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

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In this project, stabilization scenarios requested by the IPCC WG1 are investigated. A coupled climate model with moderate resolutions (T85 atmosphere model and 1 degree ocean model) is optimized for the Earth Simulator based on the NCAR CCSM-3. A 100-year control run with forcing data of 1990 is conducted to check a drift of the coupled model. Moreover, the model sensitivity is investigated through the CMIP-2 runs with 1% annual increase of CO_2, for more than 150-year integrations with both T42 and T85 coupled models.

The second goal of this project is to develop a high-resolution coupled climate model. Numerical experiments using atmosphere models are conducted to investigate reproducibility of regional scale phenomena with different model resolutions; T42-T341. Further, numerical experiments with an ocean model with a horizontal resolution of 1/10 degree are conducted. This "eddy-resolving" ocean model can realistically simulate the path of western boundary current such as Kuroshio. To evaluate impact of global warming to the Japan Sea, a regional ocean model with ultra high resolution (1/36 degree) is developed by Kyushu University. The model can reproduce the surface, intermediate circulation and water masses as well as the bifurcation of the nearshore branch of the Tsushima current.

Keywords: IPCC stabilization scenarios, coupled climate model, model sensitivity, ensemble climate simulation, tropical cyclone, eddy-resolving ocean model, regional ocean model

1. Outline of the project

The five-year Kyosei project supported by MEXT has been carried out since FY2002 by the international research consortium, members of which are CRIEPI, Kyushu University, National Center for Atmospheric Research (NCAR) and Los Alamos National Laboratory. The first goal of the project is to develop a moderate resolution coupled model for IPCC scenario runs and the second goal is to develop a high-resolution coupled model for precise prediction of regional scale climate change. As already known, the ultimate objective of the United Nations FCCC is to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with climate system (Article 2). In the IPCC Third Assessment Report TAR (2001), it is shown that "Stocker and Schmittner (1997), using an intermediate complexity model, found that the North Atlantic Thermohaline Ciculation (THC) shut-down, when the rate of 1%/year CO_2 was held fixed for approximately 100 years. However, the amount of weakening varied from model to model. The cause of this wide variation is unclear". Therefore, for the IPCC AR4 (2007), we will apply the following scenarios considering requests by the IPCC WG1 to answer a question what a level of CO_2 concentration in atmosphere might be a threshold of irreversible phenomena in climate system, such as collapse of THC in the ocean.

(1) A nominal "550 ppm stabilization" run using, as a starting point, the end of the 20th century simulations of the SRES B1 scenario for the period 2000 to 2100 and extended with constant concentrations for the period 2100 to 2350.
(2) A nominal "750 ppm stabilization" run based on SRES A1B scenario for the time period 2100 to 2350.
(3) A "committed climate change" run extended with constant concentrations at contemporary levels for the time period from 2000 to at 2050.
(4) An overshoot scenario between 750 ppm and 550 ppm for the time period 2150 to 2350.

(5) An overshoot scenario between 550 ppm and contemporary levels for the time period 2150 to 2350

2. Coupled model experiments

(1) Development of coupled model software

The Community Climate System Model version 3, CCSM-3, is an MPMD (multiple program multiple data) parallel program consisting of the atmosphere component, CAM, the land component, CLM, the sea ice component, CSIM, the ocean component, POP, and the flux coupler, CPL. The nominal resolution of the ocean component is 1 degree and the atmosphere component supports both T42 (300 km) and T85 (150 km) resolutions. This model was ported to and optimized for the Earth Simulator through the research collaboration with CRIEPI, NCAR, Los Alamos National Laboratory, Argonne National Laboratory and Oak Ridge National Laboratory.

The present-day control experiments were performed using T42 and T85 versions of coupled model to validate the port to the Earth Simulator. Figure 1 shows the annual cycle of sea ice area in the northern hemisphere, demonstrating a good agreement with observations.

(2) Global warming experiments

The CMIP-2 type global warming prediction experiments were conducted using the CCSM-3 coupled model. As shown in Figure 2, the atmospheric concentration of CO_2 is 355 ppm at the initial stage. Then, the concentration begins increasing from the year 10 with the constant increase rate of 1% per year. In addition to this constant increase experiment, the capped CO_2 concentration experiments were carried out, where CO_2 concentration was held fixed at the doubling (710 ppm) and quadrupling (1420 ppm), after the concentration reaches those values. Figure 3 shows predicted change in the global annual mean surface temperature. The transient climate response, temperature increase at 710 ppm under the constant increase scenario, is 1.39 degree centigrade in the case of T42 atmosphere model and 1.43 degree centigrade in the case of T85 atmosphere model. In the capped concentration experiments, the slight increase of surface temperature can be seen after the atmospheric concentration of CO_2 is capped.

The time-series of sea ice volume in the northern and southern hemispheres are shown in Figure 4. The decrease in the ice volume is more significant in the northern hemisphere than in the southern hemisphere. The model results imply that the sea ice in the arctic region would disappear in summer season when 100 years passed after the CO_2 increasing.

3. Development of high-resolution atmosphere models

As a preliminary study for the development of a high-resolution atmosphere ocean coupled model, we conducted numerical experiments using the NCAR CCM3 with horizontal resolutions in the range from T42 (300 km) to T341 (40 km) and compared simulated climatology.

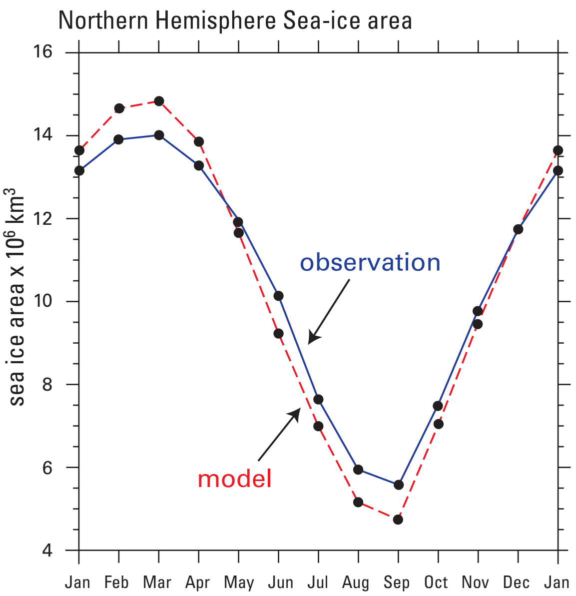

Fig. 1 Annual cycle of sea ice area obtained from CCSM-3 coupled model in comparison to observation.

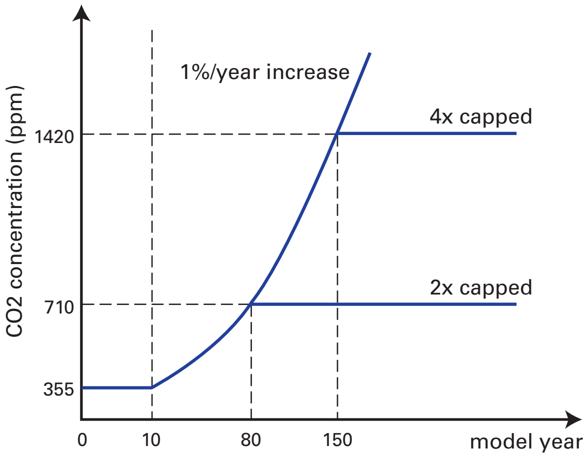

Fig. 2 Time evolution of CO_2 concentration used in the experiments.

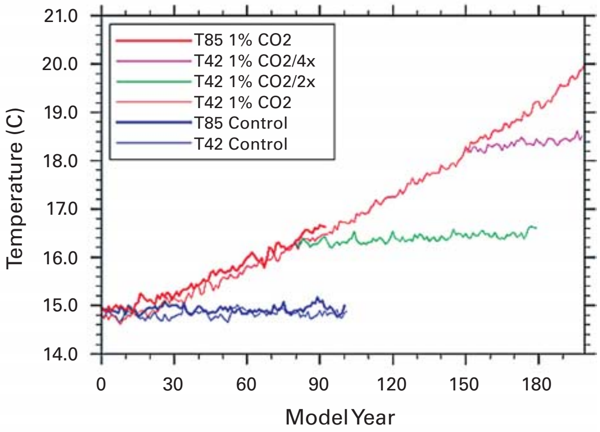

Fig. 3 Change in global annual mean surface temperature under various scenarios.

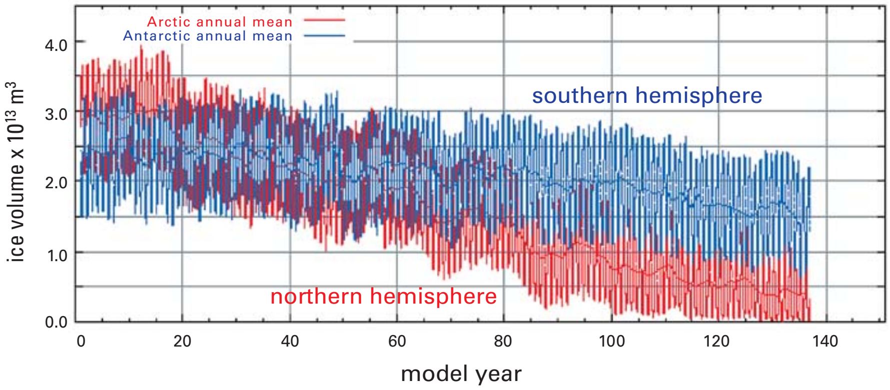

Fig. 4 Change in sea ice volume in northern and southern hemispheres under the 1% per year increase scenario obtained from T42 version of the coupled model.

Global annual mean statistics from the experiments show that the model with a higher horizontal resolution tends to generate less cloud amount and overestimated precipitation. This tendency gives us to understand that a smaller resolved area is more easily to produce moist atmospheric layers with precipitation, leading to decreased water vapor and clouds. This resolution-dependent model climatology can be improved to some extent by tuning associated physics parameters. However, precipitation processes are complicated due to nonlinear behavior among relevant physical processes. Although it is possible to reduce precipitation amount, for example, through the adjustment of a coefficient of latent heat exchange over the ocean, such an adjustment does not necessarily result in realistic climatology because of side effects in clouds and radiation processes.

In the last quarter of FY2003, we started to migrate to the CAM, which is a successor to the CCM3 and the atmosphere component of the moderate resolution coupled model used in the IPCC scenario runs mentioned above. The CAM has much improved physics parameterizations, and numerical experiments using the model with an moderate resolution of T85(150 km) resulted in reasonable climatology. Considering our experience regarding physics sensitivity of the CCM3, we continue to investigate the behavior of the CAM to apply it as the atmosphere component of our future high-resolution coupled model.

It is expected that an increased resolution brings about improved reproducibility of regional-scale phenomena. Using the CCM3 with a resolution of T341 (40 km), for example, snowfall areas over Japan are well represented on the Sea of Japan side of the main island. In this regard, realistic large-scale fields are prerequisite for the representation of regional-scale phenomena. On the contrary to the successful simulation of regional snowfall areas, the CCM3 failed to simulate Baiu front in summer around Japan even with increased resolution. Another application of high-resolution models is an examination of CO_2 flux from vegetation, which is given as prescribed conditions at the land surface. It is found from experiments using the high-resolution CCM3 that simulated annual cycles of relevant meteorological factors at representative locations in Japan are reasonable enough to discuss changes in CO_2 flux affected by different precipitation amount.

One of the objectives of the high-resolution model development is to study future changes in tropical cyclone (TC) activity. Difficulty in the prediction of TC activity comes from the fact that natural variations are dominant in historical TC records with time scales from inter-annual to inter-decadal. To study the reproducibility of the natural variability, we conducted long-term (1979 to 2000) ensemble climate simulations using the CCM3 and observed sea surface temperatures (SSTs) as boundary condition. We used the standard resolution T42 (300 km) and a high-resolution T170 (80 km) models, and the number of ensemble members for each resolution model is nine and six, respectively.

Although simulated TC frequencies do not much depend on resolution, more similarities to observed TCs are obtained with increased resolution for individual storm aspects. SST-forced inter-annual variations are more evident in seasonal frequencies. The simulation period includes two strong El Niño events, 1982–1983 and 1997–1998. During these events, suppressed activity was both observed and simulated in the late season in the first year in the North Atlantic, and in the early season in the second year in the western North Pacific. This suppressed activity is consistent with large-scale fields, such as vertical wind shear for the North Atlantic and upper-level divergence for the western North Pacific. In the FY2004, we will analyze results from the past climate simulations for a longer period with observed SSTs and future global warming simulations with the coupled model to clarify the relation between natural variability and anthropogenic climate change.

4. Development of high-resolution ocean model

The "eddy resolving" high-resolution global ocean model based on Parallel Ocean Program (POP) was applied on the ES to develop a high-resolution atmosphere-ocean coupled model in the second phase of this project. One of the purposes of the high-resolution ocean model is to clarify the role of meso-scale eddy and mixing by western boundary currents, which were parameterized in the moderate resolution ocean model. The horizontal mixing scheme was investigated to well reproduce the meridional heat transport, and the volume transport of western boundary currents and flow in marginal seas. Two horizontal mixing schemes were applied to the stand alone ocean model, where the horizontal and vertical resolution were 1/10 degree and variable 40 levels, respectively.

Figure 5 shows calculated annual mean sea surface height (SSH) after 5 years integration. The left figure shows the result using a bi-harmonic mixing scheme for temperature, salinity and momentum. The cross sections in Fig. 5 indicate the location where the barotropic (depth averaged) volume transports were estimated. The right figure shows the simulated results using an-isotropic viscosity and an-isotropic GM schemes for momentum and tracers, respectively. Both results represent the surface circulation around Japan such as the separation point of "Kuroshio Extension", etc. However, in bi-harmonic case, the unexpected unsteady dipole eddy appears in the Kuroshio meandering currents off Shikoku Island.

Table 1 shows the calculated barotropic volume transport in both cases, and observed transport volume. The good agreement is obtained between the calculated Kuroshio volume transport and observed value, which suggests that, the high-resolution ocean model can well represent western boundary current. In the Japan Sea, the transport through Tsushima St. is almost identical with the observation. However, the outflow from the Japan Sea at Tsugaru St. and Soya St. were not balanced in comparison with the observation, which may be caused by poor representation of marginal sea topography, especially around both straits.

5. High resolution Regional Ocean Circulation Model

(1) High resolution model of the Pacific Ocean circulation

A highly accurate Pacific Ocean Circulation (POC) model was developed using the RIAMOM (RIAM Ocean Model) with 70 vertical levels, two kinds of horizontal grid intervals (1/2 and 1/12 degree) and the Noh mixed layer scheme(Noh and Kim, 1999). The model (1/2 degree) successfully reproduced the equatorial current system and the Pacific Ocean water mass distributions such as the North Pacific Intermediate Water (NPIW) using GM scheme with a time scale of 100 years. The high accuracy of the model (1/12 degree) using 120 nodes of the ES was confirmed by comparing volume transports through various straits and current systems in the Northwestern Pacific region, and the equatorial current system with observations. It should be noted that the formation of the subsurface velocity core of the Ryukyu Current was clarified to be the result of the blocking effect of the Ryukyu Island Chain.

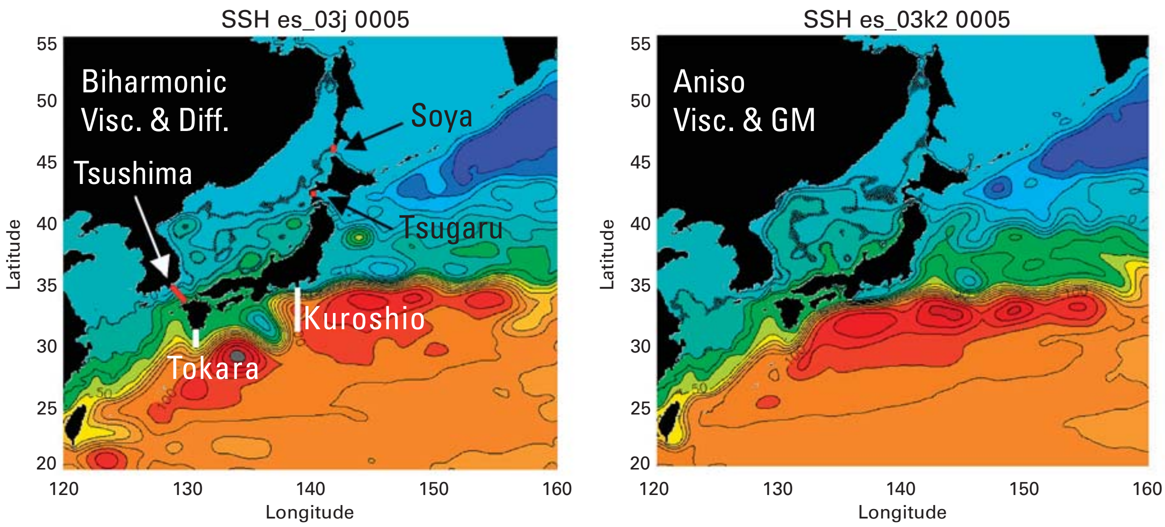

Fig. 5 Annual mean Sea Surface Height.

Table 1: Estimated volume transport around Japan

Section	Bi-harmonic	Aniso-Visc. & Aniso-GM	Transport by Observations
Kuroshio (Izu)	55.8 (Sv)	56.5 (Sv)	40–50 (Sv)
Tokara	24.3	23.0	20–25
Tsushima	2.59	3.00	2.7
Tsugaru	2.35	2.64	1.4
Soya	0.27	0.33	1.3

(2) Ultra high resolution Japan Sea circulation model

The impact of the ultra high resolution (1/36 degree) on the Japan Sea circulation was studied with 46 vertical levels and Noh scheme, but without GM scheme using 60 nodes of the ES. The model successfully reproduced the surface, intermediate circulation and water masses as well as the bifurcation of the nearshore branch of the Tsushima current, but failed to reproduce realistic deep mean cyclonic circulations with currents of 2–10 cm/s following bottom topography (the contour of f/h, f: Coriolis, h: depth), which are generated through the eddy-mean current interaction, suggesting more fine horizontal resolution required. On the other hand, the fine model resolution enabled to reproduce realistically fluctuations with the time scale of several days and length scale less than 50 km, which might be very important in mixing, diffusion and transport of tracers.

Acknowledgement

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