models

We investigated climate sensitivity of the optimized CCM3 above 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 (Kitabata et al., 2003; Tsutsui and Kitabata, 2003).

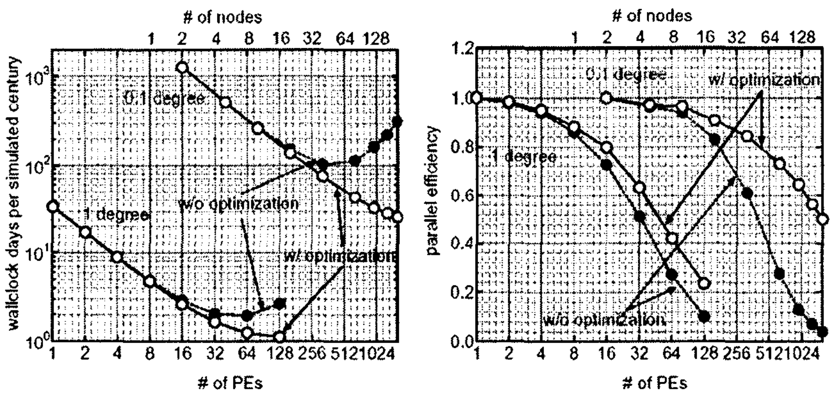
3.2.1 Resolution of atmosphere model

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.



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

Fig. 3. Parallel computing performance of CCM3 on the Earth Simulator.



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

Fig. 4. Parallel computing performance of POP code on the Earth Simulator.

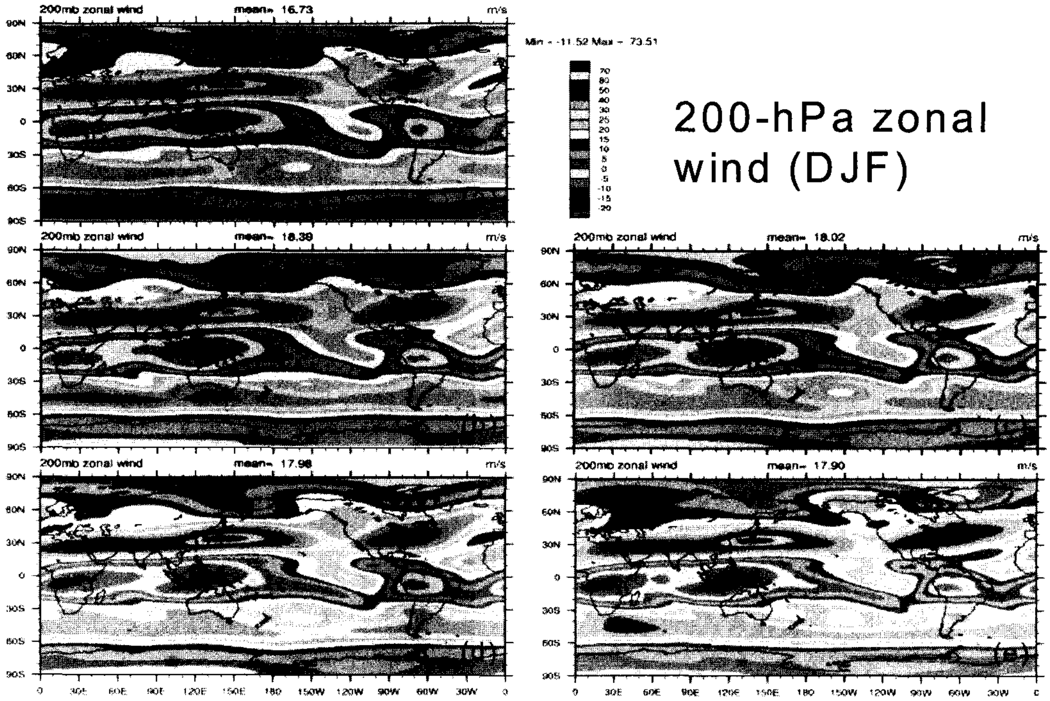


Fig. 5. Comparison of 200-hPa zonal mean wind betweenobservation(a)and simulations with T42(b), T85(c), T170(d), T341(e).

Regarding typical characteristics of simulated climatology such as spatial distribution of precipitation and zonal mean wind, simulations with the higher resolution models are similar to that with the standard T42 model shown in Fig. 5. 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.

3.2.2 Ensemble simulation

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 Nino 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

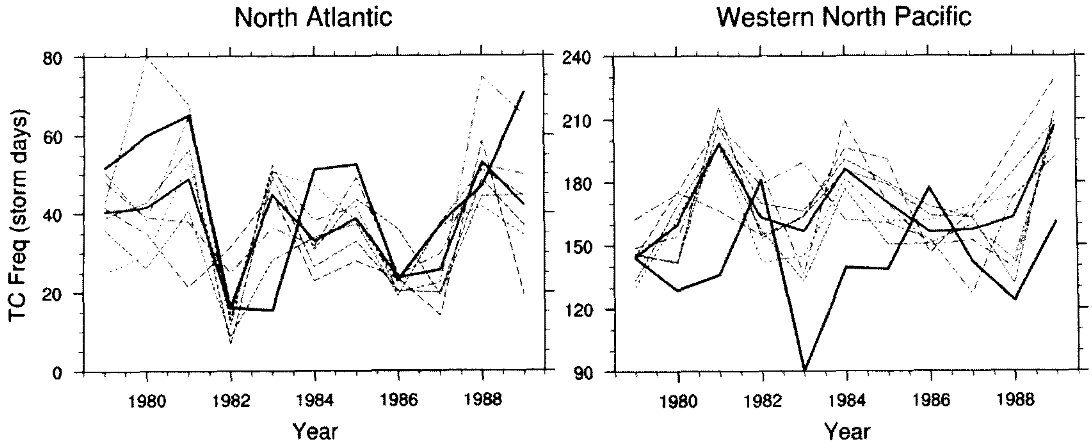


Fig. 6. Interannual variations of tropical cyclone (TC) frequencies in the North Atlantic(left) and the western North Pacific (right). TC frequencies are evaluated as total storm days in each basin. Blue, red, and black lines denote each simulation member, ensemble mean, and observation, respectively.

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 as shown in Fig. 6. 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. In particular, the model shows scattering 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.

3.3 Development of high-resolution global ocean models

We used the high-resolution "eddy resolving" global ocean model POP optimized above for 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 performance was integrated over 10 years with the time step of 220 per day (Nakashiki et al., 2003; Kim et al., 2003).

The global surface flow pattern (the Kuroshio, the Gulf Stream, Equatorial Current and Circum Polar current, etc.) is shown in Fig. 7, which is reproduced well in comparison with the computational result with "eddy permitting" model (POP 1 degree model). The left in Fig. 6 shows the snapshot of sea surface currents around Japan, illustrating a typical path of Kuroshio in the Pacific region, where the Kuroshio flows at west off Nansei Island in the East China Sea, and separates at Inubosaki Peninsula into the Kuroshio Extension. However, the unrealistic dipole eddy appears off Shikoku Island.

The top and bottom right in Fig. 7 indicate the volume transports around Japan Islands. In Japan Sea, "East Sea", the volume transports were calculated at Tsushima, Tsugaru and Soya straights. Each volume transport changes with annual cycle, and its annual mean value well represents the previous observation. In the Kuroshio region, however, the volume transport is fairly 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 has been carried out to improve the representation of the western boundary current such as the Kuroshio and the Gulf Stream more accurately. The viscosity and diffusivity of bi-harmonic mixing was reduced to 1/2 and 1/3, respectively. 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 Island was abating.

3.4 High resolution Pacific Ocean Circulation Model (Kyushu Univ.)

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 (PI: Prof. Yoon) 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 as shown in Fig.8.

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 features (Imawaki, 2003; Zhu et al., 2003). The increment of the transport is supplied by the westward current between 23 degree N and 26 degree N. As shown in the vertical section of velocity in Fig. 8, 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.

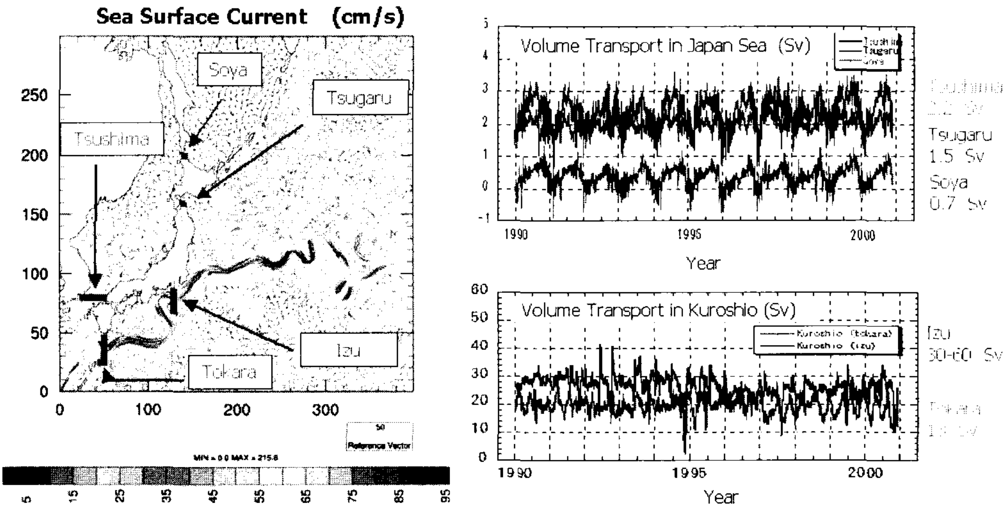


Fig. 7. Calculated flow around Japan Islands using the POP with 1/10 degree resolution.
Left: Snapshot figure of sea surface currents showing the path of Kuroshio clearly.
Right: Comparison between the calculated volume transport and the observational data.

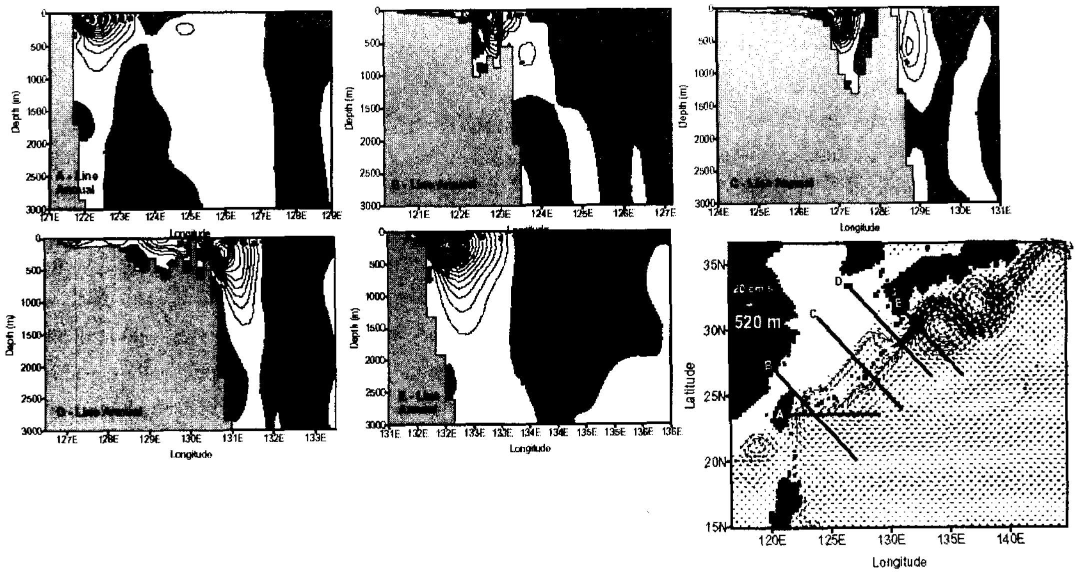


Fig. 8. Vertical sections of velocity (C.I.=5cm/s). Shaded areas indicate negative values. Subsurface maxima of northeastward velocity are found along the lines B, C.

ACKNOWLEDGMENTS

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. We used the Earth Simulator for the Project by courtesy of the Earth Simulator Center, JAMSTEC in Japan.

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