Global Warming Projections based on Greenhouse Gases Stabilization and Overshoot Scenarios using Community Climate System Model (CCSM3)

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This paper describes an overview of results obtained in the 5-year research on global warming projections done by Central Research Institute of Electric Power Industry jointly with National Center for Atmospheric Research. To contribute to the IPCC Fourth Assessment Report, multi-century global warming projections based on the IPCC SRES scenarios were conducted using the Earth Simulator. One of the features of our experiments is multi-century long-term projections under the stabilized radiative forcings of greenhouse gases. In addition, simple overshoot scenarios are proposed and hysteresis effects in climate system were investigated.

Keywords: global warming projection, SRES scenario, GHGs stabilization, overshoot scenarios

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 atmosphere at a level that would prevent dangerous anthropogenic interference with climate system. However, there exist a number of crucial questions about this goal. For example, what is the dangerous anthropogenic interference. What a level of GHG concentrations should be appropriate to prevent the dangerous anthropogenic interference. Such questions have to be resolved in discussion and negotiation on the next international framework (post-Kyoto framework) for the GHGs emission reduction and state-of-the-art scientific knowledge has to support such discussions.

To contribute to the IPCC Fourth Assessment Report, AR4 (2007), and the discussion on the post-Kyoto framework, with a special attention to scientific knowledge about the dangerous anthropogenic interference, we conducted a series of global warming projection experiments jointly with National Center for Atmospheric Research (NCAR) under the Project for Sustainable Coexistence of Human, Nature and the Earth of the Japanese Ministry of Education, Culture, Sports, Science and Technology. This paper describes an overview of this 5-year research project.

2. Model

The Community Climate System Model, CCSM3, is used to simulate past and future climate under prescribed radiative forcings. The CCSM3 is the third generation coupled climate model developed by NCAR and it consists of atmosphere, land, sea ice and ocean components and flux coupler. 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, is based on a displaced grid system where the computational north pole is displaced onto 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 at T85 resolution and the nominal 1 degree ocean component. The equilibrium climate sensitivity of this resolution of CCSM3 is 2.7˚C and the transient climate response is 1.5˚C [1]. A comprehensive overview of the CCSM3 is given by Collins et al. [2] as well as the model performance obtained in its control simulations.

3. GHG concentration scenarios

Future global warming projection experiments in the present study employ GHGs concentration profiles based on IPCC SRES (Special Report on Emission Scenarios) A2, A1B and B1 scenarios [3]. The socioeconomic backgrounds of these scenarios are as follows: The SRES A2 scenario (high-emission scenario) assumes high population growth rate and significant shift to coal at year 2100. The A1B scenario (medium-emission scenario) assumes higher economic growth and measurable introduction of renewable energies. The B1 scenario also assumes high economic growth but with substantial shift to nuclear energy.

Time-varying radiative forcings included in the numerical experiments are CO_2, CH_4, N_2O, CFC-11, CFC-12, tropospheric and stratospheric ozone, carbon and sulfate aerosols. In addition, aerosols due to volcanic eruptions and solar variability are taken into account in the 20th century historical simulation. Figure 1 shows the CO_2-equivalent concentration of GHGs (CO_2, CH_4, N_2O, CFC-11 and CFC-12) for each SRES scenario used in the numerical experiments. At the year 2100, the CO_2-equivalent concentration reaches 1235, 860, 638 ppmv under the A2, A1B and B1 scenarios, respectively.

The 20th century historical simulation and 21st century projections based on the SRES scenarios are followed by the GHGs stabilization experiments. Under the coordination by IPCC Working Group I, the stabilization experiments were carried out in such a way that the 21st century projections based on the SRES scenarios are extended beyond year 2100 with constant GHGs concentration at year 2100 levels. As discussed in the IPCC Synthesis Report [4], long-term climate responses have to be investigated for discussion about the stabilization effect of GHGs. For this purpose, we conducted multi-century stabilization experiments up till year 2450.

In addition to the GHGs stabilization experiments, simple overshoot scenario experiments are proposed. Under the overshoot scenarios, the GHG concentrations once overshoot to higher levels, 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 made clear. 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 overshoot to the A2 and A1B levels, then, linearly decrease to the B1 stabilization level from year 2150 with 100-year or 200-year GHGs decline phase as shown in Fig. 1.

4. Results

4.1 Surface air temperature

Figure 2 shows the time-series of globally averaged annual mean surface air temperatures from all the experiments. Compared to the temperature at the end of 20th century (years 1990–1999), the surface air temperatures at the end of 21st century (years 2090–2099) is predicted to increase by 3.7, 2.5 and 1.5˚C under the A2, A1B and B1 scenarios, respectively. Furthermore, the surface air temperature keeps increasing even under the stabilized radiative forcings beyond year 2100 at all the GHGs stabilization levels. Under the overshoot scenarios, the globally averaged surface air temperatures decreases to almost the same level as the B1 level and hysteresis effects are not significant.

The spatial patterns of future change in surface temperature under the A2 and A1B scenarios are shown in Fig. 3. The future change is defined as a deviation of temperature averaged over years 2090–2099 from that averaged over years 1990–1999. The warming is significant particularly in northern hemisphere high-latitude regions and over continents. Although the magnitude of temperature change is dependent on GHGs concentration levels, the spatial pattern of possible future change is very similar among all the SRES scenario experiments.

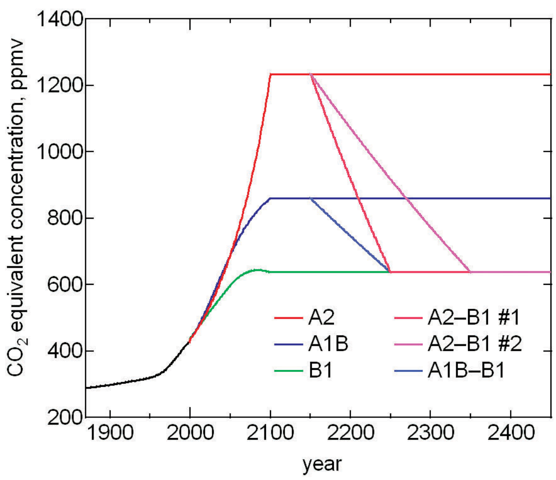

Fig. 1 GHGs concentration profiles used in numerical experiments.

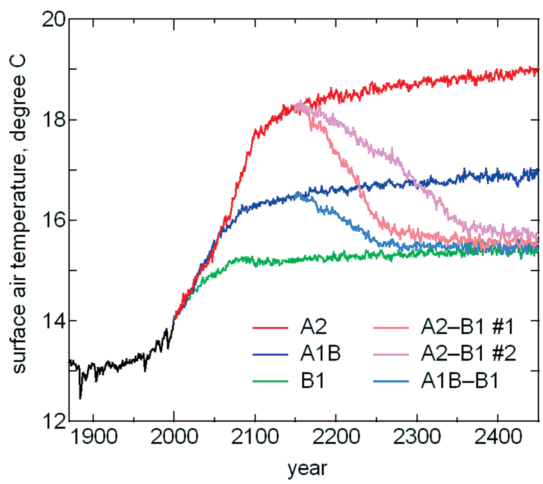

Fig. 2 Time-series of globally averaged annual mean surface air temperature.

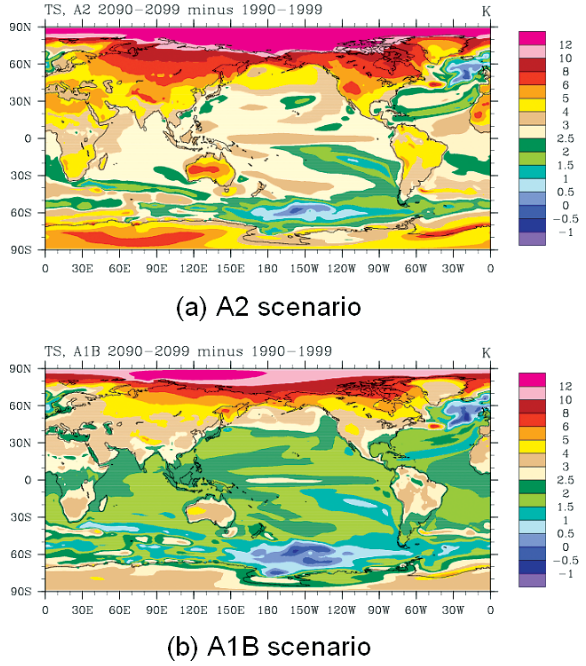

Fig. 3 Spatial pattern of surface temperature change during 21st century.

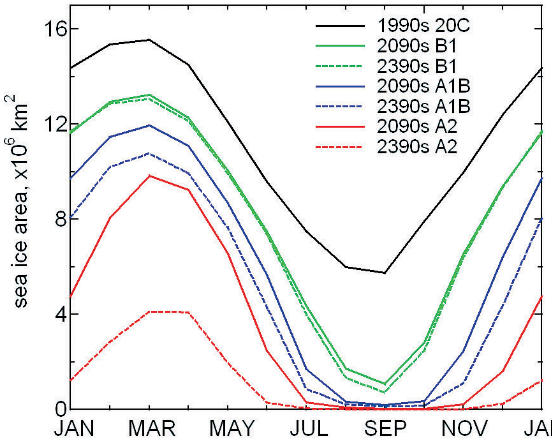

Fig. 4 Seasonal cycle of sea ice area in northern hemisphere.

4.2 Sea ice

Figure 4 shows the projected seasonal cycle of sea ice area in northern hemisphere at the end of 21st century (years 2090–2099) and at the end of 24th century (years 2390–2399) and Fig. 5 shows spatial distribution of sea ice concentration in the Arctic region under the SRES A2 scenario. In the cases of the A2 and A1B scenarios, the sea ice in the Arctic region almost disappears in late summer. Furthermore, at the highest GHGs concentration level of the A2 scenario, substantial reduction of sea ice in winter is also projected. These model results suggest that the ecosystem in the Arctic region should be subjected to severe global warming impacts, thus, the GHGs concentration levels in the A1B and A2 scenarios could be higher than a target level which satisfies the goal of UNFCCC.

4.3 Sea level

Figure 6 shows globally averaged time-series of sea level rise due to thermal expansion of seawater projected under SRES scenarios. In general, the change in sea level is attributed to the thermal expansion of seawater, melting of ice cap and glaciers on lands, and melting of ice sheets on Greenland and Antarctica. Among them, only the thermal expansion is taken into account to evaluate future change in sea level in

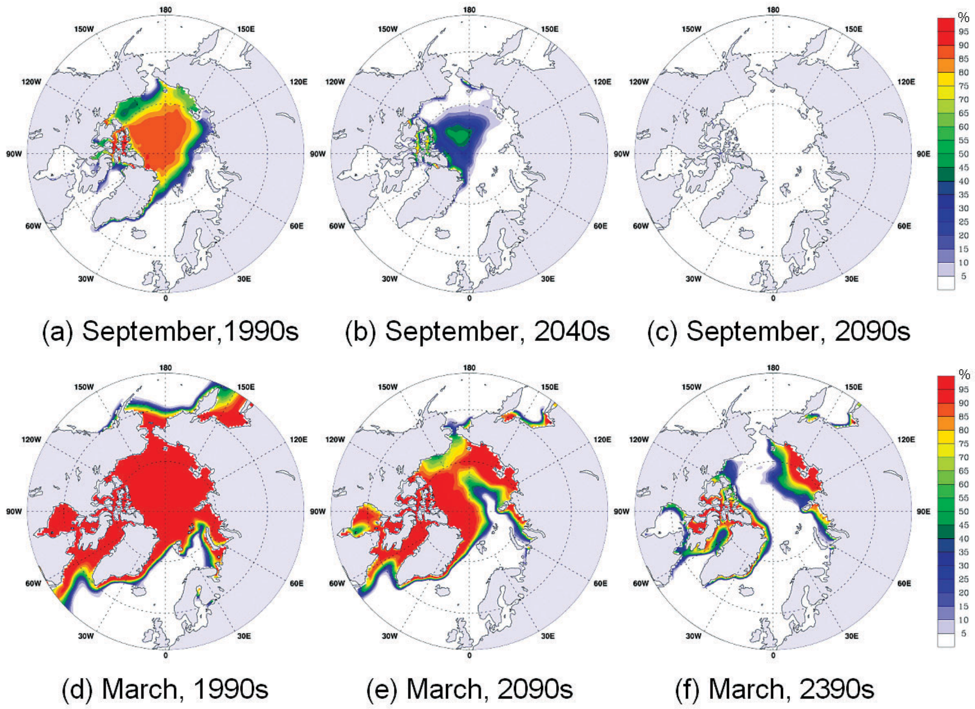

Fig. 5 Sea ice concentration in northern hemisphere under A2 scenario.

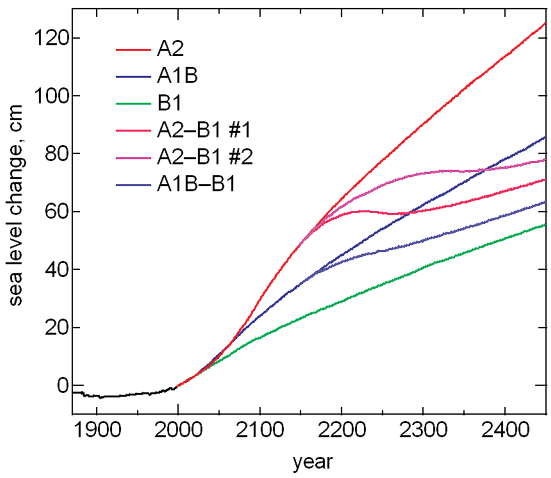

Fig. 6 Time-series of sea level rise due to thermal expansion of sea water.

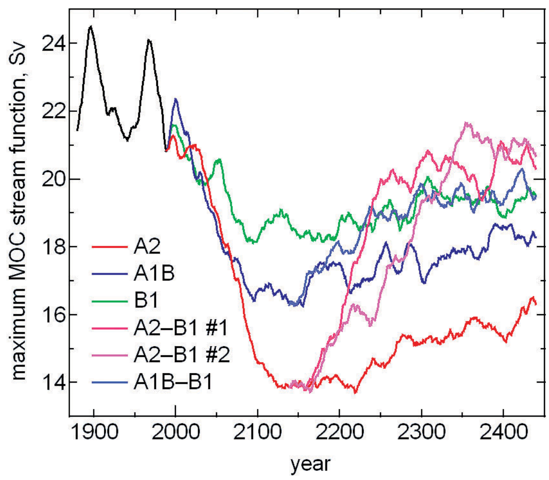

Fig. 7 Time-series of maximum stream function of Meridional Overturning Circulation (MOC) in North Atlantic (21-year running mean, below 500m) obtained in the SRES scenario experiments.

this study. Here, the sea level change due to thermal expansion is calculated offline. Then, the linear trend observed in the control run is eliminated to avoid model errors.

At the end of 21st century, the globally averaged sea level increases by 30, 24 and 16.5 cm relative to year 2000, respectively, under the A2, A1B and B1 scenarios. Even after the stabilization of GHGs starting from year 2100, the sea level is found to keep increasing for long time due to large thermal inertia of seawater. Note that the sea level under the overshoot scenarios does not recover to that at the B1 stabilization level. This is because the heat stored in interior ocean before year 2250 contributes to the residual thermal expansion and this is one of the hysteresis effects found in our simulation results.

4.4 Thermohaline circulation

Figure 7 shows time-series of maximum stream function of the Meridional Overturning Circulation (MOC) in the North Atlantic. 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 35, 25 and 15%, respectively, under the A2, A1B and B1 scenarios. However, the MOC tends to recover gradually once the GHG concentrations are stabilized. Under the overshoot scenarios, the MOC immediately recovers to the level of the B1 stabilization scenario. The shutdown of MOC predicted by Stocker and Schmittner [5] cannot be seen in our simulations. Even with the weakened MOC, the warming is still dominant over Europe as shown in Fig. 3 and only less warming or slight cooling areas can be seen near Greenland and around Antarctica.

Additional CMIP2-type numerical experiments were carried out to learn more about simulated MOC behavior and to make directly comparison with the Stocker-Schmittner hypothesis. In these experiments, the CO_2 concentration increases from present-day level at constant increase rates of 1, 2 and 4

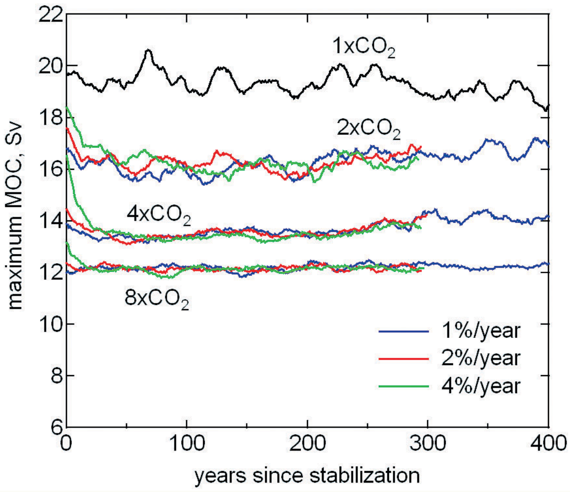

Fig. 8 Time-series of maximum stream function of MOC in North Atlantic (21-year running mean, below 500m) obtained in the increasing CO_2 experiments.

%/year, then, CO_2 concentration is stabilized at doubled, quadrupled and octupled levels. Figure 8 shows time series of the maximum stream function of MOC at CO_2 stabilization phase. Even under the octupled CO_2 level, simulated MOC slightly recovers to the present-day level. As far as the CCSM3 model projected, the shutdown of MOC and resulting abrupt cooling event such as glacial age is very unlikely to occur. However, note that the model does not take into account the fresh water supply due to melting of Greenland ice sheet.

5. Summary

The multi-century global warming projection experiments based on SRES A2, A1B and B1 scenarios were conducted using the CCSM3. The obtained results are summarized as follows:

(1) Globally averaged surface air temperature increase during 21st century under the A2, A1B and B1 scenarios are

respectively 3.7, 2.5 and 1.5˚C. The surface temperature keeps increasing even after the GHGs concentrations are stabilized, and it takes very long time for climate system to be stabilized.

(2) The reduction of sea ice in the Arctic region is significant under the stabilized radiative forcing at the A2 and A1B levels. The sea ice in late summer almost disappears in mid-21st century under the A2 and A1B scenarios, and the substantial reduction of winter sea ice is projected under the A2 scenario.

(3) The thermohaline circulation in North Atlantic, MOC, is weakened in response to the increasing GHGs during 21st century. However, it tends to recover under the stabilized GHGs concentrations and the shutdown of MOC is unlikely to occur.

(4) 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. Feedbacks from ecosystem and carbon cycle should also be taken into account for this purpose.

Acknowledgement

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大気海洋結合モデルの高解像度化

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平成18年度にはSRES A2シナリオ（高排出シナリオ）に基づく温暖化予測、高解像度大気モデル（WACCM）を用いた太陽活動の11年周期変動に関する検討、高解像度海洋モデルおよび海氷モデルの開発・改良と結合モデルの開発、超高解像度領域海洋モデルを用いた日本海における温暖化影響の検討などを実施した。主な成果は以下の通りである。

①平成17年度に引き続き、世界経済が停滞し途上国の化石燃料消費が増加するSRES A2シナリオ（2100年時点の等価CO_2濃度は1235ppm）に基づいた濃度安定化実験およびオーバーシュートシナリオ実験を行った。A2シナリオの高濃度レベルであっても、北大西洋の熱塩循環は停止せず、温暖化が生じ、寒冷化は見られなかった。一方、A2シナリオでは、北極海における海氷の減少は温室効果ガス濃度安定化後も顕著であり、さらに、グリーンランド周辺の気温の上昇量は21世紀末で5˚C（20世紀末との差）を超え、既往研究が指摘するグリーンランド氷床融解の閾値を超えると予想される。

②太陽活動と温暖化の関係を検討するため、高解像度大気モデル（WACCM）を用いた数値実験を行い、太陽活動の11年周期変動は、平均的な気候にはほとんど影響しないが、北半球中・高緯度の冬から春にかけて、季節進行や低気圧活動の変化に影響する可能性が示された。

③北海道北部の流氷変化等による地域スケールの気候変化の精度向上を目指し、空間解像度1/10度の海洋モデルと海氷モデルを結合し、現状再現実験を実施した。その結果、黒潮流路、オホーツク海の海氷の北海道への接岸時期等の季節変化がより現実的に改善された。さらに、これに解像度T85の大気モデルを結合し、結合モデルの性能評価を行い、高精度地域気候予測に有効であることを確認した。

④日本海への温暖化影響の検討の一環として、20世紀半ばまでの日本海の循環の再現を行い、底層水の形成に関わる鉛直対流は地中海型の外洋対流ではなく、ウラジオストク沿岸域の海氷生成に関わる鉛直対流であることがわかった。また、黒潮の数分の1の流量を持つ巨大な海流である日本海の深層海流を現実的に再現するのに成功した。

キーワード：温暖化予測, SRES A2シナリオ, WACCMモデル, 渦解像海洋モデル, 海氷モデル