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.

Relative contribution of equatorially trapped wave modes and internal gravity waves in driving the QBO is discussed by using a high-resolution (T213L256) atmospheric GCM MIROC-AGCM, and it is shown that the gravity waves play a crucial role in driving the QBO in its westward shear phase.

A sub-grid scale parameterization for sea-ice thickness distribution is introduced to ice-ocean coupled models and it is shown that the horizontal pattern of sea-ice thickness becomes more realistic using the parameterization.

The glacial ocean carbon cycle simulation using climate fields obtained from MIROC shows that the atmospheric $p\mathrm{CO_2}$ is reduced by 20 ppm. In the factorial analysis of the ocean carbon cycle, this reduction is mainly caused by the enhanced gas solubility associated with lowering sea surface temperature, whereas it is less contributed by the ocean stratification and the expanded sea ice.

A sub-grid snow-cover model SSNOWD is introduced into MATSIRO (land surface component of MIROC), and it is shown that the biases in simulated snow-cover ratio over eastern Siberia and the Rocky Mountains are significantly reduced.

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

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. Simulation of QBO using a high-resolution Atmospheric GCM

The relative contribution of equatorially trapped wave modes (EQWs) and internal gravity waves in driving the QBO is investigated using the T213L256 AGCM. Here EQWs are defined with order n = -1 to 2 with zonal wavenumber s≤11 (s is zonal wavenumber) and equivalent depths of 2–90 m, while gravity waves have s≥12. Figure 1a presents a time-height cross section of the EP-flux divergence due to all resolved wave components averaged for 10°S–10°N. A QBO-like oscillation is obvious. The period is shorter than the observed value, but the amplitude and bottom levels of the QBO-like oscillation are realistic.

Figure 1b shows the time series of the EP-flux divergence due to all waves, eastward EQWs, westward EQWs, and gravity waves as well as the forcing due to the residual circulation at 30 hPa averaged for 10°S–10°N. Generally, the forcing due to the residual circulation is opposite to, and smaller than, the total wave forcing. In the eastward shear phase, peaks of eastward forcing due to the eastward EQWs and gravity waves are almost coincident. The contributions of eastward EQWs and gravity waves to the eastward forcing are ~25–50% and ~50–75%, respectively. In the westward shear phase, westward EQWs contribute ~10% at most to QBO driving. On the other hand, the contribution by Rossby waves propagating from the winter hemisphere is about 10–20% (not shown). Consequently, gravity

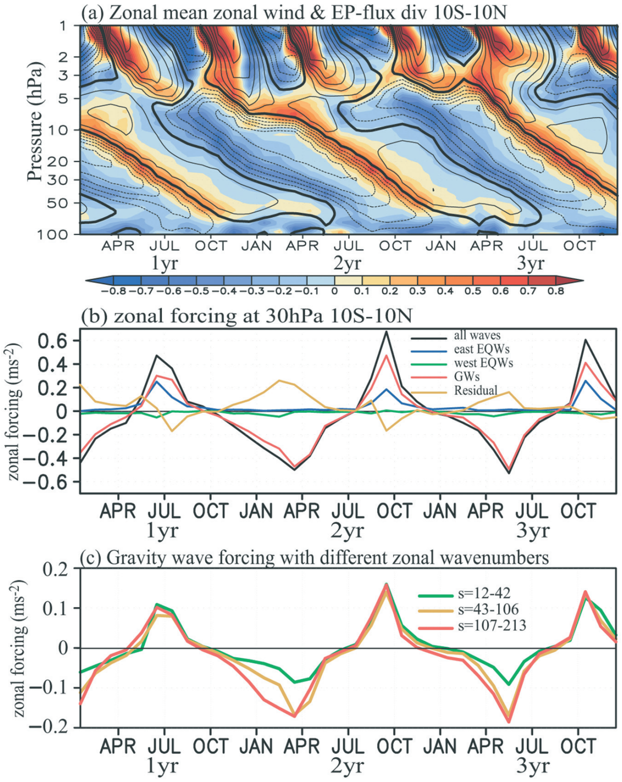

Fig. 1 Time-height cross-section of zonal-mean zonal wind (contour) and EP-flux divergence (shaded) at 10°S-10°N. Red and blue colors correspond to eastward and westward forcing, respectively. Eastward and westward winds are shown with solid and dashed lines. (b) Time variation of EP-flux divergence due to all waves (black), eastward EQWs (blue), westward EQWs (green), gravity waves (red), and forcing due to the residual circulation (yellow) at 30 hPa averaged from 10°S to 10°S. (c) The same as (b), but for EP-flux divergence due to $12 \leq s \leq 42$ (green), $43 \leq s \leq 106$ (yellow), and $107 \leq s \leq 213$ (red). Note that the range of the ordinate axis of (c) is different from that of (b).

waves play a crucial role in driving the QBO in its westward shear phase.

In order to investigate the horizontal scales of gravity waves driving the QBO, time series of EP-flux divergence are shown separately for the components of $12 \leq s \leq 42$, $43 \leq s \leq 106$, and $107 \leq s \leq 213$ (Fig. 1c). The eastward forcing due to each component is comparable in the eastward shear phase. In contrast, components with $42 \leq s \leq 213$ (horizontal wavelength $\lesssim$1000 km) are dominant for westward forcing in the QBO westward shear phase.

3. Development of Sea-ice model and Ocean GCM

We have introduced a sub-grid scale parameterization for ice thickness distribution (ITD) into an ice-ocean coupled model COCO. In the previous COCO, we employed a traditional two-category sea-ice model, in which all the sea ice in a horizontal grid has the same thickness. The new sea-ice model calculates the evolution of the sub-grid scale ITD following *Bitz et al.* [1].

The new ITD parameterization mainly affects on thermodynamics of sea ice. We perform a sensitivity experiment, in which the ITD parameterization is used but sea ice thickness is presumed to be uniform in a specific grid in diagnosing vertical heat flux through sea ice. The result shows that the ITD parameterization makes sea ice thicker, especially in the Arctic Ocean (figure not shown).

The ITD parameterization is also applied to MIROC5, the newest version of MIROC (Model for Interdisciplinary Research on Climate). In Figure 2, summertime Arctic sea-ice thickness is compared between pre-industrial simulations by using MIROC5 and older version (MIROC3). The horizontal pattern of sea-ice thickness becomes realistic (thick ice along the Canadian Archipelago and the north coast of Greenland) in MIROC5. Since sea-ice is very sensitive to climatic change and

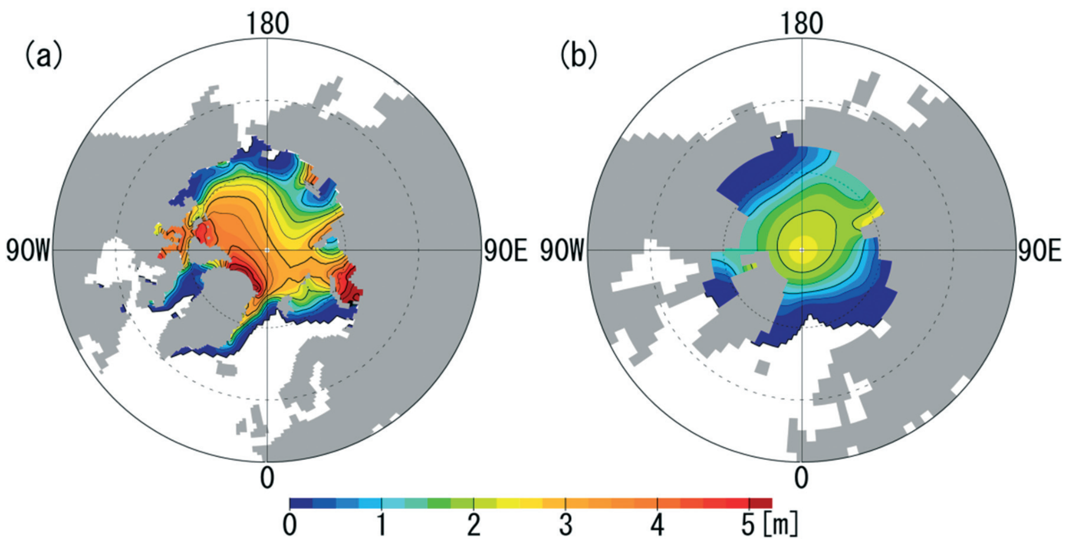

Fig. 2 Sea ice thickness in September, from simulations under pre-industrial boundary conditions. (a) MIROC5 simulation (T85 atmosphere and approx. 1-degree ocean), (b) MIROC3 simulation (T42 atmosphere and approx. 1-degree ocean).

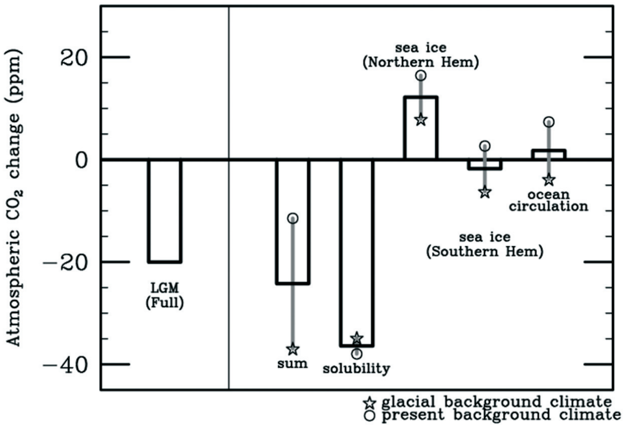

Fig. 3 Atmospheric pCO_2 responses to the climate dynamics of the glacial experiment. Thick bars are the average of the factorial estimates under the glacial and present background climate.

variability, the improvement of sea-ice fields will contribute to present and future climate simulations.

4. Glacial-interglacial simulations of the ocean carbon cycle using GCM

To investigate the glacial-interglacial atmospheric pCO_2 variability due to the climate dynamics change, we conducted factorial experiments of the marine carbon cycle under the glacial climate condition. The prescribed climate fields are obtained from runs of a coupled Atmosphere-Ocean General Circulation Model (AOGCM), MIROC, following the Paleoclimate Modeling Intercomparison Project 2 protocol. This is a new approach to evaluate the marine carbon cycle sensitivity to glacial climate factors of sea surface temperature, ocean circulation and sea ice using the fully coupled AOGCM.

In our simulations, atmospheric pCO_2 is reduced by 20 ppm (Fig. 3). This is mainly caused by enhanced gas solubility associated with lowering sea surface temperature. On the other hand, the ocean stratification and the expanded sea ice have relatively small effects on the atmospheric pCO_2. Compared with the paleo-proxy data, the modest enhancement of Southern Ocean stratification in our glacial simulation would reduce the ability of oceanic carbon uptake. In addition, the sea-ice coverage in the North Atlantic increases the atmospheric pCO_2 through less gas solubility, which is partly counteracted by the pCO_2 drawdown through prevent degassing of DIC-rich deep water in the Southern Ocean. It is the interaction between ocean circulation and sea-ice coverage that is a key factor accounting for the observed glacial pCO_2 drawdown.

We extended this method to model-data comparisons for the representation of North Pacific Ocean circulation during the deglaciation [3]. In our simulation, a North Atlantic freshwater discharge enhances the North Pacific deepwater formation, which is consistent with paleoclimate proxy records.

5. Land-surface modeling in GCM

Snow-cover ratio plays an important role in land surface energy balance because energy fluxes are calculated separately in snow-covered and snow-free portions in a grid cell in the land surface model (MATSIRO) of MIROC, and because albedos of snow-covered/free surfaces are very different. The snow cover ratio had been diagnosed with a simple function of snow water equivalent (SWE), which increases in accordance with SWE (OLD scheme). However, the snow cover ratio depends on sub-grid distribution of snow, which is affected by some factors, e.g., vegetation type and sub-grid topography. Therefore, a model of sub-grid snow cover ratio where such factors (SSNOWD; Liston, 2004 [2]) were considered was incorporated in MATSIRO and its effects were examined. In SSNOWD, a sub-grid snow distribution type is assigned for each grid cell in according to vegetation type and sub-grid topography (i.e., standard deviation of sub-grid variation in elevation), and a sub-grid ratio is prognosticated. CGCM experiments were performed with OLD and SSNOWD schemes, and the results

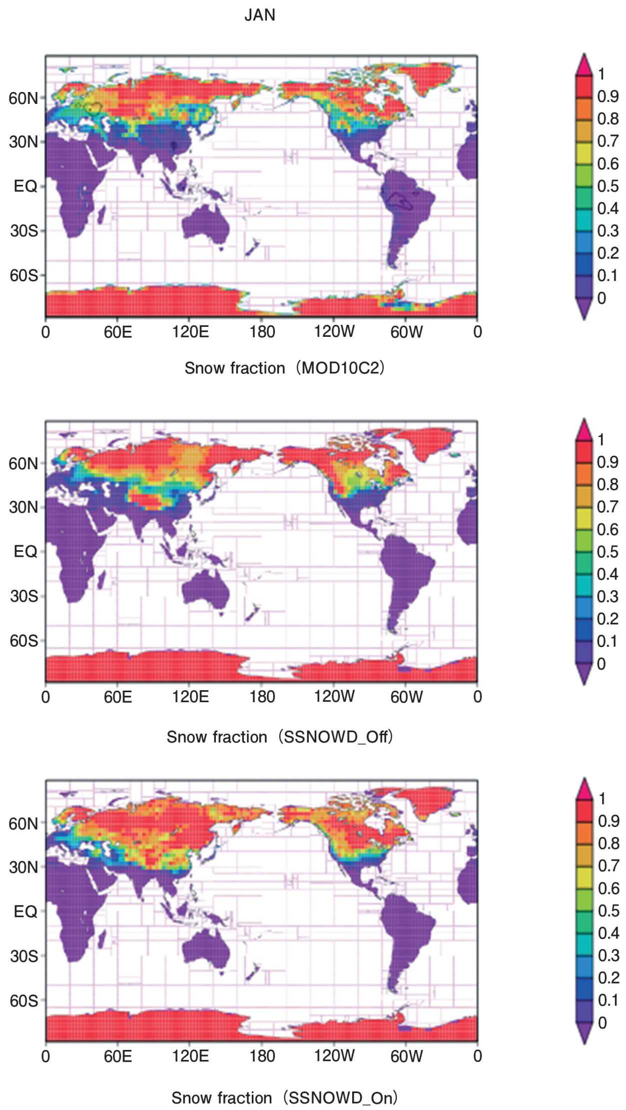

Fig. 4 Sub-grid snow distribution in January by satellite observation (upper), with OLD (middle), and with SSNOWD (lower).

were compared with a satellite observation data (Fig 4). With OLD scheme, the sub-grid snow cover ratio was underestimated in eastern Siberia, because snow amount is small and snow cover ratio is high there. Besides, the snow cover ratio was overestimated in Rocky Mountains with OLD because of the high snow amount in the mountainous region due to low temperature at high altitude. Those biases are significantly reduced with SSNOWD.

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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。

中層大気を含む気候モデルの中では世界トップクラスの水平鉛直解像度である、T213L256AGCM の出力結果を解析し、QBO の駆動に対して、赤道域にトラップされた重力波モード（赤道波）と 3 次元的に伝播可能な内部重力波の役割分担について明らかにした。更に内部重力波に適用可能な 3 次元 wave flux を用いて、wave forcing の 3 次元分布を解析した。

サブグリッドスケールの海氷厚さ分布を海氷 - 海洋モデル COCO 及び結合モデル MIROC に導入した。MIROC5 を用いた工業化以前の境界条件を用いた全球シミュレーションでは、北極域の海氷場がより現実的になった。

MIROC を用いた氷期実験の気候場における大気中二酸化炭素分圧と海洋炭素循環の応答メカニズムを調べた。氷期気候場は、大気中の二酸化炭素分圧を約 20ppm 低下させた。この低下には、水温低下に伴い二酸化炭素の海水への溶解度が強まることが大きく寄与し、大西洋の熱塩循環の弱化や海氷の拡大による影響は小さいことが解析から示唆された。

MIROC5 の陸面水文過程では、1 グリッドにおいて積雪域と無積雪域のエネルギーフラックスを別々に算定しているため、積雪のサブグリッド被覆率は地表面の熱水収支に大きな影響を及ぼす。これまでは積雪水当量とともに増大する関数を用いて診断されてきた（OLD スキーム）。これを、植生や地形を考慮して、積雪のサブグリッド被覆率を予報するスキーム（SSNOWD）を導入したところ、OLD スキームでは過小評価されてきた東シベリアでの積雪被覆率や、過大評価されてきたロッキー山脈での積雪被覆率が衛星観測による積雪被覆率に近づくことが明らかになった。

キーワード : 大気海洋陸面結合モデル , オフライン海洋生物地球化学モデル , 成層圏準二年振動（QBO）