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Multi-century ensemble global warming projections using the Community Climate System Model (CCSM3)

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Abstract Using the Community Climate System Model Version 3 (CCSM3), multi-century three-member ensemble global warming projection experiments were conducted on the Earth Simulator (ES). The scenario experiments carried out on the ES consist of 20th century historical simulation and future scenario experiments up till year 2450. The future scenarios include IPCC SRES (Special Report on Emission Scenarios) scenarios for the 21st century, the green house gases (GHGs) stabilization and overshoot scenarios beyond the 21st century, through which the long-term response of climate system to GHG stabilization levels is investigated. Future changes in surface air temperature, sea ice volume, thermohaline circulation and sea surface level are presented as an overview of the obtained simulation results. The porting of CCSM3 software to the ES and its computational performance are also described.

Keywords: Global warming projections, SRES scenarios, stabilization and overshoot scenarios, long-term response of climate system, ensemble simulation.

1. Introduction

The ultimate goal of the United Nations Framework Convention on Climate Change (UNFCCC) is to achieve stabilization of concentrations of greenhouse gases (GHGs) in the atmosphere at a level that would prevent *dangerous anthropogenic interference* with climate system. There exist, however, number of crucial questions to pursue this goal. For example, what a level of GHG concentrations in the atmosphere should be appropriate to prevent the dangerous anthropogenic interference with the climate system. When we should stop the increase of GHG concentrations in the atmosphere. Such questions have to be resolved in forthcoming discussions on the emission reduction of GHGs beyond the Kyoto Protocol and the discussion should be made on the basis of state-of-the-art scientific knowledge.

In order to enhance scientific contributions to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) planned to be published in 2007, the Ministry of Education, Culture, Sports, Science and Technology of the Japanese government has launched the Project for Sustainable Coexistence of Human, Nature and the Earth in year 2002. The goals of this project include the development of high-resolution climate models suitable for the Earth Simulator (ES) [1], one of the fastest supercomputers in the world, through which more accurate and reliable global warming projections are promised.

Within this framework, Central Research Institute of Electric Power Industry (CRIEPI), National Center for Atmospheric Research (NCAR), Los Alamos National Laboratory (LANL) and Kyushu University form an international research consortium. The first goals of this international collaboration is to conduct global warming projection experiments for the IPCC AR4 and the second goal is to develop a very high-resolution coupled climate model for accurate and reliable projections of regional scale climate changes. To meet the first goal, we use a moderately high-resolution coupled climate model which enables us to conduct multi-century, multi-member ensemble simulations of future climate changes. Although one of the important scientific contributions to the global warming issue is to obtain good understanding over the stabilization effects of GHG concentrations in

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the atmosphere, it requires very long-term simulations, in other words, it is computationally very expensive. Therefore, we employ the moderate resolution climate model in this study.

A typical spatial resolution of coupled climate models used in global warming projections in the IPCC Third Assessment Report [2] is about 300 km. For example, the resolution of the first generation NCAR coupled climate model, CSM1, is T42 in atmosphere and about 2 degree in ocean [3]. In the present study, we use the third generation NCAR coupled climate model, the Community Climate System Model Version 3 (CCSM3) [4], at two times higher resolution than CSM1: i.e., T85 in atmosphere and 1 degree in ocean. Using this moderately high-resolution model, global warming projection experiments were conducted under the IPCC SRES [5] and other future scenarios.

The rest of this paper is organized as follows. Brief description of model configuration and porting of the CCSM3 software to the ES are given in sections 2 and 3, respectively. The experimental design including future carbon dioxide concentration scenarios is described in section 4. The overview of simulated future climate changes is given in section 5. Finally, the summary is given in section 6.

2. Model

The CCSM3 is the third generation coupled climate model developed at NCAR and it consists of atmosphere, land, sea ice and ocean components and flux coupler. A comprehensive overview of improvements incorporated into the CCSM3 is given by Collins et al. [4] as well as the model performance obtained in its control simulations.

The atmosphere component, CAM, is based on the Eulerian spectral dynamical core at T31, T42 and T85 resolution with 26 vertical layers. It also supports the finite volume dynamical core at 2 by 2.5-degree resolution. The ocean component, POP, is based on a displaced grid system where the computational north pole is displaced to Greenland. It supports nominal 1 degree and 3 degree horizontal resolution with 40 vertical layers. The land component, CLM, and sea ice component, CSIM, have the same horizontal resolution as CAM and POP, respectively. The flux coupler, CPL, has a role of exchanging fluxes and state variables among the four physical components for atmosphere, land, sea ice and ocean. In the present study, we employ the atmosphere component based upon the spectral dynamical core at T85 resolution and the nominal 1 degree ocean component.

The climate sensitivity of CCSM3 is discussed by

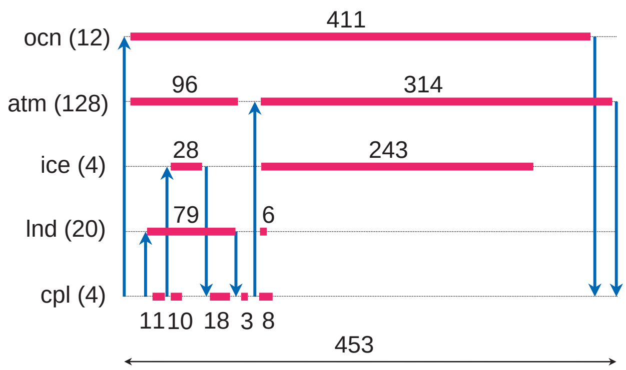

Fig. 1 A CCSM load balance diagram on the ES. Resolution of atmosphere and ocean components are, respectively, T85 and 1 degree. Red bars denote computation and blue arrows denote MPI communication. Numbers attached to red bars show wallclock seconds per simulated month (31 days).

Kiehl et al. [6]. The CCSM3 has higher climate sensitivity than previous versions of NCAR coupled climate models: At T85 resolution, its equilibrium climate sensitivity is 2.7 °C and transient climate response (TCR), which is defined as a change in globally averaged surface air temperature at the doubling of CO_2 in a 1% per year carbon dioxide increase experiment, is 1.5 °C. The second generation model, CCSM2, has an equilibrium sensitivity of 2.2 °C and TCR of 1.05 °C [7][8].

3. Porting to the Earth Simulator

To enable global warming projections on the ES, the CCSM3 was ported to the ES and optimized for its vector parallel architecture. This effort was made jointly with the CCSM software engineering group at NCAR and US Department of Energy SCIDAC (SCIentific Discovery through Advanced Computing) CCSM team. From the software engineering viewpoint, one of the goals of this effort is to develop a performance portable coupled climate model software which is able to efficiently run both on scalar and vector computing platforms. The target vector platforms include the ES, NEC SX and Cray X1. Since the CCSM3 is originally developed for scalar parallel platforms, it is necessary to implement vector constructs to exploit the outstanding hardware performance of ES vector processors. During the porting and vectorization, we had to comply with some requirements, for example, to minimize the performance degradation on scalar platforms and to utilize common codes both for scalar and vector platforms as much as possible. In addition, any code changes must not impede scientific productivity and the model must produce same climate as on scalar platforms.

From the parallel computing point of view, the CCSM3

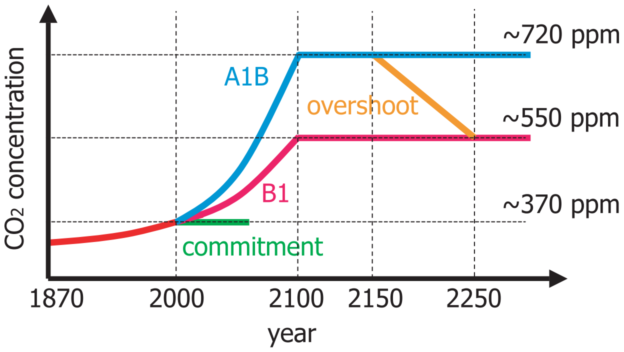

Fig. 2 A schematic of carbon dioxide concentration scenarios used in the experiments in this paper.

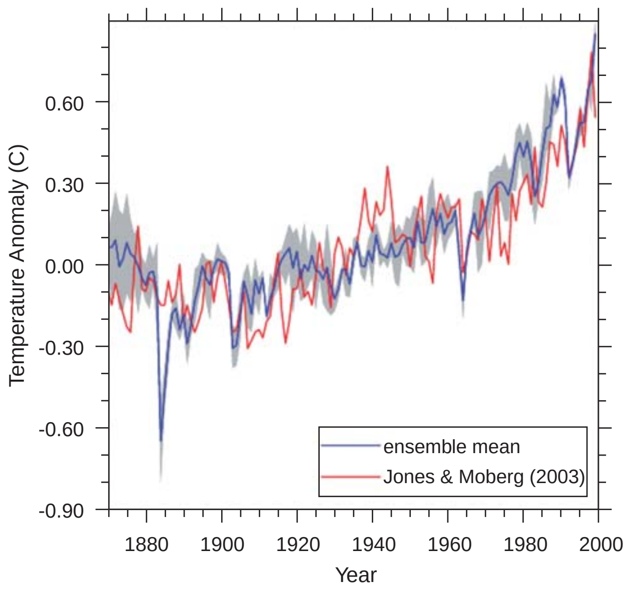

Fig. 3 Globally averaged annual mean surface air temperature from year 1870 to year 2000. Model results compared to the observation [12].

is an MPMD (Multiple Program, Multiple Data) parallel program consisting of five executables: The CAM and CLM are hybrid MPI/OpenMP programs, while the CSIM, POP and CPL are flat MPI programs. The CCSM3 is a hub-and-spoke system software, where each component runs on unique sets of hardware processors and all communication goes through the flux coupler. After the extensive vector/parallel optimizations of each component, the load balance is adjusted in the fully coupled configuration. At the target model resolution, we have finally achieved turnaround of 16 simulated years per wallclock day using 21 nodes (168 processors) of the ES, where 128, 20, 4, 12, 4 vector processors are assigned respectively for CAM, CLM, CSIM, POP and CPL. Figure 1 shows a load balance diagram on the ES which demonstrates how computation and communication proceed with time.

4. Experimental design

Three-member ensemble simulations of past and future climate are conducted on the ES under the carbon dioxide concentration scenarios schematically shown in Figure 2. The 20th century historical simulation from year 1870 till year 2000 is followed by two future scenarios for the 21st century with prescribed carbon dioxide concentration in the atmosphere. These scenarios are taken from the IPCC Special Report on Emission Scenarios (SRES) [5] and called the A1B and B1 scenarios.

As discussed in the IPCC Synthesis Report [9], long-term climate responses have to be investigated to discuss about the stabilization effect of GHGs. For this purpose, the SRES A1B and B1 scenario experiments are extended beyond year 2100 till year 2350 with constant concentrations at the year 2100 concentration levels of each SRES scenario. These two stabilization experiments are referred as the A1B stabilization and B1 stabilization in this paper. Note that one of three ensemble members is extended beyond year 2350 up till year 2450.

Another simulation presented in this paper is a committed climate change experiment. This is an experiment requested by the IPCC Working Group I, where the GHG concentrations are held fixed to the contemporary (year 2000) level after year 2000 until year 2050. The purpose of this experiment is to demonstrate how humans have already committed to the global warming during 20th century.

One last experiment is a simple overshoot scenario experiment proposed by the authors. The GHG concentrations once overshoot to higher level, then, they are decreased to and stabilized at a lower target level. This scenario implies that the GHG concentrations in atmosphere may be reduced due to innovative technologies in future. Even with introduction of such technologies, the influence of taking different development pathways on the climate system is unknown and should be clarified. Therefore, the aim of this experiment is to investigate hysteresis and irreversible effects in climate system against different pathways of GHG concentrations. In the present study, we assume that the GHG concentrations once overshoot to the A1B stabilization level, then, linearly decrease to the B1 stabilization level from year 2150 till year 2250 as shown in Figure 2.

The other time varying forcings included in the experiments are CH_4, N_2O, CFCs, tropospheric and stratospheric ozone, and sulfate and carbon aerosols. Concerning the aerosols, only the direct effect is taken into account. In addition, the solar variability and aerosols due to volcanic eruptions are included in the 20th century historical simu-

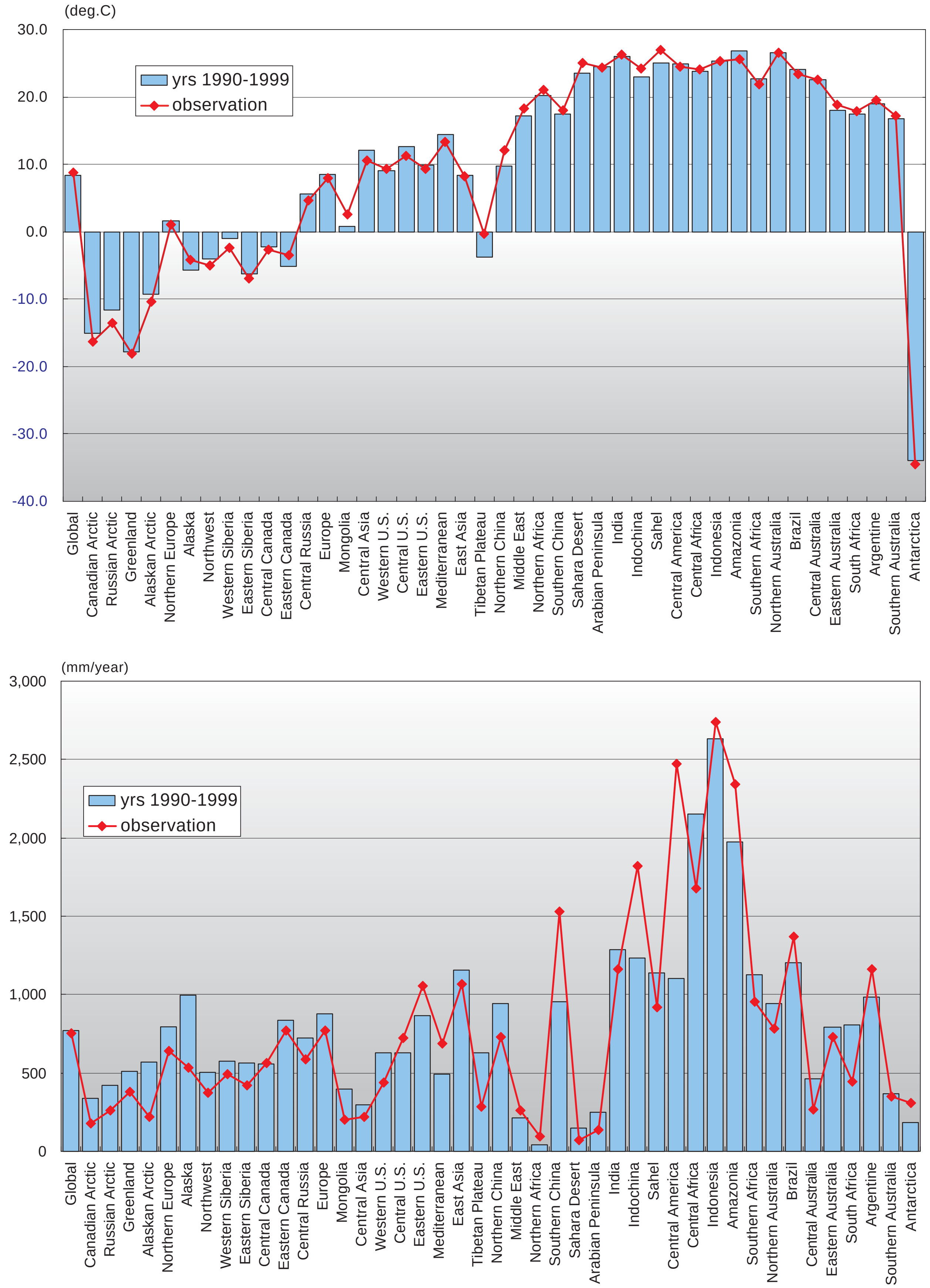

Fig. 4 Ensemble means of (a) surface air temperature and (b) precipitation at the end of 20th century (years 1990–1999) averaged over 43 areas in the world. Model results compared to climatological data.

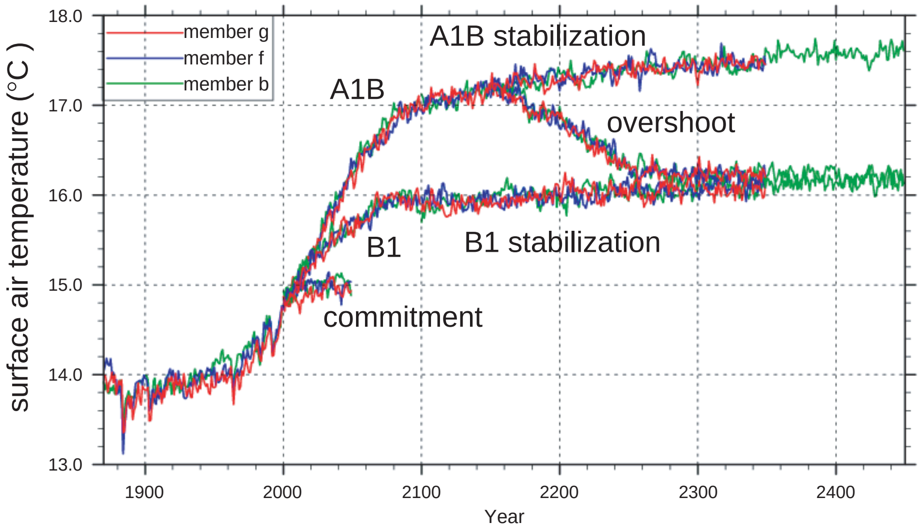

Fig. 5 Time-series of globally averaged annual mean surface air temperature from all the ensemble simulations (20th century historical simulation, SRES A1B, SRES B1, A1B stabilization, B1 stabilization, committed climate change, and overshoot experiments).

lation. Details of forcing conditions are given in Meehl et al. [10] and Tsutsui et al. [11].

5. Results

5.1 Past and present climate

Figure 3 shows the time-series of globally averaged surface air temperature anomaly during the period from year 1870 to year 2000 in comparison with the observation [12]. The temperature anomaly is defined as deviation from the average over years 1901–1960. One of the deficiencies with this model simulation is that high temperatures observed around year 1940 is not well represented. However, the other aspects are in very good agreement with the observation.

Figure 4 shows ensemble means of surface air temperatures and precipitations for the period from year 1990 till year 1999 averaged over 43 regions in the world, where only land areas are included in the area average and oceans are excluded. The observed climatological data are also plotted for comparison purpose. The simulated surface temperature at the end of 20th century agrees very well with the observation. The precipitation results are also fairy in good agreement although there are some differences, in particular, over the tropical regions such as Amazon, Central America and so on.

5.2 Surface air temperature

Figure 5 shows the time-series of globally averaged annual mean surface air temperatures from all the scenario experiments, where three ensemble members are denoted by members “b”, “f” and “g”. Compared to the temperature at the end of 20th century (years 1990-1999), the ensemble mean of surface air temperatures at the end of 21st century (years 2090-2099) is predicted to increase by about 2.5 °C and about 1.5 °C under the A1B and B1 scenarios, respectively. Furthermore, the surface air temperatures keep increasing even under the stabilized GHG concentration conditions beyond year 2100 both in the cases of A1B and B1 scenarios. More discussions on such long-term climate response under stabilized forcings are presented by Tsutsui et al. [11]. In the committed climate change experiment, the surface air temperature rises by about 0.2 °C from year 2000 to year 2050. Under the overshoot scenario, the globally averaged surface air temperatures decreased to almost the same level as the B1 stabilization after year 2300 and hysteresis effects are not significant.

The spatial patterns of future change in surface air temperature under the A1B and B1 scenarios are shown in Figure 6. The future change is defined as a deviation of temperature averaged over years 2090–2099 from that averaged over years 1990–1999. The upper and lower panels show the results under the A1B and B1 scenarios, respectively. The warming is significant especially in northern hemisphere high-latitude regions and over continents. Although the magnitude of temperature change is dependent on GHG concentration levels, the spatial pattern of possible future change is very similar under both scenarios. One remarkable point in Figure 6 is that less warming can be seen in the North Atlantic and southern oceans. This is significant under the B1 scenario where local cooling can be seen in Ross Sea and off Iceland.

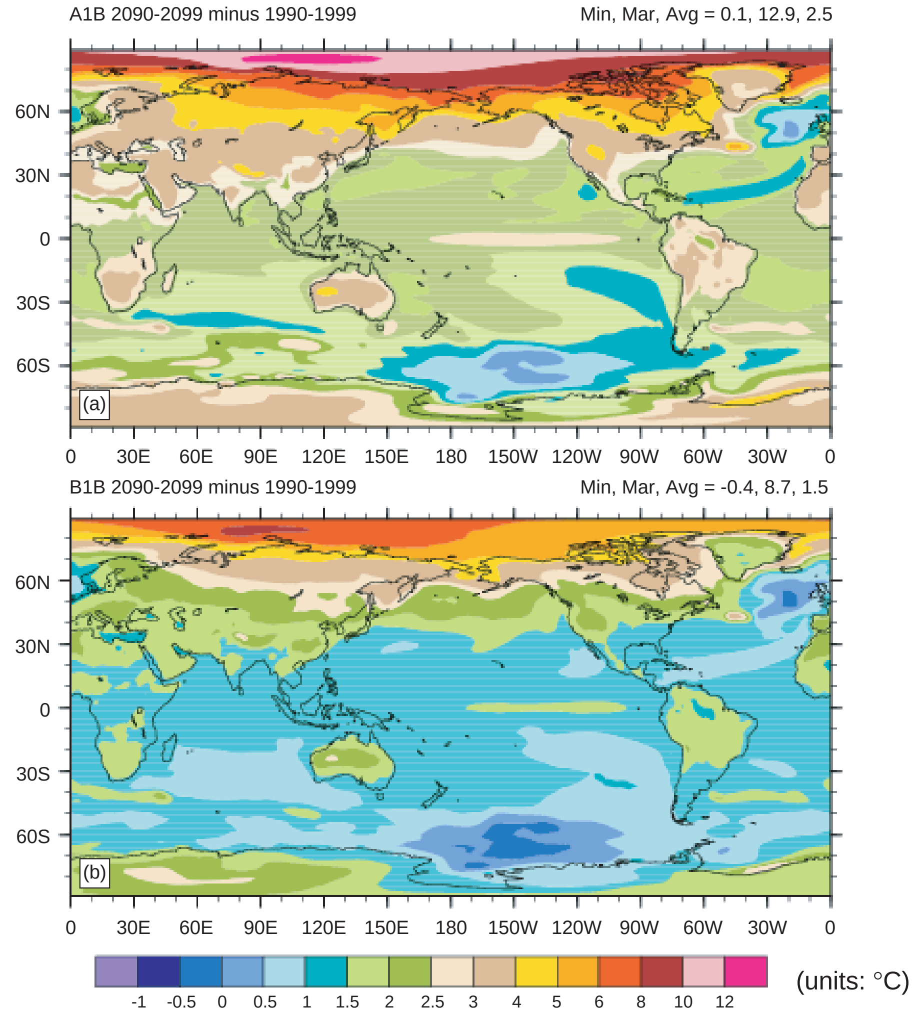

Fig. 6 Spatial distributions of change in annual mean surface air temperature during the 21st century under the A1B (upper panel) and B1 (lower panel) scenarios.

5.3 Sea ice volume

Figure 7 shows the time series of annual mean sea ice volume in the Arctic region. The result from the year 1870 control simulation is also plotted. A slight drift can be seen in the control simulation for last 150 years. Under the A1B scenario, the sea ice volume at the end of the 21st century is reduced by about 80% of that at the end of 20th century. In the case of the B1 scenario, the decrease in ice volume is slower but about 65% of ice volume disappears at the end of the 21st century. Furthermore, the ice volume keep decreasing slightly even under the stabilized GHG concentrations. Such decrease is more significant under the A1B stabilization than under the B1 stabilization. This suggests that the concentration level in the A1B stabilization case might be higher than a target level which satisfies the goal of UNFCCC. The ice volume is rapidly restored to the state of the B1 stabilization under the overshoot scenario and hysteresis effect is not significant.

5.4 Thermohaline circulation

The thermohaline circulation has an important role of transporting the heat into high latitudes in the northern hemisphere. Figure 8 shows time-series of maximum meridional overturning circulation (MOC) stream function in the North Atlantic (30 °N to 50 °N, below 500 m). During the 21st century, the thermohaline circulation is weakened due to the global warming: the maximum values of MOC stream function are reduced by about 24% and 16%, respectively, under the A1B and B1 scenarios. However, the MOC tends to recover gradually once the GHG concentrations are stabilized. Under the overshoot scenario, the MOC stream functions immediately recover to the level of the B1 stabilization scenario.

The shutdown of thermohaline circulation predicted, for example, by Stocker et al. [13] cannot be seen in our simulations. Even with the weakened MOC, the warming is still dominant over Europe as shown in Figure 6 and only less warming or slight cooling areas can be seen

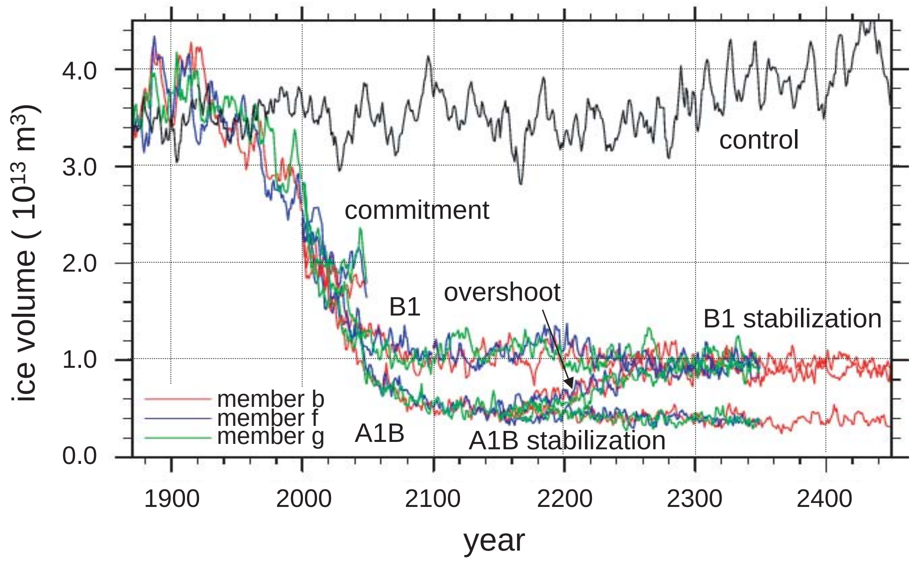

Fig. 7 Time series of the annual mean sea ice volume in the Arctic region.

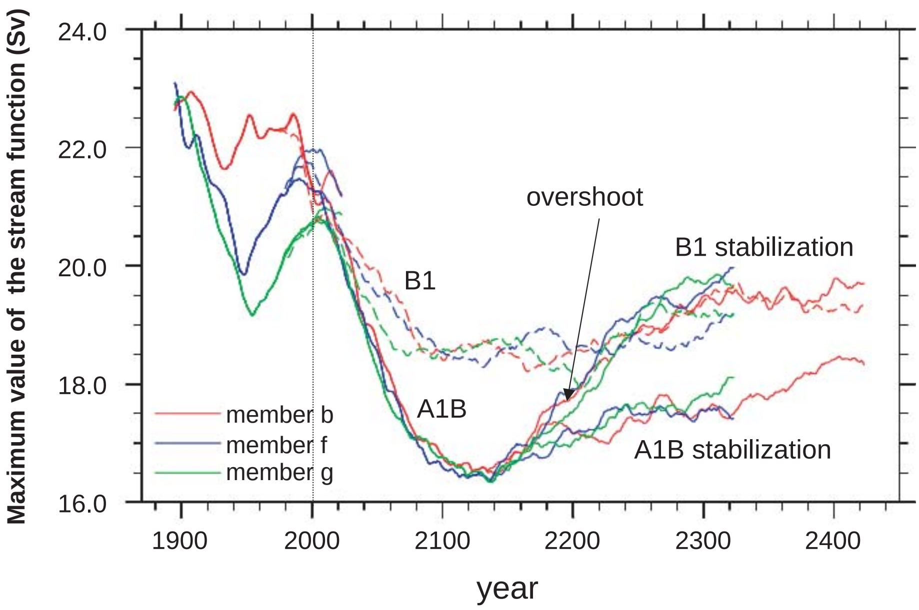

Fig. 8 Time series of maximum values of the meridional overturning circulation stream function in the North Atlantic (30 °N to 50 °N , below 500 m).

near Greenland and around Antarctica. The mechanism of the local cooling is complicated because there are many factors such as the weakened MOC, melting of sea ice, and changes in current path of the Gulf Stream and the Antarctic Circumpolar Current. Further investigations are necessary to reveal the mechanism.

5.5 Sea level rise

The sea level rise due to the global warming is of particularly high interest to the public. Figure 9 shows the time series of sea level averaged over the world oceans. The change in sea level is attributed to the thermal expansion of sea water, melting of ice sheet and glaciers over Antarctica and Greenland, and changes in current paths in ocean which lead to changes in dynamical sea surface height. Among them, only the thermal expansion is taken into account to evaluate future change in sea level. At the end of 21st century, the globally averaged sea level increases by 13 cm and 8 cm relative to year 2000 under the A1B and B1 scenarios, respectively. Even after the stabilization of GHGs starting from year 2100, the sea level is found to keep increasing for long time. The sea level under the overshoot scenario does not recover to that at the B1 stabilization level. This is because the heat

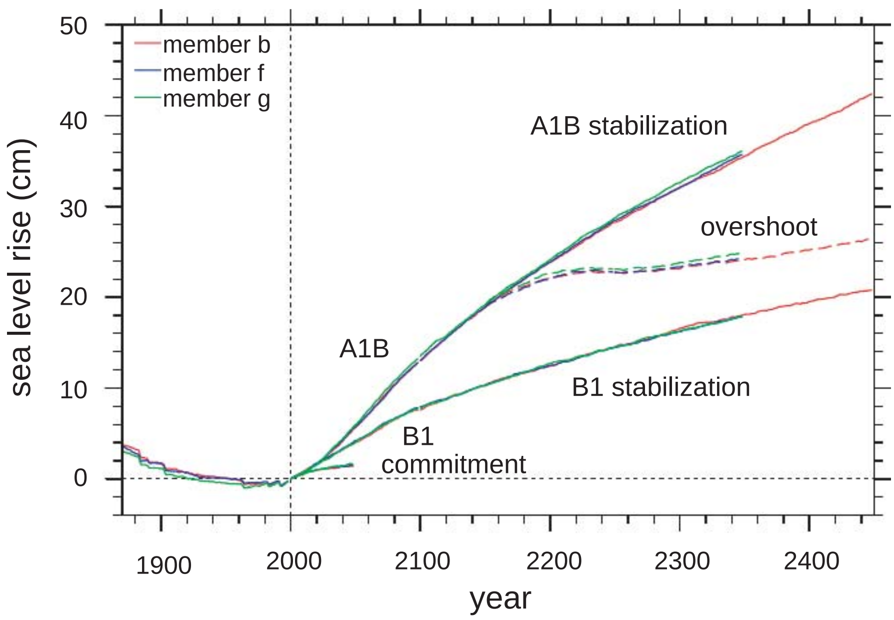

Fig. 9 Sea revel rise due to only thermal expansion is predicted to increase by 8 cm (B1) and 13 cm (A1B) at the end of 21st century relative to 2000.

stored in ocean before year 2250 contributes to the thermal expansion and this is one of the hysteresis effects found in our simulation results.

6. Conclusion

The multi-century multi-member ensemble simulations of future climate change are conducted using the CCSM3 on the ES. From the obtained simulation results, implications to the world energy policy are summarized as follows:

(1) GHGs stabilization level under the A1B stabilization scenario may not meet the goal of UNFCCC because the sea ice will vanish in the Arctic region which might correspond to the dangerous anthropogenic interference with climate system.

(2) GHGs stabilization level under the B1 stabilization scenario might be one of the target levels. However, an appropriate level of carbon dioxide concentration in the atmosphere should be decided from a clear criterion, which still remains unknown.

(3) A further research of overshoot scenarios should be pursued because it is expected to be useful for risk managements to cope with low and late emission reduction of carbon dioxide in the world.

The three-member ensemble experiments carried out on the ES are a part of more comprehensive ensemble simulations done jointly by NCAR, US Department of Energy and CRIEPI. The simulation results are accessible through the Earth System Grid [14] and the reduced resolution data are provided through the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for analysis toward IPCC AR4.

Acknowledgement

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