Development of High-Resolution Atmosphere-Ocean Coupled Model and Global Warming Projections

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New experiments of global warming projection were carried out based on the SRES A2 stabilization and overshoot scenarios using the CCSM3 coupled climate model. The projection results suggest that the shutdown of thermohaline circulation is unlikely to occur even at high greenhouse gases concentration level at year 2100 from the A2 scenario. However, the ocean environment in arctic region was projected to be dramatically changed. With regard to the development of high-resolution coupled climate model, the Whole Atmosphere Community Climate Model and the high-resolution sea ice model were introduced in FY2005. Furthermore, high-resolution regional ocean models are applied to know the global warming effects on the regional ocean surrounding Japan, such as the Sea of Japan.

Keywords: global warming projections, SRES A2 scenario, WACCM model, eddy-resolving ocean model, high-resolution sea ice model.

1. Introduction

This research project consists of two goals: One is to conduct global warming projection experiments using medium-resolution coupled climate model and the other is to develop high-resolution coupled climate model. For the first goal, we conducted global warming projections based on the SRES A1B and B1 scenarios in FY2004 [1]. In this fiscal year, we have conducted new experiments based on the SRES A2 scenario that has higher green house gas (GHG) concentration levels than the A1B and B1 scenarios. This is to contribute to the discussion about the emission reduction of GHGs and appropriate target for GHG stabilization.

For the second goal, we have newly introduced the Whole Atmosphere Community Climate Model (WACCM) as an atmosphere component of our high-resolution coupled climate model. In addition, we have started development of the high-resolution sea ice model which has the spatial resolution of about 1/10 degree. Furthermore, very high-resolution regional ocean models are being developed and applied to estimate global warming impacts, especially, on the Sea of Japan.

2. Global warming projection based on SRES A2 stabilization and overshoot scenarios

Global warming projection experiments based on the SRES A2 stabilization and overshoot scenarios were carried out to obtain scientific knowledge needed for the discussion on target levels for the GHG stabilization. In the experiments, we used the medium-resolution CCSM3 [2] which consists of T85 atmosphere model and one degree ocean model. Fig. 1 illustrates the atmospheric CO_2 concentration employed in the experiments: the GHG concentrations are held fixed at the level of year 2100 in the stabilization experiment. The overshoot experiment consists of two phases: the first one is linear

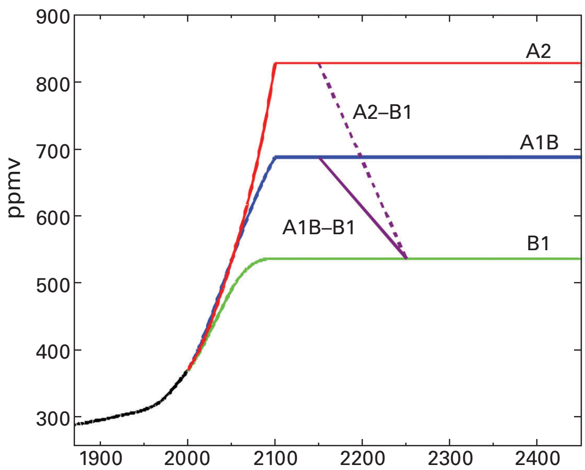

Fig. 1 Atmospheric CO_2 concentration employed in global warming projection experiments. "A2-B1" and "A1B-B1" denote overshoot profile from A2 to B1 and from A1B to B1, respectively.

decline phase from year 2150 till 2250, where GHG concentrations decrease from the A2 level to the B1 level, which is followed by the stabilization phase where GHG concentrations are constant at the B1 level. The initial conditions at year 2100 are taken from SRES A2 scenario experiment conducted by National Center for Atmospheric Research [3].

Time series of globally averaged annual mean surface air temperature is shown in Fig. 2. The temperature increase throughout 21st century under the A2 scenario is 3.7 degree C, while temperature increases under the A1B and B1 scenarios are respectively 2.5 and 1.5 degree C. One of the features in the A2 stabilization result is higher temperature rise through the stabilization phase. The temperature rise during 22nd and 23rd centuries under the A2 stabilization scenario is about 1.2 degree C, while the increases under the A1B and B1 scenarios are respectively 0.5 and 0.1 degree C. With regard to the A2 overshoot experiment, there can be seen no significant hysteresis effect in the globally averaged temperature. It almost recovers to the B1 level in 25th century.

Figure 3 shows time series of maximum stream function of meridional overturning circulation (MOC) in the North Atlantic. The MOC stream function decreases to about 14 Sv in the mid 22nd century. However, it gradually recovers in the rest of the experiment under the stabilized GHG condition. Furthermore, the MOC in the A2 overshoot experiments recovers very rapidly and it reaches the B1 level in the mid 23rd century. These results imply that the reduction of MOC under the A2 scenario could not lead to dangerous anthropogenic interferences, such as the shutdown of MOC.

Figures 4 shows time series of annual mean sea ice area in the northern hemisphere. The sea ice decreases gradually in the A2 stabilization experiments and this is similar to the A1B and B1 stabilization experiments. Hysteresis effect in the A2 overshoot scenario experiment is not significant and the sea ice area almost recovers to the B1 level. The seasonal cycle of arctic sea ice area is shown in Fig. 5. The reduction of sea ice area in summer season is dramatically. The disappearance of arctic sea ice continues for almost 6 months of a year at the end of 23rd century under the stabilized GHGs at the A2 level.

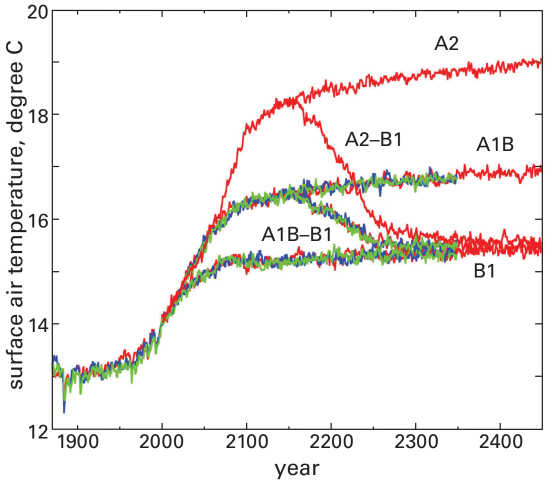

Fig. 2 Time series of globally averaged annual mean surface air temperature.

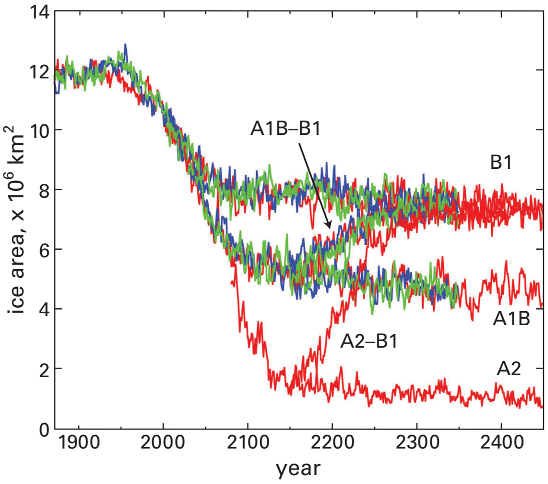

Fig. 4 Time series of annual mean sea ice area in northern hemisphere.

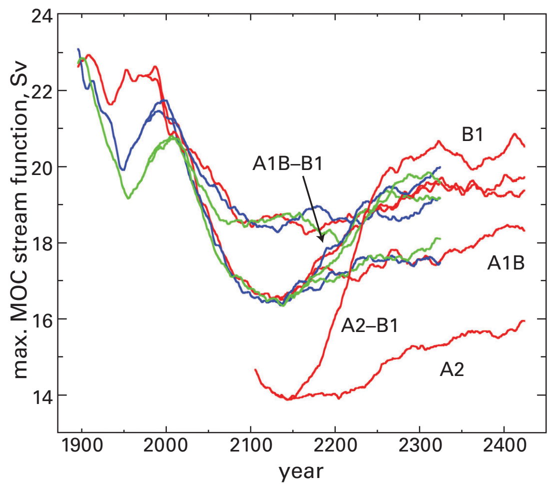

Fig. 3 Time series of maximum stream function of meridional overturning circulation in North Atlantic (51-year running mean, below 500 m).

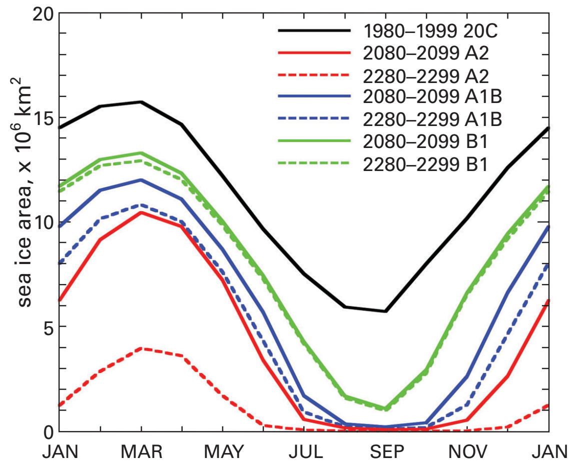

Fig. 5 Seasonal cycle of sea ice area in northern hemisphere at the end of 20th, 21st and 23rd centuries.

3. Development of high-resolution atmosphere model

The atmosphere component of the high-resolution atmosphere-ocean coupled model we are developing as a final product is based on the WACCM (http://waccm.acd.ucar.edu/waccm.html). The WACCM is an interactive dynamical and chemical general circulation model (GCM) extending from the surface to the lower thermosphere near 150 km. The vertical resolution is enhanced so that it has 66 vertical levels with intervals of approximately one-half of the local scale height above 65 km, 1.75 km near the stratopause, and 1.25 km in the lower stratosphere and troposphere. The WACCM is based on the software framework of the Community Atmosphere Model version 3 (CAM3). The dynamical and transport equations are solved using the explicit flux-form semi-Lagrangian scheme of Lin and Rood [4]. This numerical method calculates explicitly fluxes in and out of a given model volume, thus ensuring mass conservation. The chemistry module is derived from the three-dimensional chemical transport model for ozone and related chemical tracers [5]. The WACCM is being used for studies of the structure and composition of the atmosphere and its potential changes over the next 100 years.

In addition to the development of the high-resolution coupled model, we apply the WACCM as a stand-alone model to climate change studies featuring its facility. In this project, we focus on atmospheric impacts of 11-year solar variability. The purpose of this solar cycle study is to identify any physical mechanisms whereby solar variability affects the state of the atmosphere. Currently, many fundamental questions regarding the impact of solar variability on the atmosphere remain unresolved. Successful attribution of changes due to solar variability is necessary to better isolate changes that may be brought about by human activities, such as the increase in the concentration of greenhouse gases.

In FY2005, we installed the latest (version 3) model on the Earth Simulator with appropriate code optimization and conducted short-term runs to adjust physical processes mainly for the scheme of the gravity wave drag. Gravity waves grow in amplitude as they propagate upward and break at critical levels, leading to turbulence and dissipation. This scheme plays an important role to produce realistic zonal-mean flow and thermal structure at higher atmospheric levels. Figure 6 illustrates zonal-mean zonal winds of model climatologies in January and July with comparison to observed data. The spatial distributions, such as an easterly (westerly) jet in the summer (winter) hemisphere and local minima near 90 km,

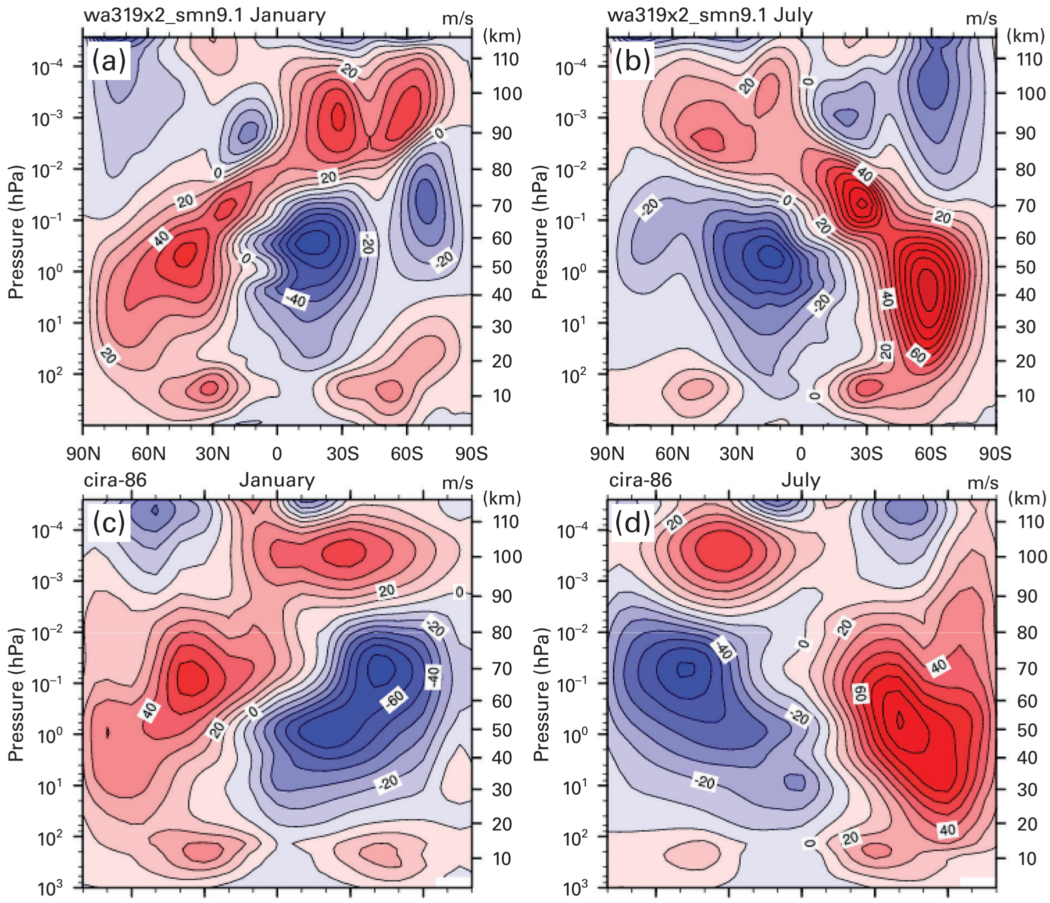

Fig. 6 Zonal-mean zonal winds in January and July from 5-year averaged results from the control run below 120 km (a and b), and observed data by COSPAR International Reference Atmosphere 1986 (c and d). Contours are drawn by 10 m/s interval.

are reasonably simulated by the model. Also, it is confirmed that simulated troposphere climate is mostly equivalent to that simulated by its base model, CAM3.

Then, we conducted a long-term (~100-year) run to investigate the influence of solar variability on climate. Wavelength-resolved solar irradiance is specified as a function of observed solar radio flux at 10.7 cm (F10.7). We also conducted a 40-year run with fixed solar minimum conditions to consider the model's internal variability. All boundary conditions not related to the solar cycle are held constant or climatological annual cycles. Results from these experiments show some impacts of the solar cycle on monthly temperatures and zonal winds. In general, correlations between the temperatures and F10.7 are statistically significant in most latitudes over 80 km and in latitudes of high insolation near the maximum of ozone heating. In addition to these general responses, some significant correlations are seen in specific locations and months. We will further investigate these responses focusing on indirect impacts of the solar cycle on the lower stratosphere and the troposphere.

4. Development of a high resolution ocean - sea ice coupled model

Mixing process of a meso-scale eddy plays an important role in the ocean heat transport by a western boundary current, and the air-sea gas exchange following surface water mass subduction at high latitude. In FY2005, the test on coupling of the high resolution ocean model and sea ice model was carried out using the flux coupler.

Figure 7 shows the schematic diagram of the high resolution ocean model - sea ice model coupling procedure. The study on the high resolution sea ice model has been limited as against many researches of ocean models. The performance of the high resolution sea ice model (CICE) was investigated on the same global 0.1 degree resolution grid as used in the ocean model. The sea ice is classified into five categories based on their thickness. The mixed layer ocean was applied as the oceanic boundary condition, where temperature is calculated prognostically, and the result of high resolution ocean model was used as the monthly averaged ocean current distribution. The thickness of the ocean mixed layer was assumed everywhere as 10 m, although which is unrealistic in subduction area. NCEP reanalysis data was used as the monthly atmospheric boundary conditions.

Figure 8 shows the sea ice concentration in the northern and southern hemispheres. The lower plates show the calculated result of high resolution sea ice model. The middle plates show the satellite observational data by SMMI. For the comparison, the calculated sea ice concentration by moderate resolution sea ice model (1 degree) in the couple model CCSM3 are shown in upper plates. In the 1 degree model, the ice extent area is larger in some extent, especially in Antarctic region. The calculated ice concentration distribution and sea ice extend are improved in the 0.1 degree model, compared with the 1 degree model. However, too much ice is formed near Greenland, which is attributed to unrealistic setting of the shallow mixed layer depth. The

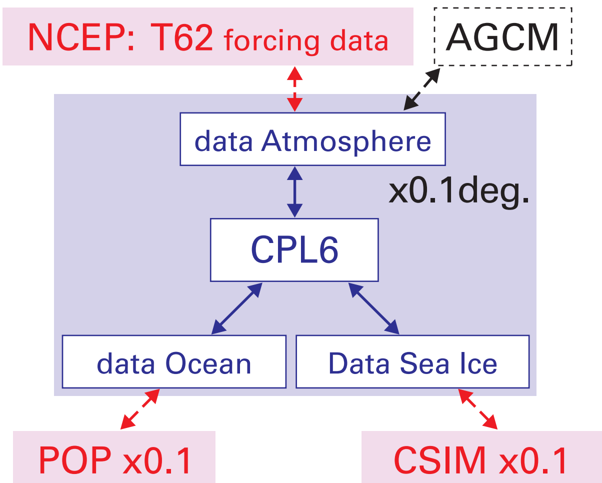

Fig. 7 Schematic diagram of high resolution ocean model (POP) and sea ice model (CSIM) coupling procedure.

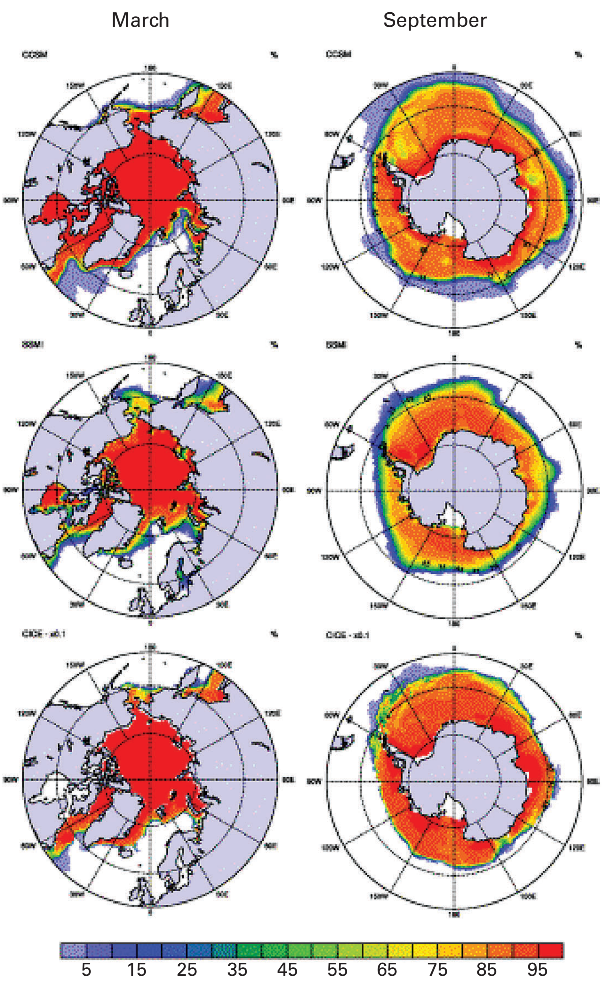

Fig. 8 Calculated sea ice concentration using 0.1 degree sea ice model (lower plates). Upper and middle plates show the calculated result by 1 degree model (CCSM3) and observational data by SMMI, respectively.

abrupt decrease of ice concentration at the edge of sea ice area seems to be caused by inconsistency between the calculated sea ice extent area and the ocean current distribution in the mixed layer ocean, which is estimated from the separately calculated 0.1 degree ocean model result.

5. Development of high-resolution regional ocean model

Our main goal is to know the global warming effects on the regional ocean surrounding Japan, such as the Japan Sea. The development of the high resolution regional model is primarily important to make reliable prediction of the future Japan Sea circulation suffering from the global warming influences.

In this fiscal year, we tried to develop the high resolution regional model, focusing on three themes, 1) the reproduction of the past Japan Sea oceanic structure, 2) the analysis of the ultra-high resolution model of the Japan Sea, 3) the application of the high resolution Japan Sea model. The model used is the RIAMOM which is a three dimensional ocean circulation model with free surface.

1) The reproduction of the past Japan Sea oceanic structure

To predict the future of the Japan Sea oceanic structure, it is necessary to simulate realistically the past oceanic structure of the Japan Sea. The simulated structure of 1940's shows many features similar to those of present structure, but much deeper open ocean winter convection than the present one as shown in Fig. 9. The fact that the winter convection in the past does not reach the bottom suggests that the bottom water formation takes place in relation to the sea ice formation in the continental shelf and break area. In fact, the T-S diagram simulated could not show the salinity maximum at the bottom.

The Greatbatch method [6] for the parameterization of eddy induced volume transport to reproduce the observed deep mean current was tested. Obtained deep mean flow was compared well with observed one.

2) The analysis of the ultra high-resolution model of the Japan Sea

The ultra high-resolution, 1/36°, enabled us to construct a new schematic surface circulation of the Japan Sea with many findings as shown in Fig.10. The first branch of the Tsushima current flowing along the Japanese coast, the development of southwestward summer coastal jet along Russian and Korean coast, and current reversal from southwest to northeast along North Korean coast generated by an anti-cyclonic wind vortex of winter monsoon south of Vladivostok, etc. are realistically reproduced.

The ultra high-resolution also highlighted the small scale energetic disturbances at the Tsushima Straits with scales of 5-10 days and 50-100 km which are observed by the ADCP measurement between Pusan and Hakata using a ferry boat "Camellia".

3) The application of the high resolution Japan Sea model

Using the Japan Sea circulation model developed through this project, various applications were carried out. The forecasting system of the Japan Sea was established in October, 2004. Short (5days) and long (2 month) range forecasts are provided through the home page (http://jes.riam.kyushu-u.ac.jp). This forecasting system enables us to predict the behavior of the Echizen Kurage (Nomura Jellyfish) in the Japan Sea as a joint

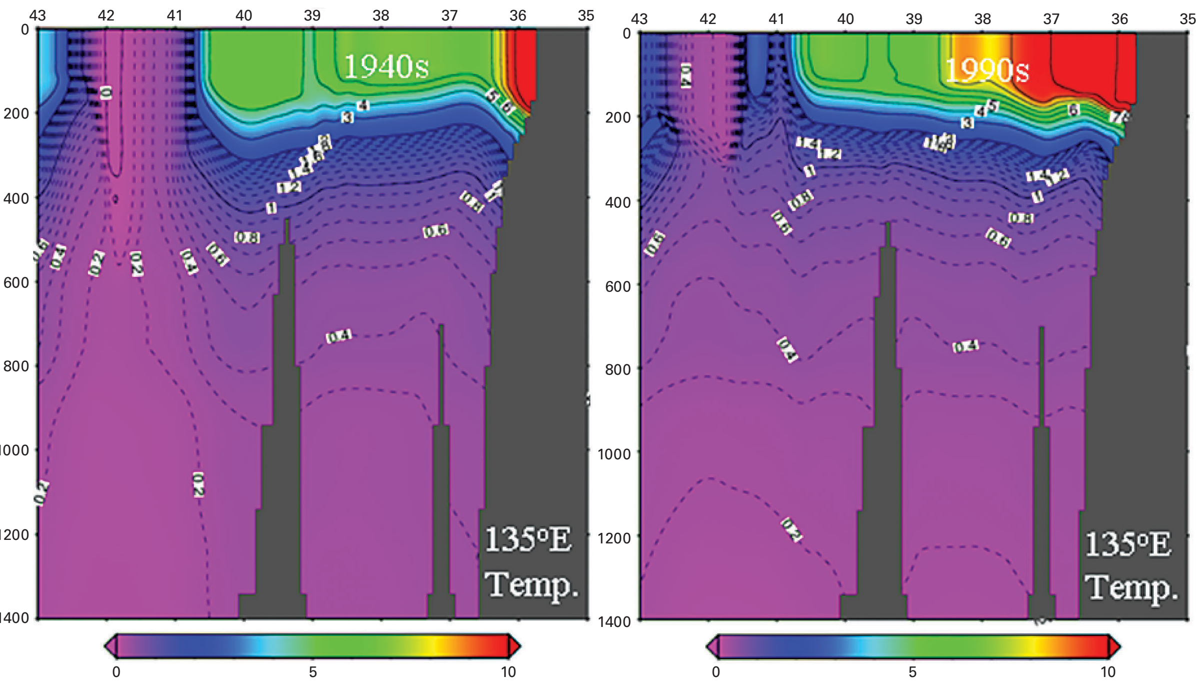

Fig. 9 Vertical sections of temperature along 135°E.
Left: 1940's, Right: present.

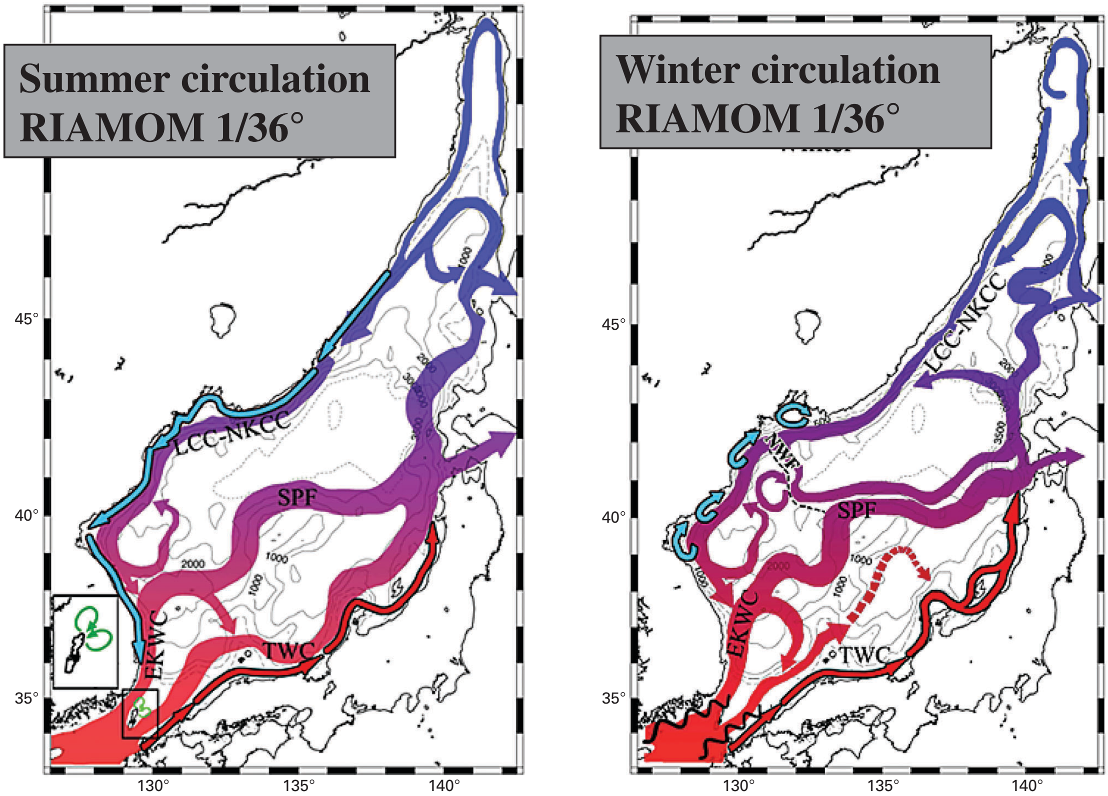

Fig.10 A schematic surface circulation of the Japan Sea.

study with the Fisheries Research Agency (FRA), the behavior of spilled oil and the Kyucho associated with typhoons, which appears frequently around Noto peninsula.

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17年度には、前年度に実施した温暖化予測実験結果の解析、温室効果ガスの高排出シナリオであるSRES A2シナリオに基づく濃度安定化およびオーバーシュートシナリオ実験、高解像度結合モデルの要素モデル開発、高解像度領域海洋モデルによる日本海の循環の検討などを実施した。主要な成果は以下の通りである。

① 平成16年度に実施したIPCC SRESシナリオおよび濃度安定化シナリオに基づく超長期温暖化予測結果に関して、再解析との比較によるモデル精度の厳密な検討を実施するとともに、温暖化時には地中海性気候の地域で降水量が減少する可能性、および、高緯度地域で永久凍土が急速に融解する可能性を指摘した。また、CO2増加により北大西洋の熱塩循環は減少するものの、濃度安定化によってその減少には歯止めがかかり、氷河期のような大規模な気候変化は生じないことが分かった。
② 気候系へ危険な人為的干渉を引き起こす閾値を検討するため、途上国の化石燃料消費増を考慮したA2シナリオとその2100年時点の濃度で安定化したシナリオ（およびovershootシナリオ）について、温暖化予測計算を行い、海氷消滅等の危険な干渉について解析を行った。
③ 不可避的な気候変化に適応するため、地域スケールの気候変化等の精度向上を目指しモデルの高度化を実施した。大気については、中層大気を拡充したモデルを開発し、太陽活動の変化が気候におよぼす影響を評価するための検討を行った。さらに、空間解像度0.1度の海氷モデルを新たに開発し、海洋モデルに結合することを目指して、テスト計算を実施した。
④ 温暖化影響評価の基準となる過去の日本海の循環を検討するとともに、日本海の高解像度海洋モデルの応用を重点的に行い、大量発生した越前クラゲの移動予測、日本海沿岸の船舶事故による油流出予測等を行い、これらのモデルが実用に役立つことを示した。

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