Development of a High-Resolution Coupled Climate Model for Global Warming Studies

Project Representative

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The purpose of this project is to further develop physical models for global warming simulations, and to investigate mechanisms of changes in global environment as a successor of a previous ES joint project. We have obtained the following results this year.

The change of the QBO in a double CO_2 climate is investigated for the first time by using a climate model that simulates the QBO by model-resolved waves only. The period, amplitude and lowermost level of the QBO in a double CO_2 climate become longer, weaker and higher than those in the present climate.

A new time integration method is introduced into COCO (ocean component of MIROC), and it is shown that the method improves the computational performance of the model significantly.

The difficulty in representing Atlantic Meridional Overturning Circulation (AMOC) in LGM simulations is widely known. The multi GCM intercomparison and several sensitivity experiments have been presented by using MIROC GCM. It is found that the model improvement of the warming bias and seaice formation in the Southern ocean are crucial for reproducing the strengthening the Antarctic Bottom Water (AABW) and shoaling and weakening of the AMOC at LGM.

An advanced scheme for sub-grid snow-cover ratio (SSNOWD) has been introduced, and the type of snowmelt at each grid is changed to be determined internally in MIROC. It revealed from the results of sensitivity experiments on the sub-grid distribution parameter that sub-grid snow-cover ratio is decreased by the vegetation effects, and that the variability of the sub-grid ratio is decreased by the topography effects. Besides, examinations on climatic impacts of the changes in volatile organic carbon induced by land-use change by changing secondary organic aerosols are being proceeded.

Optimization of an ice sheet model IcIES is examined for high-resolution (until 5 km) Greenland experiment. Further development including model parallelization will be required for much effective numerical simulation.

Keywords: Atmosphere-Ocean-Land coupled model, offline biogeochemical model, stratospheric QBO, ice-sheet model

1. Introduction

This project is a successor of one of the previous ES-joint projects named "Development of a High-resolution Coupled Atmosphere-Ocean-Land General Circulation Model for Climate System Studies." The purpose of this project is to further develop physical models for global warming simulations, and to investigate mechanisms of changes in global environment.

To achieve the purpose, we focus on the development of ice sheet model, permafrost model and sea ice model, improvement of subcomponent models for atmosphere, ocean and land-surface processes in the climate model MIROC, as well as sensitivity studies using climate models relevant to global warming and paleo-climate.

2. The Quasi-biennial oscillation in a double CO_2 climate

The Quasi-Biennial Oscillation (QBO) is most evident in the zonal-mean zonal wind near the equator which undergoes reversals from easterlies to westerlies through each QBO cycle. There is no evidence that any of the models employed in the IPCC AR4 model intercomparison simulated the QBO. This is the first study to investigate how the QBO changes in a double CO_2 climate using a climate model that simulates the QBO by model-resolved waves only. A high-resolution version of the MIROC atmospheric GCM is used. We performed a long control integration of the model in the present climate and double CO_2 climate.

Figure 1 shows a time-height cross-section of the monthly-

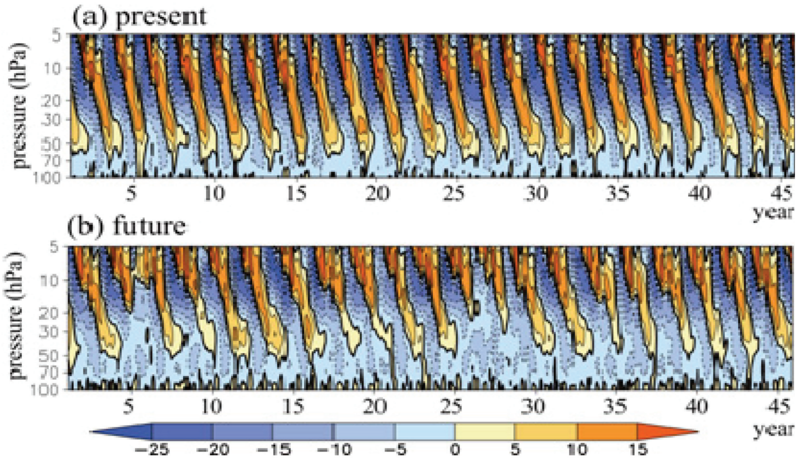

Fig. 1 Time-height cross sections of zonal mean zonal wind at equator in (a) present and (b) double CO_2 climates. The contour intervals are 5 ms^{-1}. Red and Blue colors correspond to westerly and easterly, respectively.

mean zonal-mean zonal wind over the equator in the present and future climates. In the future climate, the QBO period becomes longer and QBO amplitude weaker than in the present climate. The downward penetration of the QBO into the lowermost stratosphere is also curtailed in the future climate. In the future climate, a warming in the troposphere and cooling in the stratosphere are evident and the upper parts of the subtropical jets strengthen. The wave propagation changes in the mid-latitude, associated with background zonal wind changes, result in a significant increase of the mean upwelling in the equatorial stratosphere, and the effect of this enhanced mean circulation overwhelms counteracting influences from strengthened wave fluxes in the warmer climate. The momentum fluxes associated with waves propagating upward into the equatorial stratosphere do strengthen overall by ~10-15% in the warm simulation, but the increases are almost entirely in zonal phase speed ranges which have little effect on the stratospheric QBO.

3. Implementation of a new time integration method into the ocean model

In addition to the leap-frog method, the time staggered method is implemented into COCO (ocean component of MIROC). This time staggered method discretizes time derivative of tracer and momentum equations with a forward time step and time of these fields are staggered by one-half time step (e.g., Griffies [1]). In the calculation of the momentum advection term, third-order Adams-Bashforth scheme is used in order to avoid numerical instability. This method solves tracer and momentum equations alternatively in time so that it has higher computational performance than the leap-frog method, which solves these equations simultaneously in time and calculates two independent solutions.

The calculated sea surface height using the leap-frog method and the time staggered one are shown in Fig. 2. Blue and red dotted lines are results of the leap-frog and the time staggered

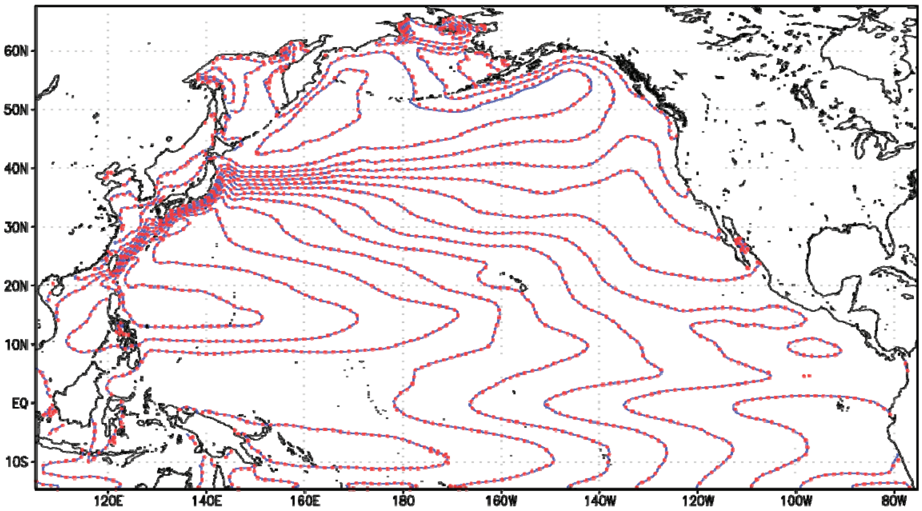

Fig. 2 Time-averaged sea surface height calculated using the leap-frog method (blue lines) and time staggered method (red dotted lines). The model is integrated 10 years and time average is done for the last one year. Contour interval is 10 cm.

methods, respectively. There is little difference between these two results. The calculation of the leap-frog method is stable with time interval of 2400 seconds but unstable with that of 2700 seconds. On the other hand, the calculation of the staggered method is stable with time interval of 4000 seconds. The newly implemented time staggered method significantly improves the computational performance of the model.

4. Modelling the Atlantic Meridional Overturning Circulation (AMOC) at the Last Glacial Maximum

Despite the importance of reproducing the Atlantic Meridional Overturning Circulation (AMOC) by Coupled Atmosphere Ocean General Circulation Models (AOGCMs) used for future projection for the heat transport and carbon cycle, it is often not well reproduced in the simulations of the Last Glacial Maximum (LGM). We present that many models suffer from the warming bias of the sea surface temperature (SST) around Antarctica in the modern Southern Ocean region for the present day simulations (CTL) and the strengthening of the AMOC at LGM (Fig. 3). Additional sensitivity experiments using MIROC AOGCM showed the dependence of the AMOC at the modern and LGM upon the key factors within the range of the uncertainty such as the reproduction of the proper effect of oceanic mixing in the sinking area. Figure 3 shows the correlation between SST bias over the Southern Ocean and the change of the AMOC circulation LGM-CTL for the different AOGCMs and five MIROC sensitivity experiments.

The improvement of the warming bias and sea ice formation in the Southern Ocean are crucial for strengthening the Antarctic Bottom Water (AABW) and shoaling and weakening of the AMOC at LGM through brine rejection and insulation and for controlling the oceanic convective activity. If there is a warming bias, the sea ice around Antarctica is not forming enough to strengthen the AABW and results in the stronger AMOC due to the strong cooling in the high Northern latitude because of the ice sheet. The result depends critically on the balance between the strengthening of the AABW formation caused by the cooling due to the decrease of CO_2 and the strengthening of AMOC by the growth of the ice sheets over the northern hemisphere.

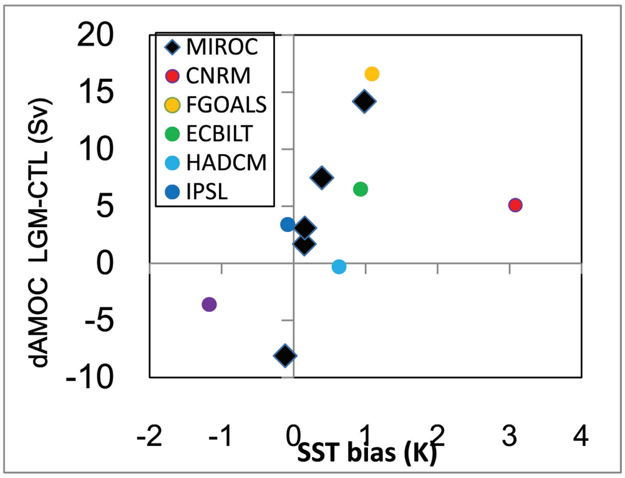

Fig. 3 The correlation between SST bias over the Southern Ocean and the change of the AMOC circulation between LGM and CTL for the different AOGCMs and five MIROC sensitivity experiments.

5. Land-surface modeling in GCM

Snow cover has large effects on the surface energy/water balances. An advanced scheme for sub-grid snow-cover ratio (SSNOWD, [2]) has been introduced in a global climate model (MIROC). In SSNOWD, the effects of vegetation, topography and climatological temperature were considered. A type of sub-grid snow depth distribution used in SSNOWD had been specified as an external boundary data, but it was modified to be internally determined in MIROC: using the vegetation map for the surface energy/water balances, the sub-grid topography variation data for gravity wave drag and runoff, and the surface air temperature diagnosed in MIROC. So that, the sub-grid snow depth distribution type became to be consistently determined in MIROC.

The coefficient variation (CV) of sub-grid snow distribution is a key parameter for reproducibility of SSNOWD. Thus a sensitivity experiment was conducted by specifying CV to a globally unique value at low vegetation (grassland) and low topographic variations (plain) in cold regions, i.e., arctic coastal tundra. It revealed that the changes in vegetation types lead to a decrease in sub-grid snow-cover ratio, and that the changes in topography variation lead to a decrease in the range of the

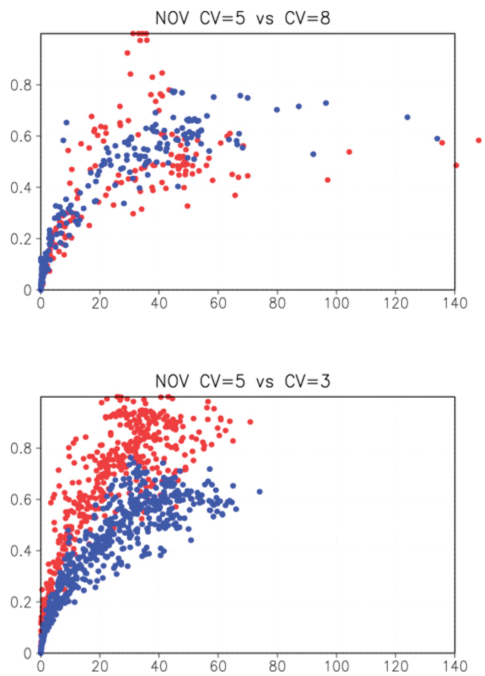

Fig. 4 Scatter diagram of snow water equivalent (horizontal axis) versus sub-grid snow cover ratio (vertical axis). Red dots denote the scatter with realistic distribution of sub-grid snow distribution type, and blue dots denote those with a unique type. Upper shows the scatter of the points where topography type was changed from mountains to plain, and lower shows the scatter of the points where vegetation type was changed from forests to grassland.

Table 1 Summary of CPU time used for 10kyr of integration of Greenland experiment by IcIES.

Resolution	Average time step	Total grid points	CPU time of 10kyr of model integration
5 km	0.1 year	301 x 561 x 26	18,000 sec.
10 km	0.25 year	151 x 281 x 26	2,200 sec.
20 km	0.5 year	76 x 141 x 26	400 sec.

sub-grid snow-cover ratio (Fig. 4). Those changes in snow-cover ratio lead to the changes in surface albedo, and hence the changes in surface air temperature by ± 1 or 2°C. Besides, surface air temperature was increased in summer where the changes in snowmelt lead to the decreases in soil moisture in spring and summer.

In addition to the refinement of land surface scheme, impacts of land use changes on Asian climate have been investigated. There have been numerous studies on thermal and hydrological impacts of vegetation changes (e.g., [3]). However, effects of the changes in volatile organic carbon (VOC) induced by land use change have never been examined, which would lead to changes in the formation of secondary organic aerosols (SOA). The changes in VOC emission from vegetation since the pre-industrial period were estimated using the land use harmonization (LUH) datasets [4]. Sensitivity experiments will be conducted using that estimation.

6. Optimization of an ice-sheet model IcIES

Ice-sheet Model for Integrated Earth-system Studies (IcIES) has been developed for serial-computing environment. Current IcIES performance on 1 CPU of SX-8R is 99.5% in the vector operation ratio with average vector length 252.5, which is already highly tuned for a vector processor. We have tried automatic parallel optimization as well as assignable data buffer (ADB, applicable on ES2). However, it is found that these were effective only for small part of the IcIES.

Table 1 is current status of IcIES for a typical Greenland experiment, which does not significantly demand the computational resources. However, in order to apply IcIES on much higher resolution, or to apply it on much larger domain ice sheet (such as Antarctic ice sheet and Northern hemisphere ice sheet), MPI (Message-Passing Interface) optimization is necessary for effective use of multi-core nodes.

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地球温暖化予測研究のための高精度気候モデルの開発研究

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本研究は、地球温暖化予測のための各種物理モデルの開発を進めながら、地球環境の変動メカニズムの解明を行う。具体的には（1）氷床モデル・凍土モデル・海氷モデルの開発、（2）大気、海洋、陸面の物理過程の評価と改良、（3）地球温暖化予測ならびに古気候再現に関わる気候モデルの感度実験を行う。

本年度は以下の成果を得た。

赤道準 2 年振動（QBO）を陽に表現できる AGCM を長期積分し、地球温暖化時における QBO の振る舞いを調べた。その結果、地球温暖化時に QBO の周期は長く、振幅は弱くなり、また QBO が下部成層圏まで降り難くなることを初めて明らかにした。

Time staggered 時間積分法を海洋モデル COCO に導入した。その結果、これまで用いられてきた leap-frog 時間積分法と比べて、より大きな時間ステップ幅を用いることができるようになった。

大西洋子午面循環（AMOC）の再現性は地球温暖化予測に重要であるが、温暖化予測に用いるモデルを使って過去の氷期の気候（LGM）を再現する際、データが示すような AMOC の状態を再現することが難しいことが知られている。本研究では南大洋の現在気候シミュレーションの海面水温バイアスが LGM の AMOC の状態に影響することを示した。海面水温バイアスは、南大洋の海氷量に深く関わっている。そのため、海面水温バイアスを改善すると、LGM において南大洋の海氷からの塩分の濃い海水の沈み込みによる南極底層循環が強まり、その結果北半球に広がっていた氷床による北大西洋深層循環の強まりとのバランスが変わる。

地表面モデルに関しては、積雪のサブグリッド被覆率を高度化したスキーム SSNOWD の導入に当たって、融雪タイプを MIROC 内部で診断できるようにした。また、サブグリッド分布パラメタに対する感度を調べたところ、植生の効果によって積雪被覆率が小さくなり、地形の効果によって積雪被覆率のばらつきが小さくなることが分かった。このほか、植生改変による揮発性有機炭素の発生量がエアロゾル変化を介して気候に及ぼす影響評価を進めている。

氷床モデル開発に関しては、グリーンランドの高解像度実験を通じて水平解像度 5km までの最適化を実装した。さらに高解像度化、効率化のため、今後の並列化が必須である。

キーワード : 大気海洋陸面結合モデル , オフライン地球生態化学モデル , 成層圏準二年振動（QBO）, 氷床モデル