Multi-century Ensemble Global Warming Projections by CCSM3 Using the Earth Simulator

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To get good understanding of an effect of stabilization of atmospheric concentrations of greenhouse gases, such as CO_2, methane and CFCs, multi-century three-member ensemble global warming projections were conducted on the Earth Simulator using the optimized codes based on NCAR coupled climate model CCSM3. For the projections, we applied two scenarios for the 21st century, stabilization and overshoot scenarios beyond the 21st century. We analyzed the long-term response of climate system to stabilization levels of atmospheric concentrations of greenhouse gases. Future changes in surface air temperature, sea ice volume, thermohaline circulation and sea level rise were projected including hysteresis effects in the climate system revealed through the projection experiment of the overshoot scenario.

Keywords: global warming projections, IPCC SRES scenarios, stabilization and overshoot scenarios, long-term response of climate system, ensemble projection

1. Introduction

The ultimate goal of the United Nations Framework Convention on Climate Change (UNFCCC) [1] is to achieve stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent *dangerous anthropogenic interference with climate system*. There remain, however, number of crucial questions, such as, what a level of GHG concentrations in the atmosphere should be appropriate to prevent *the dangerous anthropogenic interference with the climate system* or when we should stop the increase of GHG concentrations in the atmosphere. Such questions have to be resolved for forthcoming discussions on emission reduction of GHGs beyond the Kyoto Protocol.

In order to get good understanding about stabilization effects of GHG concentrations in the atmosphere to prevent global warming, we have conducted the five-year Kyosei project supported by MEXT using the Earth Simulator (ES) since FY2002 through the international research collaboration with CRIEPI, Kyushu University, National Center for Atmospheric Research (NCAR) and Los Alamos National Laboratory (LANL). The first goal of this project is to conduct global warming projections for the IPCC Forth Assessment Report (2007). To meet the goal, we succeeded in multi-century ensemble projections of global warming (IPCC runs) using the ES in the FY2004 ([2]- [6]). Moreover, for the second goal of this project we developed a high-resolution atmosphere model and ocean models including the regional ocean model (RIAMOM) applied to Japan Sea by Kyushu University. However, in this report, we described results of global warming projections (IPCC runs) with special emphasis on stabilization effects of GHG concentrations.

2. Climate model

We used the optimized codes of CCSM3 for projections. 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 (Collins et al. [7]). The atmosphere component, CAM, is based on the Eulerian spectral dynamical core at T31, T42 and T85 resolution with 26 vertical layers. The ocean component, POP, supports nominal 1 degree and 3 degree horizontal resolution with 40 vertical layers with the displaced computational north pole on Greenland. 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 model components such as atmosphere, land, sea ice and ocean. In the present study, we employ the moderate

resolution model with the atmosphere component based upon the spectral dynamical core at T85 resolution and the nominal 1 degree ocean component.

3. Experimental design

As shown in Fig.1, several kinds of stabilization scenarios were applied for projections based on A1B and B1 scenarios in the IPCC SRES (2001) [8], which deal with a term up to the year 2100. Both scenarios assume a high economic growth (3% and 2.5%, respectively) and A1B shows the world with reduction in regional difference in per capita income among nations, while B1 shows the world with emphasis on sustainability of environment. As for primary energy supply system in the world, A1B features significant shift to renewable energy sources, while B1 features drastic shift to nuclear power generation particularly in Asian countries.

As discussed in the IPCC Synthesis Report (2001) [9], long-term climate responses have to be investigated to estimate effects of stabilization of GHG concentrations in the atmosphere. For this purpose, the SRES A1B and B1 scenario are extended beyond year 2100 till year 2350 to 2450 (one ensemble member, discussed later) with constant concentrations at the year 2100 concentration levels of the "nominal" 750 ppm and "nominal" 550 ppm, respectively. The term of "nominal" means the nominal level of CO_2 concentration but with the combined anthropogenic climate forcing of GHGs, such as CH_4, N_2O, CFCs, tropospheric and stratospheric ozone, and sulfate and carbon aerosols. These two stabilization scenarios are referred as the A1B stabilization and B1 stabilization scenarios, respectively. A commitment scenario is a kind of stabilization scenario requested by the IPCC Working Group 1, where the GHG concentrations are held fixed to the contemporary (year 2000) level after year 2000 until year 2050. The purpose of this scenario is to demonstrate how humans have already committed to the global warming in the future.

In addition to above scenarios, CRIEPI proposed an overshoot scenario with linearly decreased GHG concentrations

from stabilized A1B level at "nominal" 750 ppm of CO_2 concentration to stabilized B1 level at "nominal "550 ppm during 2150-2250 and with subsequent stabilization at "nominal" 550 ppm up to 2350-2450 (one ensemble). This scenario is to be used to investigate hysteresis or irreversible effects in the climate system against different pathways of stabilization of GHG concentrations.

Moreover, we newly adopted an ensemble projection method with three members, where each member adopted different initial condition and ensemble mean of projections of all members were taken to obtain statistically reliable results.

4. Results

Validation of the model compared with observed data

Fig. 2(a)(b) show ensemble means of simulated surface air temperatures and precipitations for the period from year 1990 till year 1999 averaged over 43 regions in the world, respectively. The observed data are also plotted for comparison. The simulated surface temperatures agree very well with the observations. 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.

Surface air temperature

Fig. 3 shows projection results 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 projected 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 concentrations beyond year 2100 both in the A1B and B1 scenarios. In the committed climate change experiment, the surface air temperature rises by
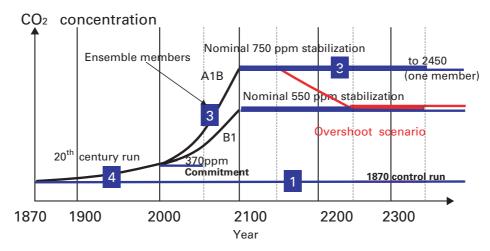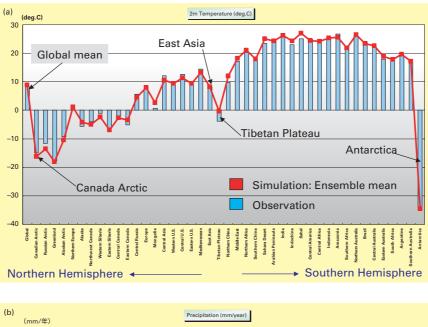
Fig. 1 A schematic of scenarios based on IPCC SRES used for global warming projections.
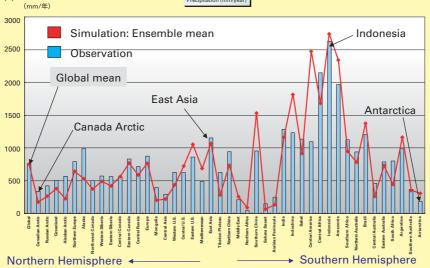
Fig. 2 Ensemble means of (a) surface air temperature and (b) precipitation at the end of 20th century (years 1990-1999) averaged over 43 regions in the world. Model results are compared to climatological observed data.
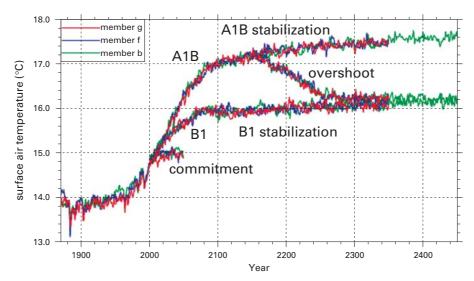

Fig. 3 Time-series of globally averaged annual mean surface air temperature from all the ensemble projections (20th century historical simulation, SRES A1B, B1, A1B stabilization, B1 stabilization, committed climate change, and overshoot scenario experiments).

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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.

Fig. 4 shows the spatial patterns of future change in surface air temperature under the A1B scenario (the upper panel) and B1 scenario (the lower panel). The future change is defined as a deviation of temperatures averaged over years 2090-2099 from that averaged over years 1990-1999. The warming is significant especially over high-latitude regions in the northern hemisphere. 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 Fig. 4 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 near Greenland.

Sea ice volume

Fig. 5 shows the projected annual mean sea ice volume in the Arctic region. Under the A1B scenario, the sea ice volume at the end of the 21st century is reduced by about 80% compared to the end of 20th century. In 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 keeps 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.

Thermohaline circulation

The thermohaline circulation has an important role of transporting the heat into high latitudes in the northern hemisphere. Fig. 6 shows time-series of maximum stream function of the meridional overturning circulation (MOC) 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 by

A1B 2090-2099 minus 1990-1999   Min, Max, Avg = 0.1, 12.9, 2.5

B1 2090-2099 minus 1990-1999   Min, Max, Avg = -0.4, 8.7, 1.5

(units: °C)

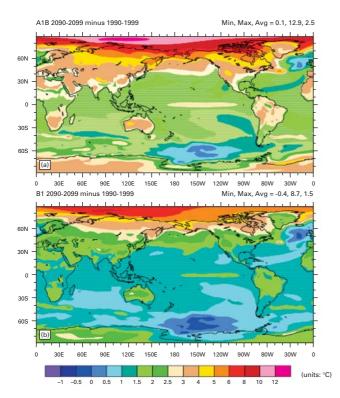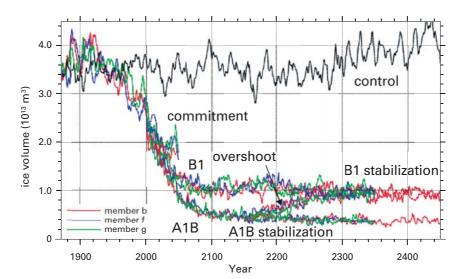−1 −0.5 0 0.5 1 1.5 2 2.5 3 4 5 6 8 10 12

Fig. 4 Spatial distributions of change in annual mean surface air temperatures during the 21st century under the A1B (the upper panel) and B1 (the lower panel) scenarios.

Fig. 5 Time series of the projected annual mean sea ice volume in the Arctic region.

Stocker and Schmittner [10] cannot be seen in our projections. Even with the weakened MOC, the warming is still dominant over Europe as shown in Fig. 4 and only less warming or slight cooling areas can be seen 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.

Sea level rise

The causes of sea level rise due to global warming are very complicated and are attributed to the thermal expansion of seawater, melting of ice sheet and glaciers over Greenland and Antarctica and so on. However, Fig. 7 shows the sea level change averaged over the world oceans due to only the thermal expansion of seawater. 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 transported in the deep ocean before year 2250 contributes to the thermal expansion and might be one of the hysteresis effects revealed in our projection results.
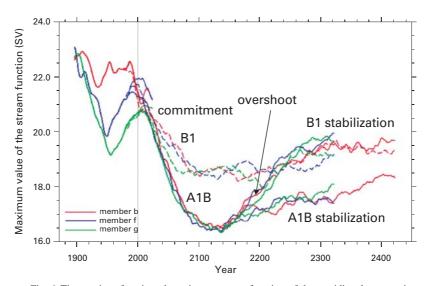
Acknowledgement

Fig. 6 Time series of projected maximum stream function of the meridional overturning circulation in the North Atlantic (30°N to 50°N , below 500 m).
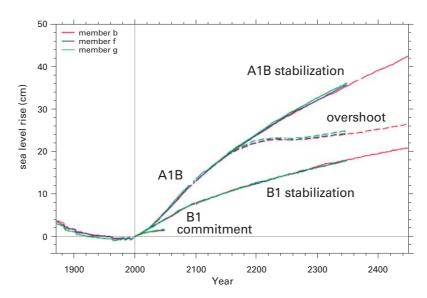

Fig. 7 Sea revel rise due to only thermal expansion of seawater is projected to increase by 8 cm (B1 scenario) and 13 cm (A1B scenario) at the end of 21st century relative to 2000.

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地球シミュレータを活用したCCSM3による
超長期アンサンブル温暖化予測

プロジェクト責任者

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1. 概要

　「国連条約(UNFCCC)」の究極の目標は、「気候システムに対して"危険な人為的干渉"を及ぼさないよう、大気中の温室効果ガス濃度を安定化(一定)すること」である。しかし、「大気中の温室効果ガスをどの程度の濃度レベル(ppm)で、また何時ころ安定化するべきか？」「"危険な人為的干渉"とは何か？」といった点についての科学的知見は不十分である。電力中央研究所では、濃度安定化による温暖化抑制効果についての科学的知見を得るため、平成14年度から文部科学省の「人・自然・地球共生プロジェクト」に参加し、九州大学、NCAR、ロスアラモス国立研究所(LANL)と協力し、世界最高速クラスの地球シミュレータを用いて、温暖化研究を実施している。本プロジェクトの3年目として、2004年8月末には、IPCCの要請による濃度安定化効果の予測計算を無事完了した。

　この予測計算では、将来シナリオとして、IPCCの特別報告書(SRES)の2種類のシナリオA1B、B1(2000年〜2100年)、2100年時点の温室効果ガス濃度を一定にしたA1B+名目750 ppm濃度安定化、B1＋名目550 ppm濃度安定化の2種類のシナリオ(2100年〜2450年)、さらに電中研独自のOvershootシナリオ(2150年〜2450年)を採用した。予測には、NCARのCCSM3をベースとして、地球シミュレータ上で最適化した計算コード(解像度は大気モデルが約150 km、海洋モデルが約100 km)を使用し、新たに3メンバーによるアンサンブル予測を採用した。この方法では、約6000年分の膨大な温暖化予測を行う必要があるが、超高速の地球シミュレータを活用することによって、極めて短期間(200年4月〜8月までの約4ヶ月弱)のうちに、全ての計算を無事完了した。

2. 予測結果

　100年後(21世紀末と20世紀末との10年間のアンサンブル平均の差)、A1Bシナリオでは全球の地上気温は約2.5℃上昇、全球降水量は6.0％増加し、2100年に温室効果ガス濃度を安定化しても気温は徐々に増加し、平衡状態には数百年程度の時間がかかることが分かった。B1シナリオでは、約1.5℃上昇、降水量は約3.9％増加と予測され、濃度安定化後、気温は比較的早く平衡に至ることが分かった。A1Bシナリオでは、北極海の海氷体積は約80％も減少し、濃度安定化後でも僅かに減りつづける可能性がある。B1シナリオでは、減少量は約65％であり、濃度安定化後、比較的早く平衡に至る。海洋の深層海流(熱塩循環)はいずれのシナリオについても弱まるが、寒冷化等の急激な気候変化は生じないことが分かった。また、海面上昇の原因となる海水の温度上昇は、濃度を安定化しても長期間継続し、海水の熱膨張による海面上昇は数百年以上もの長期間継続する可能性がある。オーバーシュートシナリオでは、気温、海氷体積、熱塩循環等は550 ppm濃度安定化レベルに復元する可能性が高いが、海氷の厚さや永久凍土のように復元しない現象もあることが分かった。

　今回の結果から、世界エネルギー政策に対して、「A1Bシナリオ+名目750 ppm濃度安定化シナリオでは、気候安定化に数百年程度の長い時間がかかり、その間に海氷の消滅などの"危険な人為的干渉"を引き起こす可能性があるため、温暖化防止の濃度目標としては高すぎる可能性がある」ことが示唆された。

キーワード：地球温暖化，IPCC SRES シナリオ，濃度安定化シナリオとオーバーシュートシナリオ，長期気候応答，
　　　　　アンサンブル予測