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Global Warming Simulation using the High-Resolution Climate Model

A Summary of the K-1 Project

Akimasa Sumi

Center for Climate System Research, The University of Tokyo,
5-1-5 Kashiwanoha, Kashiwa-City, Chiba, 277-8568 Japan
E-mail: sumi@ir3s.u-tokyo.ac.jp

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Abstract A high resolution climate model has been developed in order to improve the simulation of Global Warming. Based on preliminary experiments, characterization of the model such as resolution and physical process subroutines has been determined as follows. An atmospheric component employs the T106 global spectral model with 56 levels and an ocean component involves a 1/4˚ × 1/6˚ grid point model with 46 levels. A land surface model (MATSUSIRO = Minimal Advanced Treatments of Surface Interaction and RunOff) and a river run-off model are also incorporated. Corresponding to the increase in horizontal and vertical resolutions, all the physical processes have been retuned. Various options of parameterization schemes have been examined and a final specification has been decided upon. The atmospheric component and the ocean component are allocated to different nodes and comunicated through a coupler. 10 nodes in the Earth Simulator (ES) are allocated to the atmospheric component and 76 nodes are allocated to the oceanic component.

The climate model has been run, covering 100 years, as a control run and it is noted that there is no climate drift result even though the flux correction technique is not applied. The globally averaged surface temperature is about 14˚C and the amplitude of the annual variation is about 3.5˚C. Compared with climatology, the global mean is 4˚C cooler and the annual cycle is of the same order. A low surface temperature bias is noted in the mid-latitude of the northern hemisphere, although warm surface temperature is noted in the southern hemisphere. Meridional circulation in the Atlantic Ocean is maintained at about 20 Sv, and ocean currents and convection in GIN (Greenland-Iceland-Norway) Sea region are well simulated. In the tropics, a dominant double ITCZ feature is found, consistent with an ENSO-like SST pattern. The Asian monsoon variability is well simulated.

Many runs were then conducted for the IPCC AR4 (the 4-th Assessment Report). The globally averaged surface temperature increase by 2100 in the SRES A1B scenario was about 3.5˚C. Much information has been obtained concerning regional climate change, such as the changes in precipitation in the Baiu and the Kuroshio Current. In summary, the high-resolution climate model is able to represent many features of the mean states and variability of the present climate, and offer more detailed information about the future climate. It is concluded that the high-resolution climate model is an indispensable tool for conducting Global Warming simulations.

Keywords: high resolution climate model, Earth Simulator, Global Warming

1. Introduction—Background to the development of the high-resolution climate model

Climate change associated with the Global Warming is one of the most important problems with which the 21st century society is confronted. Immediate action is necessary by all governments, and for this purpose, demand for a more reliable assessment of Climate Change at the regional-scale is increasing. For example, we are frequently asked whether, or not, the numbers of severe storms and typhoons have increased recently. However, the present climate model is not sufficient to answer these questions accurately, mainly because our knowledge of the climate system is insufficient and model capability is imperfect. On the other hand, it is true that we do not make a maximum use of our present knowledge. For example, in case of short-range weather forecasting, we are able to make better and reliable forecasts. If we can apply a weather forecasting model to the Global Warming issue, better results are expected to be obtained. The reason why this knowledge of the daily weather forecast cannot be applied to climate modeling is because our computational capability is limited.

In general, more processes and higher resolution are required in order to achieve a reliable Global Warming simulation. An example of invoking more processes is the coupling of a carbon cycle with a climate model. An example of higher resolution is the increased spatial and temporal resolutions within the climate model. However, increasing resolution does not directly guarantee a better quality of simulation. Better representation of physical processes, consistent with the high resolution grid system, is critical for improved simulation. At the same time, we have to pay attention to any uncertainty associated with the simulation. In order to increase reliability, an ensemble technique has become widely used. Through these improvements of models and underatanding of processes in the natue, more reliable assessment of future change, such as extreme events and floods, should be obtained.

It goes without saying that a huge computer capability is necessary to achieve the goals described above. With respect to computer hardware, the Earth Simulator project which was conducted from 1998 to 2002, has opened a door to the new era of high-end computing! Subsequent to the Earth Simulator project, USA and Japan as well as South Africa and Singapore are developing a new super computer.

Once a high-end computing capability is provided, it becomes an issue of how to make a maximum use of it. We have discussed as to whether higher resolution or complexity or both are needed. As a result, we have chosen the high resolution option, rather than including processes such as a carbon cycle. The reasons are as follows; (1) In order to obtain a support from people for the adaptation and mitigation policies, we have to present detailed information regarding the future climate situation when greenhouse gases are doubled. (2) For that purpose, we have to present information as to what kind of weather may occur in the future. We require information of climate change at finer scales in both temporal and spatial scales in order to provide society with more reliable climate scenarios. Thus, it is considered that a climate model, which can be used in weather forecasting, is necessary for the Global Warming simulations. (3) With the carbon-cycle and other processes, there are many unknown processes and fundamental research is still necessary. In short, we have decided to develop a high resolution, atmosphere-ocean coupled model. As computer resources for the Earth Simulator are limited, a project to develop a high resolution, atmosphere-ocean coupled model has been started, jointly, by CCSR (Center for Climate System Research, The University of Tokyo), NIES (National Institute of Environmental Studies) and FRCGC (Frontier Research Center for Global Change).

2. Model design

Although the Earth Simulator has a huge computational power, there is a limit to the capability. Thus, we have to design the characterization of the high resolution climate model. For this, we have to define the requirements and objectives of the model. Then, in order to satisfy those requirements and achieve the objectives, the specifications of the model must be determined. In the past, computing capability was a limiting factor. We have frequently determined the specifications of the model in order to maximize performance with the available computer capability, without consideration of the objectives and requirements.

First, we have to consider the computer resources available, because many experiments need to be done for the Global Warming Simulation. For IPCC runs, the following numerical experiments were proposed;

(1) CO_2 transient experiment, increasing CO_2 by 1% per year

(2) Simulation of the 20th century climate

(3) Simulation, based on the IPCC SRES scenario.

Furthermore, when we consider the time schedule for submitting results to IPCC, a 100 year time integration of the coupled model should be completed in one month, using the Earth simulator. This is the first requirement.

How about the objective? Our objectives are to provide information about the regional climate changes over the East Asia. Thus, the second requirement is to represent the prominent phenomena in the East Asia such as the Baiu phenomena and the Kuroshio.

Next question is as to what depth of resolution is necessary. It is obvious that resolution should be consistent with the subroutines for physical processes. We have determined this by reference to previous AGCM experiment results. For example, Kawatani and Takahashi (2003) ran the T106L60 AGCM to simulate the Baiu front. They succeeded in simulating the mean profile of the Baiu front as well as disturbances in it. Kimoto (2002) examined the frequency distribution of daily precipitation in T42 and T106 AGCM, and observations over a 5.0 × 5.0 box (Fig. 1, top), 2.5 × 2.5 boxes (Fig. 1, middle) and 1.0 × 1.0 box simulations (Fig. 1, bottom) around Japan. It was clearly shown that the light rain is more frequent in the T42 simulation than actually observed. On the other hand, frequency of heavy rainfall became larger in T106. It is concluded that the T106 simulation well represents the observed distribution.

Regarding the ocean component, characterization was determined by reference to the past experiments over the North Western Pacific region. For example, the variability of sea surface height over the North-eastern Pacific region from simulations with different resolutions has

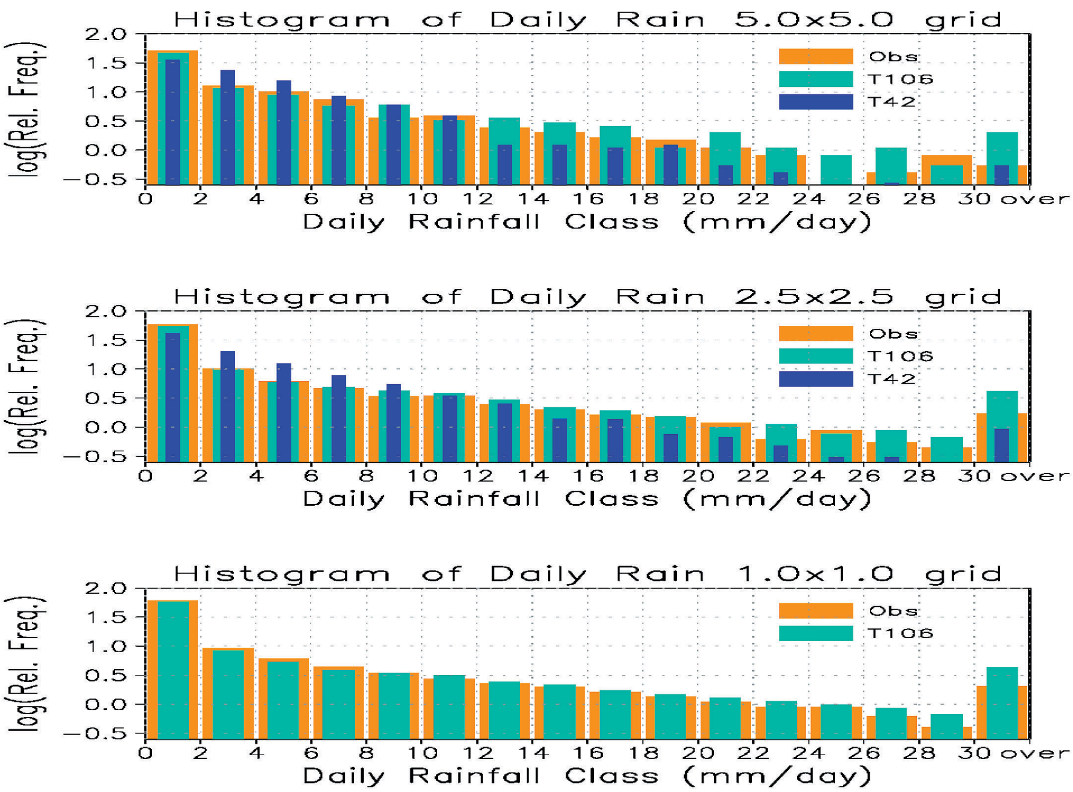

Fig. 1 Histogram of daily rainfall over the Japan, simulated by the T42 (blue) and T106 (green) AGCM. Observation (brown) is also shown. Daily rainfall is averaged over 5 degrees in longitude by 5 degrees in latitude (top), 2.5 degrees by 2.5 degrees (middle), and 1 degree by 1 degree (bottom) regions.

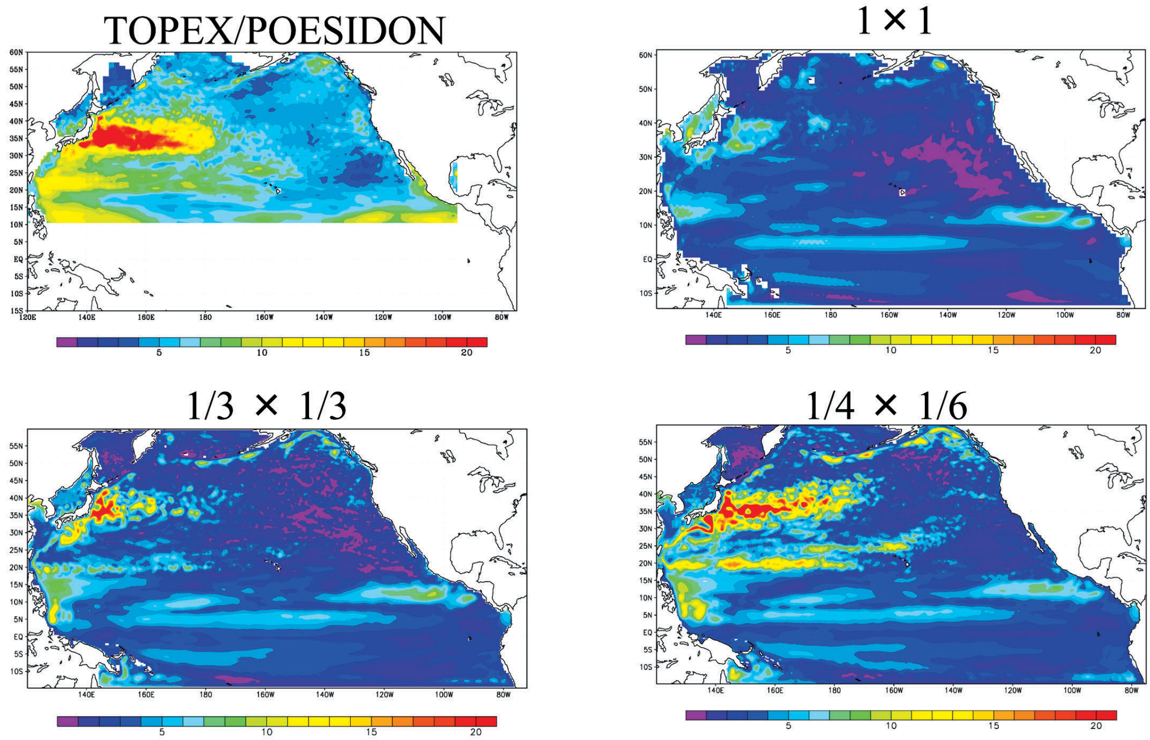

Fig. 2 Variability of surface height over the north Pacific region. (Top left) is an observation by satellite altimeter (TOPEX/POESIDON). Results over 1 degree by 1 degree (top right), 1/3 degree by 1/3 degree (bottom left) and 1/4 degree by 1/6 degree (bottom right) OGCM are displayed. These model results were obtained by observed wind forcing.

Table 1 Characterization of the high resolution atmosphere-ocean coupled model. For more details, see K-1 Model developers (2004).

(1) Atmospheric component;
① T106 spectral dynamical core with 56 level sigma levels,
② Grid advection for tracer transport,
③ K-distribution DOM/Adding radiation with maximum-random cloud overlapping,
④ Direct and indirect aerosol effect,
⑤ Prognostic Arakawa-Schubert cumulus convection scheme,
⑥ Meller-Yamada level 2 + non-local PBL,
⑦ Topography induced gravity drag.
(2) Oceanic component;
① Grid ocean model with a free surface(hybrid sigma-z model),
② Rotated lat.-lon. Grid (Poles are in Greenland and Antarctic),
③ 48 vertical levels with 8 sigma levels near the surface,
④ UTOPIA/QUICKEST advection scheme,
⑤ Smagorinsky horizontal viscosity,
⑥ Isopycnal diffusion,
⑦ Surface Boundary layer,
⑧ Bottom boundary layer,
⑨ Convective adjustment.

been examined. In Fig. 2, the simulation results from a 1 degree × 1 degree model, 1/3 degree × 1/3 degree model and 1/4 degree × 1/6 degree model are shown, with the observed height variability using the Topex-Poseidon. Compared with the satellite observations, it is considered that the 1/4 degree × 1/6 degree model result well represents nature (Nakano and Hasumi, 2003). Besides this comparison, various aspects have been examined, such as the separation of the Kuroshio from Japan Island. In this case, we concluded that 1/4 degree × 1/6 degree resolution is sufficient.

Based on the reasoning described above, we have determined the characterization of the high resolution climate model (see, Table 1). This model is named the MIROC (Model for Interdisciplinary Research on Climate)-high in the IPCC AR4 archives. At the same time, since the project is named as the first component of *Kyousei Project (in Japanese)*, we often call the model the K-1 model. Coupling of atmospheric component and oceanic component is achieved through MPMD (Multiple Programming and Multiple Data). Another feature of the model is the inclusion of an interactive aerosol model, where 5 species of aerosols (dust, sea salt, sulfate, black carbon and organic carbon). A direct effect and the first and the second indirect effects of the aerosols are included, as a unique feature of this model (Takemura et al, 2005). Other component models include the land surface model (MATSUSIRO) and the river run-off model. For more detailed information, refer to the document(K-1 Model developers, 2004) Besides the high-resolution climate model, the medium-resolution climate model, whose atmospheric component is T42L20 AGCM and ocean component is 0.5–1.4 × 1.4 degree OGCM with 44 levels, is also employed. Codes for the physical processes are common to both models, although it is impossible to make the effects of the physical processes equal in the two models. We have investigated the mechanism of the climate system by applying both models. For example, an ensemble run has been conducted by using the medium resolution model, because of computational efficiency. To obtain the regional impacts, however, the high resolution climate model is used.

3. Performance of the K-1 climate model

Many simulations including runs for IPCC AR4 have been conducted and analyzed, using this model, (Emori et al, 2005a; Suzuki et al, 2005a; 2005b, Yokohata et al, 2005a; 2005b). In this section, the basic performance of the K-1 model is described.

First, climate drift is examined. Here, it should be noted that a flux correction method is not applied in our simulation. The time-sequence of monthly mean globally averaged 2-m temperatures in the control run over 100 years are shown in Fig. 3 (top) and the sea-ice contents in the northern hemisphere(red) and the southern hemisphere (black) are shown in Fig. 3 (bottom). The globally averaged 2-m temperature is about 14˚C and the amplitude of the annual cycle is about 3.5˚C. Compared with the climatology (about 18˚C), the global mean is 4˚C cooler than the observation, but the amplitude of the annual cycle is of the same order. The content of sea-ice is stable for all 100 years in the control run, suggesting that heat balance is maintained in the climate model. In summary, it is concluded that the model shows no climate drift.

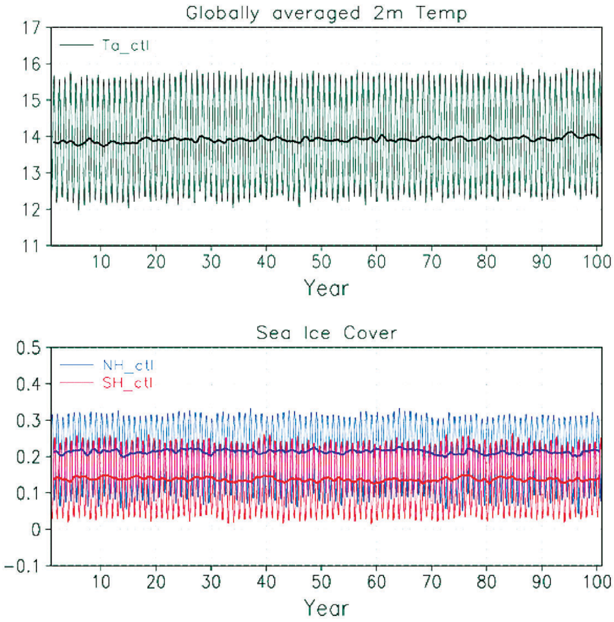

Fig. 3 Time-sequence of the globally averaged 2 m temperature (top) and sea-ice cover (bottom). Blue color represents the Arctic sea-ice and the red color represents the Antarctica sea-ice.

Performance of the climate can be briefly judged by using the annual mean of precipitation field and the Sea Surface Temperature (SST) field. Thus, the precipitation (top) and SST (middle) fields, averaged over 100 years, in the control run (left) and from observation (right), are shown in Fig. 4. First, the annual mean observed rainfall is examined. In general, detailed feature of the precipitation pattern is well simulated, for example, the Baiu front is well simulated. On the other hand, the SPCZ is poorly simulated, and the double ITCZ features are emphasized. Compared with the observed SST (middle, left in Fig. 4), it is noted that the general features of the SST are well represented, although there are many points to be improved. The warm water pool in the western tropical Pacific is narrower than the observation and the expansion of the warm water pool into the subtropical western Pacific in the northern hemisphere is not well

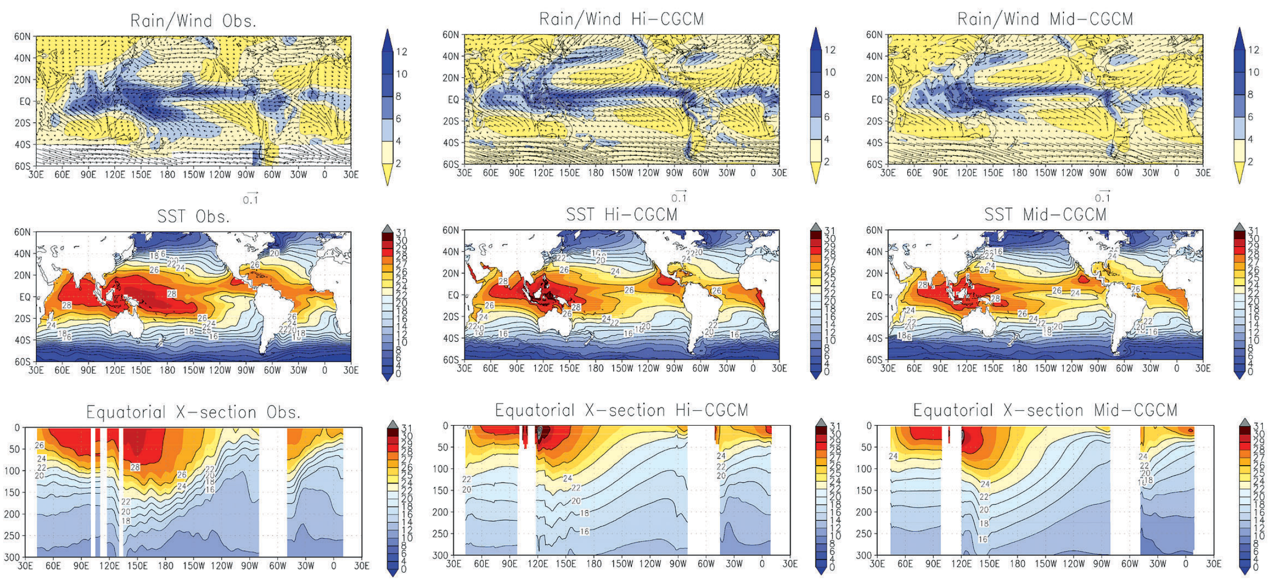

Fig. 4 Annual mean of precipitation and wind fields at 850 hPa (top), Sea Surface Temperature (middle) and cross section of sea temperature along the equator (bottom). Observations (left) and the results from the high-resolution model and the medium resolution (right) are shown. Counters for SST are 2 degrees.

simulated. The warm SST bias off the Peru coast is also noted. In other words, we can say that the model is biased toward an ENSO-like situation. Finally, the zonal-depth cross-sections of the sea temperature structure along the equator are shown at the bottom of Fig. 4. Compared with the observations, the structure of the main thermocline in the simulation tends to be diffusive. These are common features to most of climate models, which suggest that basic knowledge of the key processes is insufficient. This may be improved in the future. In the mid-latitude, a cold bias is noted, both in the Pacific ocean and the Atlantic ocean in the northern hemisphere, but a slightly warm bias is noted in the southern hemisphere. However, the SST distribution is maintained during the 100 year time integration. Although there are many unsatisfactory aspects, it can be said that the major features of the present climate system are well represented in this climate model.

Next, we will examine the possibility of representing severe events of precipitation. Main concern is whether extreme and severe events will be well simulated or not. As an example, we have examined the frequency distribution of daily precipitation over a 2.5 degree by 2.5 degree region around the Japan area (Fig. 5). In the same figure, the medium resolution (T42) climate model result is displayed. This figure is similar to Fig. 1, but the results from the coupled model are presented in Fig. 5. It is found that there exits a higher frequency of light rain in T42 than in T106. On the other hand, a higher frequency in heavy rainfall exists in T106. Compared with the observed frequency distribution, it can be said that the result simulated by the high resolution climate model is able to well represent the observed frequency distribution. Compared with Fig. 1, the frequency of heavy rainfall in T42 is not found in Fig. 5. This is because the SST is specified in Fig. 1 but the result in Fig. 5 is provided by the coupled model. In contrast, there is no difference for T106 between Fig. 1 and Fig. 5. This suggests that the SST is well maintained by the high resolution climate model.

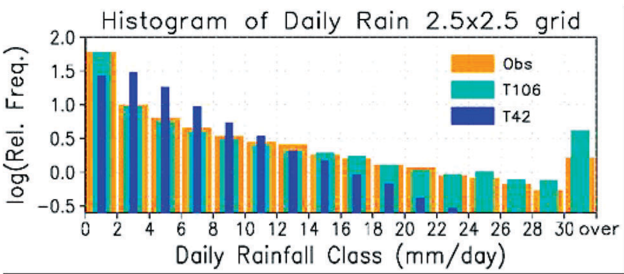

Fig. 5 Histogram of daily rainfall over the 2.5 degree by 2.5 degree region around Japan from the high-resolution (green) and the medium resolution (blue) climate models.

4. Impacts of high resolution

4.1 Global Features

As the high-resolution global model produces huge amount of data, it is almost impossible to summarize its impact over all fields in this paper. As is described in the introduction, it is expected that the local impact would be greater than the global impact. Then, the impact on the global features of the atmosphere is briefly summarized. Readers who are interested in other aspects may refer to other papers (Emori et al, 2005a; Takemura et al., 2005; Inatsu and Kimoto, 2005; Hirota et al., 2005). Impacts on the ocean have been analyzed by Oka and Hasumi(2006) and Suzuki et al.(2005).

Although there are many methods to evaluate performance of a climate model, we have used a Taylor diagram, which represents RMSE (Root Mean Square Error) and anomaly correlation, as a measure of the global performance of the climate model. Many variables are included in the model and it is, therefore, difficult to compare all the variables. Here, we select the following variables, such as 2 m temperature (Sat), sea-level pressure (Slp), zonal wind (U250) and meridional wind (V250) at 250 hPa, geopotential height (Z500) at 500 hPa, temperature at 850 hPa (T850), relative humidity at 700 hPa (RH700), specific humidity at 700 hPa, cloud cover (Ccover), Precipitation (Prcp), outgoing longwave radiation at TOA (Top Of Atmosphere), outgoing shortwave at TOA, LW (Long Wave) cloud forcing and SW (Short Wave) cloud forcing. The Taylor diagrams of these variables in the control run have been computed for the annual and seasonal means. It is noted that some variables, such as Z500 and U250, are better represented in the high resolution model, but others are not. These features differ with the season and it is difficult to say that the high-resolution climate model is better, overall, than the low-resolution model. However, during December, January and February (DJF), most variables are better in the high resolution model (see, Fig. 6).

In general, the large-scale variables relating to dynamic factors, such as a zonal wind at 200 hPa, and geopotential height at 500 hPa, are better represented in the high resolution model. However, it should be noted that performance of the model results is not automatically improved, simply by increasing resolution. In order to achieve a better performance, careful tuning of physical processes in the climate model must be exercised.

4.2 Regional Features

Local climate features are expected to be well represented by using the high-resolution model. Therefore, impacts due to the increase in resolution are expected to be found in the local phenomena. As all of the regional cases cannot be described, a few examples are discussed

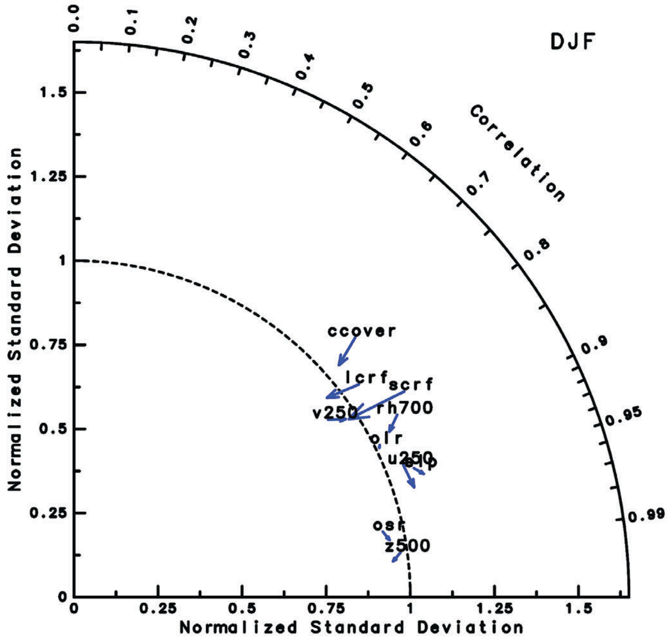

Fig. 6 Difference between the high resolution climate model and the medium-resolution model. Heads of arrows correspond to the high-resolution model and roots of arrows correspond to the medium-resolution model. Regarding variables, please refer to the text.

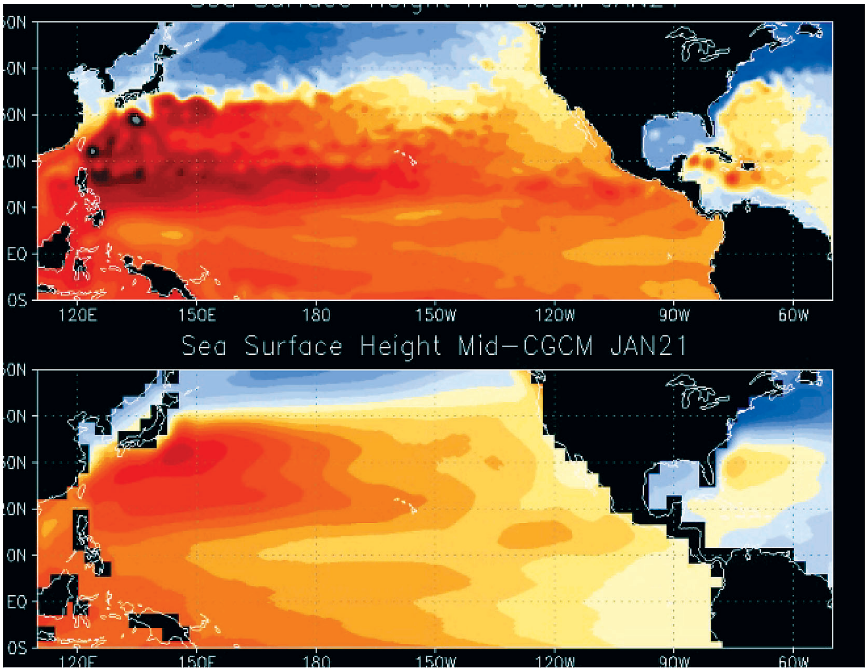

Fig. 7 Simulated ocean surface height, (Top) using the high-resolution climate model. (Bottom) using the medium-resolution model.

here. One example is the interaction between an island or coast line, the atmosphere and the ocean. In Fig. 7, a sea-surface height distribution over the Pacific basin and in the Caribbean Sea, simulated by the high-resolution climate model (top) and medium-resolution model (bottom), are displayed. It is noted that many vortices, originating in the Hawaiian Islands, propagate westward to the Philippine Islands. Similarly, many vortices are found leeward of the islands in the Caribbean Sea. These vortices are excited by the wind fields on the lee-side of the Hawaiian Island and islands in the Caribbean Sea. It should be noted that these phenomena cannot be simulated by the medium resolution model (bottom), because these islands are not represented. Vortices are generated and propagated westward from the Hawaiian Islands, because oceanic vortex is excited by the wind, influenced by the Hawaiian Island mountain. This phenomenon has been observationally investigated by Xie et al. (2001) and this far-reaching effect of the Hawaiian Island in the sea-surface height, simulated by the high-resolution climate model, has been demonstrated by Sakamoto et al. (2004).

Another example is the behavior of the Kuroshio to the east of the Japan Island (Honshu). Here, we should recall that the sensitivity of resolution to the Kuroshio has been demonstrated in the stand alone OGCM experiments, with given wind stress (see, Section.2). In Fig. 8, the Kuroshio and SST off the Japan Island are presented using the high and the medium resolution models. In this figure, results from the high-resolution atmosphere model, coupled with each of the medium-resolution ocean model and the medium-resolution atmosphere model and the high-resolution ocean model, are also shown. By comparing the four figures, we can estimate impacts due to the horizontal resolution. In the cases of the medium resolution models (hAmO and mAmO), the Kuroshio current tends to flow northward along the Japan Island. By contrast, the Kuroshio tends to depart from the Japan Island and flows eastward in a meandering fashion in the high-resolution ocean model. The mechanism of the Kuroshio separation has been the subject of discussion and the shape of the coast line of the Japan Island is considered to be critical (Mitsudera et al., 2005). As the

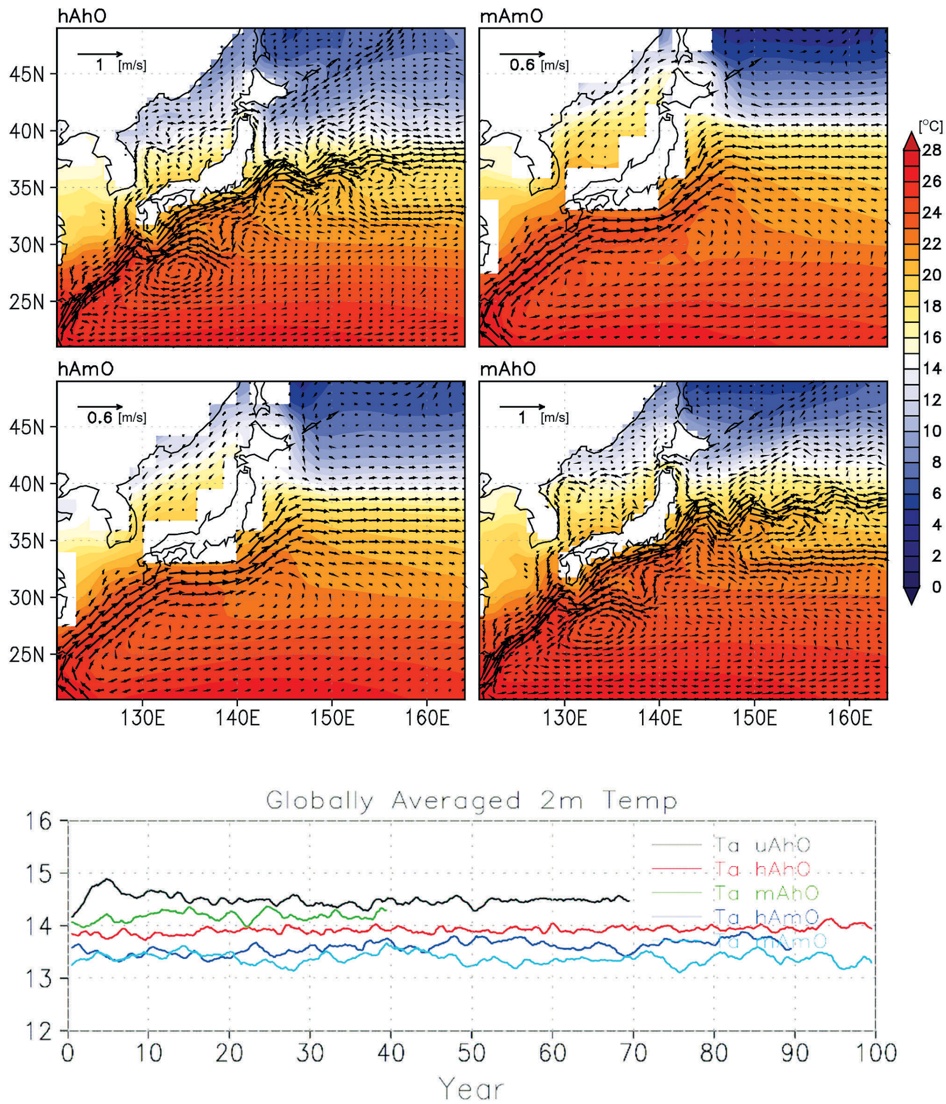

Fig. 8 (Top) Averaged SST and ocean currents around the Japan Islands in hAhO (top left), mAmO (top right), hAmO (bottom left) and mAhO (bottom right). Explanation of hAhO, mAmO, hAmO, mAhO is given in the text. (Bottom) Time sequence of the globally averaged 2 m temperature of hAhO, mAmO, hAmO, mAhO and uAhO. uA corresponds to T213AGCM.

coast line of the Japan Island is well represented in the high resolution model, the Kuroshio separation is also considered to be well represented in the high resolution model. This result is also suggested by the OGCM experiments. The Oyashio current has also been simulated around the Hokkaido with the high resolution climate model (hAhO), although it is difficult to simulate in other cases (mAmO, hAmO and mAhO). This difference is considered to stem from the difference of wind stress over the northern Pacific Ocean.

It is noteworthy that little drift is found when component models are interchanged. In Fig. 8 (bottom), the global averaged 2 m temperature is displayed, resulting from the five models (uAhO, hAhO, hAmO, mAmO, and mAhO). Here, uA denotes T213L56AGCM. Although the global averaged surface temperature is not the same in each run, there is no drift. This means that once energy balance and water balance in each component model is realized, a model, coupling these components tends to show little drift. As air-sea interaction is dependent on resolution, the globally averaged surface temperature is not the same. If we wish to simulate with the same resultant value, a little tuning is necessary.

It is concluded that the behavior of the Kuroshio Current is mainly determined by the resolution of the ocean model. However, the horizontal resolution of the atmosphere plays an important role in the heat exchange between the atmosphere and the ocean.

When we compare hAhO with mAhO, SST in hAhO is cooler that that in mAhO. A similar result is obtained, comparing hAmO and mAmO. When we use the high resolution atmosphere model, the smaller scale and high frequency components of air-sea interaction can be represented, explaining the reason for the above. Thus, it should be noted that air-sea interaction is sensitive to horizontal resolution.

Another example is improvement in the simulation of high-frequency phenomena. In Fig. 9, standard deviations of daily precipitation during June and July are displayed. The top left panel is the standard deviation, estimated by satellite observation, whilst the bottom figures are estimates from the high-resolution climate model (middle) and the medium resolution climate model (bottom). It is clearly shown that high frequency variability along the Baiu front is improved in the high resolution run.

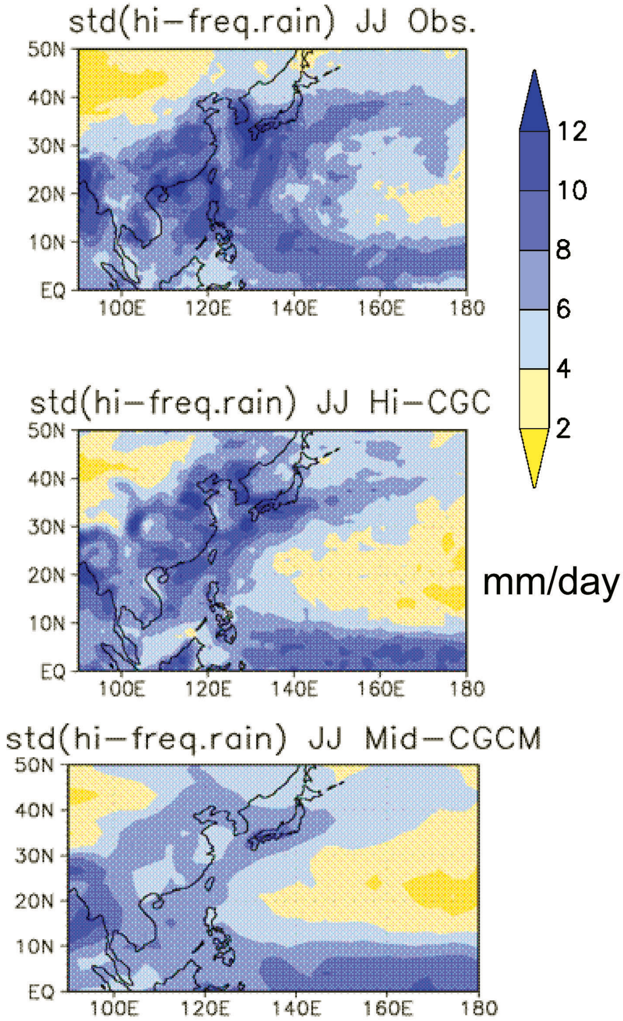

Fig. 9 Standard deviation of high-frequency (less than 10 days) rainfall in June and July, estimated by Satellite observation (top), and standard deviation in the high-resolution (middle) and the medium-resolution climate models (bottom). The results are averaged for 6 years of the control run.

5. Global warming simulation

Global Warming simulation has been conducted, using the high resolution and medium resolution climate models. In responding to requests by IPCC, simulations for IPCC AR4 have been conducted, in the form of (1) a control experiment, (2) 1% CO_2 increase experiment, (3) the 20th Century Climate Change (203C) simulation, (4) an experiment with a mixed layer ocean and (5) IPCC SRES scenario run (A1B, A2 and B1). These results have been submitted to the IPCC Data Center and are available through the Data Center. These data are denoted as MIROC-hi and MIROC-low. In Fig. 10, the time-sequences are displayed for globally averaged surface temperature (Ts) in the different runs for IPCC AR4. Global aspects of the warming are similar to previous experiments, in that there is much warming in the high latitudes and over the continents. In this figure, results due to a stabilization scenario are also presented. Thick lines represent results from the high-resolution climate model and thin lines represent results from the medium resolution. It is noted that no drift exists in the control run of both models. In the 1% increase run, a similar increase

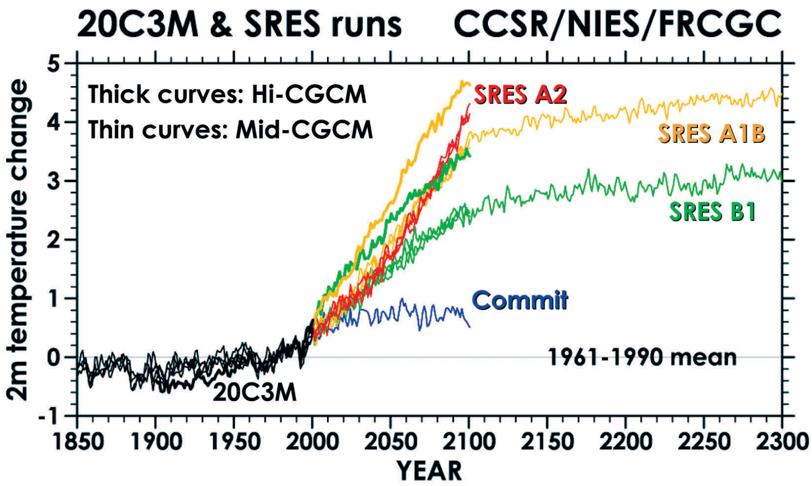

Fig. 10 Globally averaged 2 m temperature in the various IPCC runs (SRES A2, A1B and B1). Thick (thin) lines denote the high (medium)-resolution climate models, respectively.

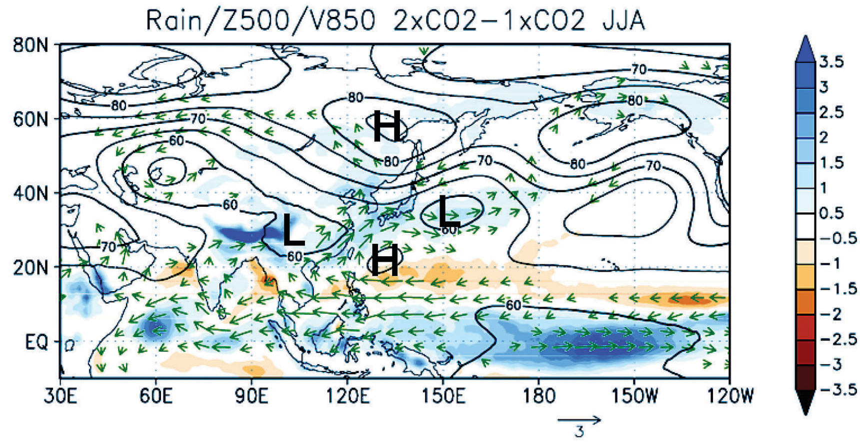

Fig. 11 Changes of precipitation field, geopotential height field at 500 hPa and wind field at 850 hPa, due to CO_2 doubling during June, July and August, over the East Asia. Unit is 10gpm for the geopotential height, and cold (warm) color corresponds to increasing (decreasing) precipitation.

in the surface temperature is noted, although a greater increase is found in the high resolution climate model (about 0.6 C after 70 years). This difference is considered to be due to difference in resolution. It is considered that the ice-albedo feedback effect and the ocean heat uptake is different in these two models (Yokohata, 2007).

New information regarding the regional impacts due to the Global Warming has been obtained with these simulations. One example relates to the climate change in the East Asia summer (see, Fig. 11). Both the subtropical high and the Okhotsk high are intensified. At the same time, the low pressure zone between these two high pressure systems is intensified, indicating that the rainfall intensity associated with the Baiu front becomes greater. It should be noted the days of heavy precipitation and days with no rain both increase. In conclusion, heavy rainfall and dry days are anticipated in the warmer climate (Kimoto et al., 2005). Furthermore, analysis of the change in heavy rainfall due to warming, using these data (Emori and Brown, 2005b), suggests that information regarding extreme events will, in future, be obtained using the high-resolution climate model.

Another example relates to the change in the Kuroshio Current. The Kuroshio separation is a prominent feature and the high-resolution climate model is able to simulate this separation (refer to 4.2). Fig. 12 shows ocean current and SST around the Japan Islands in the present climate simulation (top, left) and in the warmer climate (bottom left). In previous simulations we could not say anything about the change in Kuroshio Current because grid distance in the ocean model was so coarse and the Kuroshio Current was not well represented. However, the current model successfully simulates the Kuroshio Current around the Japan Islands. In the warmer climate, the currents

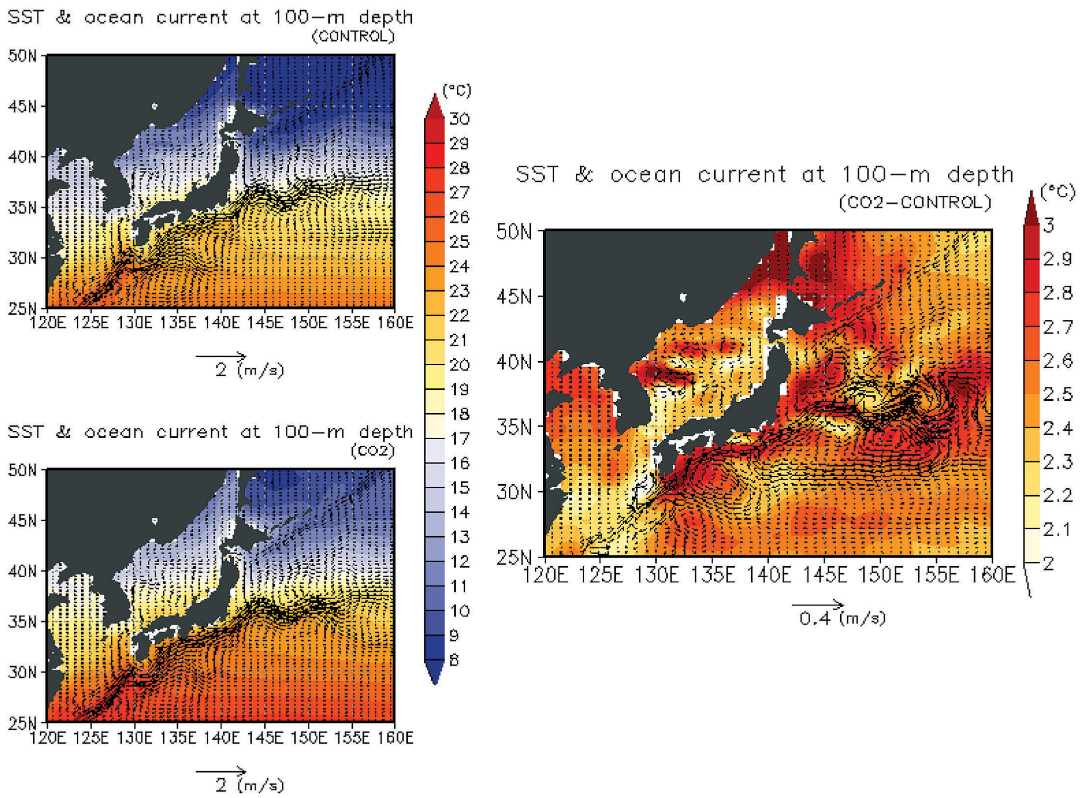

Fig. 12 SST and ocean current at 100 m depth in the control run (left top) and in the CO_2 doubling run (bottom left). The unit of current is 2 m/sec and the unit of SST is 1˚C. Difference between these two runs is displayed (right). The unit of current is 0.4 m/sec and the unit of SST is 0.1˚C.

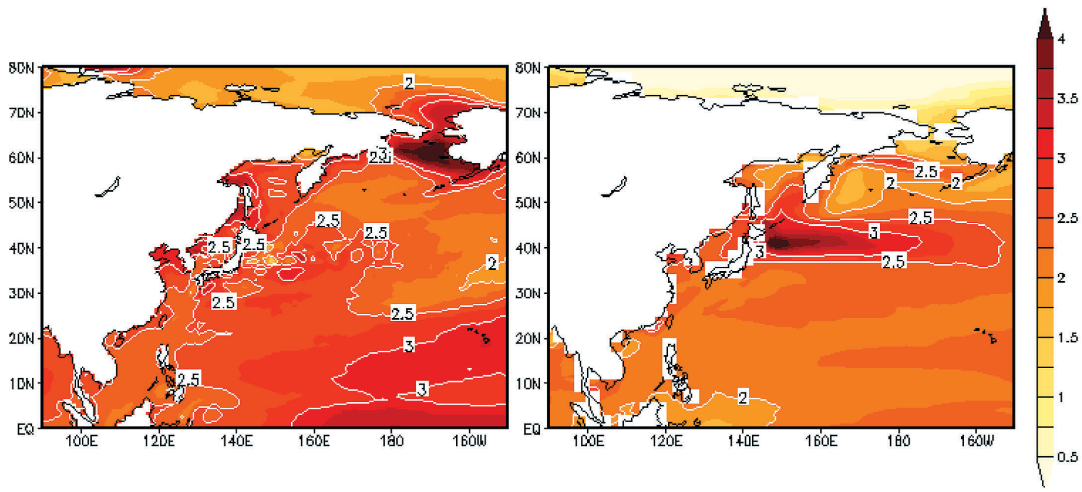

Fig. 13 The increase in SST from the CO_2 doubling run around the Japan Island, using the high resolution coupled model (left) and the medium-resolution coupled model (right).

around the Japan Island are similar to those in the current climate. However, current speed is intensified and SST is increased (right; Sakamoto et al, 2005). These results are very important to the investigation of the impact of the warming to fisheries around the Japan Islands.

Regarding the behavior of the Kuroshio Current around the Japan island, the SST anomaly due to CO_2 doubling tends differ with the model used. In the medium resolution model, the Kuroshio tends to flow northwards. However, the Kuroshio is separated from the Japan Island around 35N in the high resolution model. When Global Warming occurs, the Kuroshio tends to move further northwards in the medium resolution model, although the location of the Kuroshio extension remains at the same latitude in the high resolution runs. The differences in SST between 60–80 year averages in the 1% CO_2

increase run are shown in Fig. 13 for the high-resolution climate model, (left), and the medium-resolution model, (right). It is well noted that a large difference exists between two regions in the northern Pacific Ocean, east to the Japan (Honshu) Island. The difference in the Arctic region is due to the difference in the sea-ice distribution, which results from the difference in the performances between the two ocean components in the Arctic Sea. Thus, when we apply a time-slice method to this SST anomaly, the different results may be obtained, and it must be carefully examined to judge whether a given SST anomaly is reasonable, or not.

6. Summary

A high resolution climate model has been developed by CCSR, NIES and FRCGC researchers, because the Earth Simulator been made available to us. This model has approximately 100 km resolution in the atmosphere and 20 km resolution in the ocean. The interactive aerosol model is included and the direct and the first and second indirect effects of aerosols are all taken into account. Their performance for the present climate is better than that obtained from the medium resolution climate model. The general performance of the large-scale features is improved for many variables when the high-resolution climate model is used. However, more direct impacts are obtained for regional phenomena. For example, the influence of the Hawaiian Island on the north-west Pacific Ocean is clearly demonstrated. Regional climate, such as disturbances in the tropics and the Baiu front, is well simulated. Another important aspect is an improvement in the ocean current simulation. Behavior of the Kuroshio is well simulated.

It is quite obvious that increasing resolution does not automatically guarantee good performance. However, the results shown in this paper strongly suggest that the high-resolution climate model will provide us with many stimulating and interesting results. Firstly, there exists no climate drift without a flux correction. The globally averaged surface temperature and the sea-ice contents are maintained in the integration. Although the global average exhibits a cool bias, the amplitude of the annual cycle is the same as in the climatology. Secondly, when one component model (the high-resolution atmosphere model) is replaced by the other component model (the medium resolution atmosphere model), there are no biases to the atmosphere-ocean coupled model. These results suggest that, when careful treatment of each component model is undertaken, the coupled model shows little climate drift.

However, there remain many problems, most of which are common to many of the climate models. We need to develop many aspects within a climate model. In general, it is concluded that the performance of the high resolution climate model is promising, and increasing the resolution in the climate model is one direction for the strategy in future developments of a climate model.

The Global Warming simulation has been conducted by using these models. The results have submitted to IPCC AR4. The global aspects are similar to previous experiments, but new findings for regional climate change have been obtained. For example, it is shown that rainfall activity, associated with the Baiu, front will be intensified in the climate of the future. Another example is a change in the Kurosio current around the Japan Islands. It is particularly important that the impact of the Global Warming on the marginal sea region is obtained, using the high-resolution climate model, because the environmental change in the marginal sea region is very important to society. It is concluded that, in order to consider the regional climate change due to the Global Warming, the high resolution climate model, described in this paper, is indispensable.

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Table 2 Members of the K-1 project.

CCSR	Masahide Kimoto, Hiroyasu Hasumi, Ken Oka, Ayako Abe, Teruyuki Nakajima, Masaaki Takahashi, Yukari Takayabu
NIES	Seita Emori, Toru Nozawa, Tatsuya Nagashima, Tokuta Yokohata, Hideo Shiogama
FRCGC	Tatsuo Suzuki, Takeshi Sakamoto, Akira Hasegawa, Yoko Tsushima, Fuyuki Saito, Teruyuki Nishimura

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