Research on the Climate Change Mechanisms in the Arctic Regions Based on Improvements of the Cold-Region Processes and Validations of the Arctic Climate Reproducibility Using Global Climate Models

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Numerical modeling is a key to deepen our knowledge of the global climate systems. We have evaluated and improved cold-region processes in global climate models.

Firstly, a large bias of the sea ice extent in the northern North Atlantic seen in the CMIP5 experiments using MRI-CGCM3 is investigated. Appropriate choices of the mixing scheme of the oceanic upper layer and the bulk exchange coefficients of air-ice momentum transfer improve the bias. Secondly, impact of subgrid-scale parameterization of sea ice thickness distribution in MIROC on surface heat budget is evaluated. The annual-mean conductive heat flux through the ice and snow is underestimated by 5.4 W/m^2 when the thickness distribution scheme is ignored. Thirdly, we incorporate SSNOWD subgrid snow cover parameterization, into MATSIRO land surface model. A comparison between global offline simulations and satellite-based observational dataset show that SSNOWD improves the intra- and interannual variability of snow cover area in Northern Hemisphere especially in the accumulation season. The effects of those changes in snow cover on the other land surface properties are not negligible. Lastly, anthropogenic impact on precipitation in the late 20th century is studied. It is suggested that human activities have significant impact on an increase in spring precipitation over middle to western part of the Eurasian continent in the late 20th century; precipitation increase may be caused by reduction of anthropogenic aerosols over Europe, while it may be caused by retreat of snow cover area due to the GHGs increase.

Keywords: sea ice extent in the northern North Atlantic Ocean, subgrid-scale ice thickness distribution, subgrid snow cover, anthropogenic impact

1. Introduction

The Arctic environment has rapidly changed in recent years. Numerical models also project continuing, or even accelerating, changes in the future Arctic. Since the Arctic and global climate systems closely interact with each other, research on the Arctic climate change is important for better understanding of changes in the global climate system as well as the Arctic regional climate.

Numerical modeling is a key for the Arctic climate study. Large uncertainties remain, however, in present climate models, particularly in the Arctic. The purpose of this project is to evaluate the Arctic climate reproducibility, and to develop and improve cold-region processes, in global climate models.

2. Improvement of ocean-sea ice component of MRI-CGCM3

In the CMIP5 experiments of MRI-CGCM3 [1], the sea ice in the northern North Atlantic spread wider than the observation in winter (Fig. 1a). This wide winter sea ice extent was maintained by the low sea surface salinity, which was considered to be caused by the weak mixing between surface water and the subsurface water. Use of a turbulence closure model that tends to enhance mixing between the surface and the subsurface layers reduces this bias of sea ice extent in the region around the Labrador Sea (Fig. 1b). The new mixing scheme mixes the surface low temperature and low salinity water and the subsurface high temperature and high salinity water, keeping the sea surface temperature in the region around the Labrador

Sea high even in winter.

However, the wide bias of the sea ice extent in the Norwegian Sea is not improved. A close examination revealed that the speed of the sea ice drift is small. Owing to this slow sea ice drift, the sea ice that flows into the Norwegian Sea from the Arctic Ocean does not flow out further southward but the large fraction of it melts there. This results in the low sea surface salinity. By using a large bulk-exchange coefficient at the air-ice interface, the sea ice in the Norwegian Sea moves faster and the winter sea ice distribution in the Norwegian Sea is improved (Fig. 1c).

3. Impact of subgrid-scale ice thickness distribution on heat flux on the Arctic sea-ice in an ice-ocean coupled model

In an ice-covered ocean, the heat exchange between the atmosphere and ocean nonlinearly depends on the ice thickness [3]. Subgrid-scale ice thickness distribution (SITD) scheme

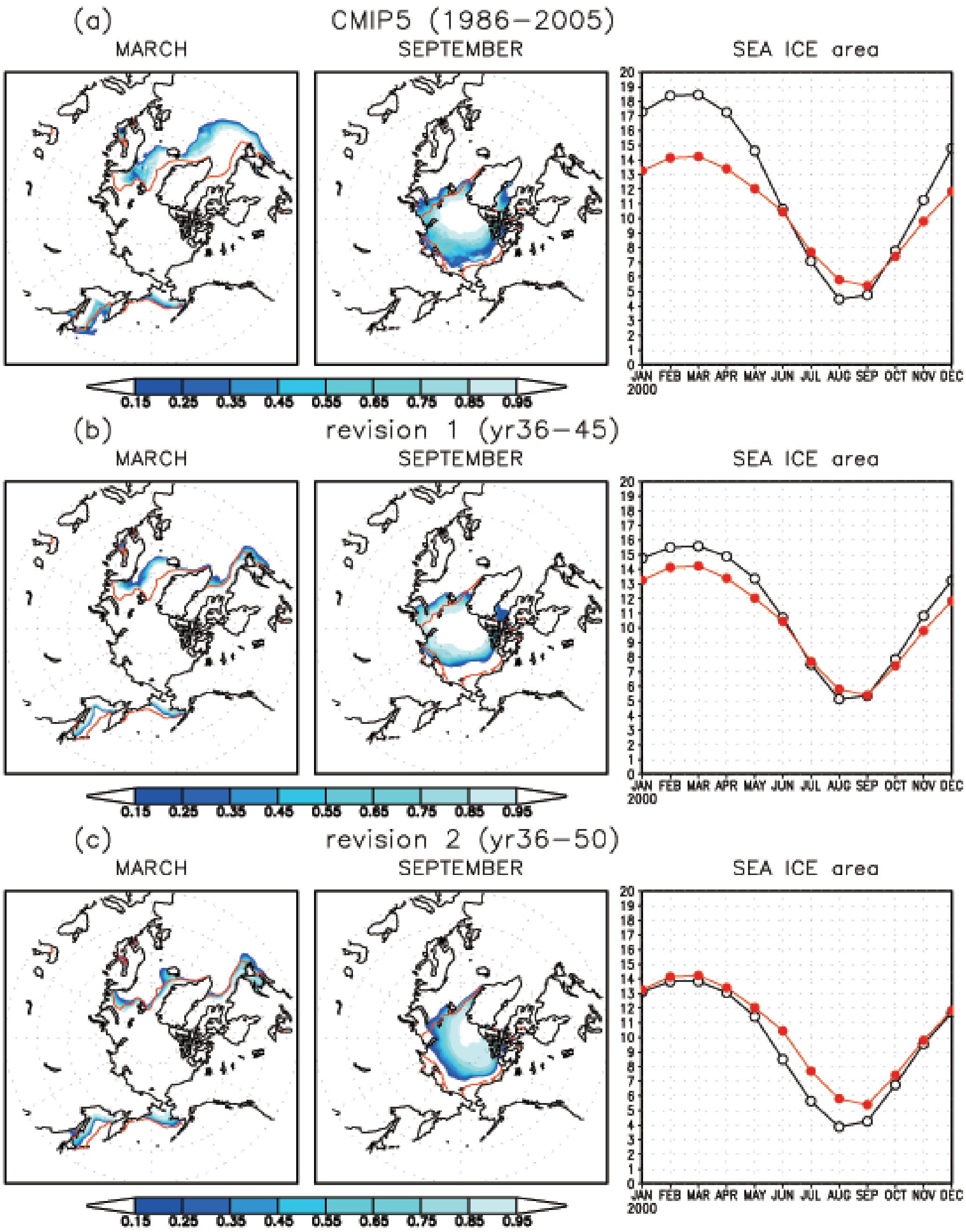

Fig. 1 (left panel) Distribution of long-term mean sea ice concentration in March. (shade) model and (red line) the edge of the sea ice extent from HadISST [2]. The edge of the sea ice extent is represented by the contour line of the value of 0.15 of the twenty year (1986-2005) mean sea ice concentration field. (middle panel) Same as the left panel but September. (right panel) Monthly mean Northern Hemisphere sea ice area (Units 10^{12} m^2, black: model, red: the twenty year mean (1986-2005) of HadISST). (a) CMIP5 experiment (the average from 1986 to 2005) (b) The experiment where a turbulent closure scheme that enhances mixing between surface and subsurface layers is employed (the average from 36th to 45th year of the model integration). (c) The experiment where a large bulk exchange coefficient is used to impose a large surface wind stress (the average from 36th to 50th year).

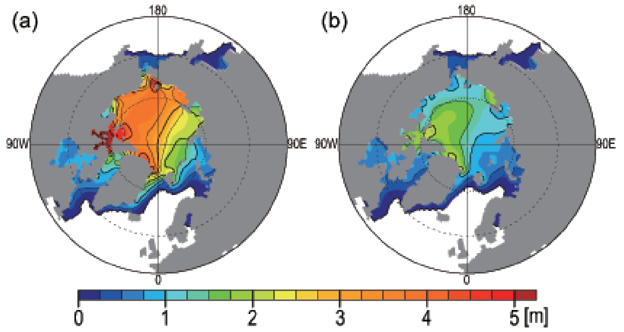

Fig. 2 Annual-mean Arctic ice thickness for (a) the present-day simulation and (b) the sensitivity experiment.

is often used for representing such a dependency in sea-ice models. In this topic, impact of the SITD scheme on heat flux on the Arctic sea-ice is qualitatively evaluated. An ice-ocean coupled model with SITD scheme, COCO4.5 [4], is forced by an atmospheric climatology to simulate the present state of the sea ice and ocean. The number of the thickness categories is set to 15.

The heat flux on and through the sea ice is established using the grid-averaged sea-ice and snow-on-ice thickness from the results of the simulation, and is compared with the flux which actually drives the model. When the grid-averaged thickness is calculated as a weighted arithmetic mean, the annual-mean conductive heat flux through the ice and snow is underestimated by 5.4 W/m^2 or 47%. The underestimation in conductive heat flux is also found in the Southern Ocean, but it is not so significant as that in the Arctic Ocean; the annual-mean bias is –1.7 W/m^2 or –18%.

We also perform a sensitivity experiment in which the model is forced by the biased heat flux identified using the arithmetic mean of the ice thickness. A significant decrease in ice volume is found, notably in the Arctic Ocean (Fig. 2). These results suggest that sea-ice models without an ice thickness distribution scheme underestimate the conductive heat flux through ice, and thereby the resultant sea-ice thickness, because the ice thickness from these models typically corresponds to the weighted arithmetic mean thickness.

4. Representing subgrid snow cover and snow depth variability in a global land model: Offline validation

Because of its large impact on surface temperature and the surface energy and moisture budgets, seasonal snow cover is a key variable in the global climate system. In this study, we incorporate the SSNOWD subgrid snow cover parameterization [5] into the MATSIRO land-surface model [6]. SSNOWD assumes the subgrid snow water equivalent (SWE) distribution follows a lognormal distribution function that accounts for the physical processes that produce subgrid SWE variability. Two 29-year offline simulations are performed, one with and one without SSNOWD. The simulations are forced with a global meteorological dataset [7] that combined Japanese 25-year Reanalysis Project atmospheric reanalysis data with an observed precipitation dataset. The simulated mean monthly snow-cover fractions are compared with satellite-based Moderate-Resolution Imaging Spectroradiometer [8] (MODIS) observations of the snow-cover fraction (see Fig. 3). In the Northern Hemisphere, the daily snow-covered area is validated using Interactive Multisensor Snow and Ice Mapping System [9] (IMS) snow analysis. Together, these comparisons show that the original MATSIRO model underestimates the snow-cover fraction, especially for the accumulation season and/or regions with relatively small amounts of snowfall. In contrast, the inclusion of SSNOWD improves the spatial pattern of the snow-cover fraction. The SSNOWD simulation largely agrees with the IMS snow analysis and leads to an improved seasonal cycle for the snow-covered area in the Northern Hemisphere. This is because SSNOWD formulates the snow-cover fraction differently for the accumulation season and ablation season, and represents the

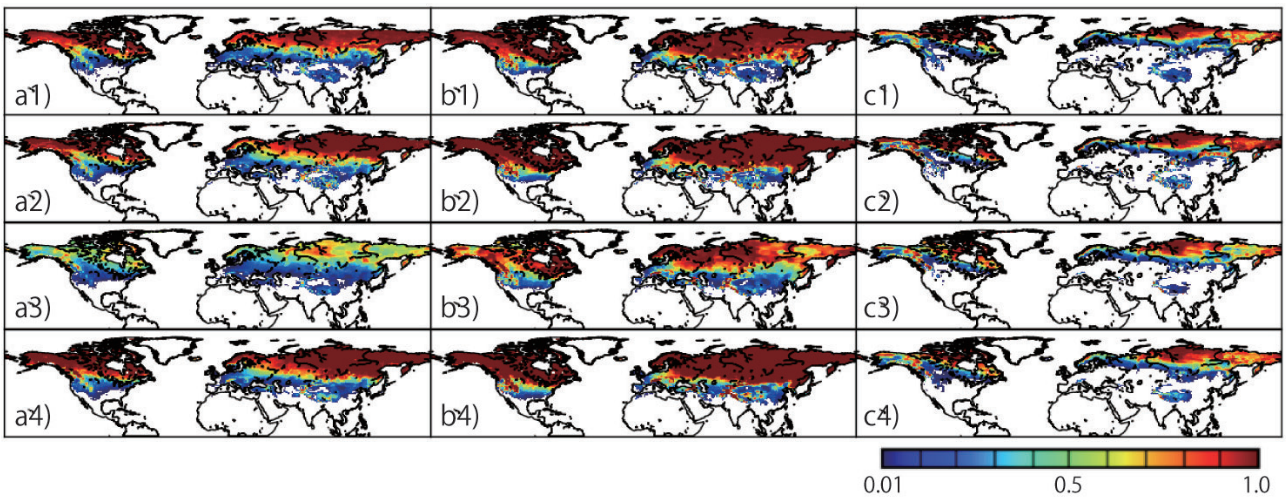

Fig. 3 Northern Hemisphere snow cover fraction (2001-2007). 1) MODIS, 2) IMS, 3) simulation without SSNOWD, 4) simulation with SSNOWD, a) November, b) February, c) May.

hysteresis of the snow-cover fraction between different seasons. The effects of SSNOWD parameterization on surface energy fluxes and hydrological properties are also examined.

5. Anthropogenic impact on spring precipitation over Eurasian continent in the late 20th century

Global warming due to anthropogenic greenhouse gases (GHGs) causes an increase in mean and extreme precipitation. It also causes a decrease in snow cover duration and snow water equivalent (SWE) in mid-latitude and lower altitudinal area, whereas it causes an increase in SWE in high-latitude and high altitudinal area [10]. On the other hand, anthropogenic emissions of aerosols have decreased over European countries, the U.S., Japan, etc., although they are still increasing in China, India, and developing countries. Changes in the anthropogenic aerosols alter the surface radiation fluxes through the scattering and absorbing processes of aerosols. These changes in surface radiation fluxes affect the surface energy budget. Recently, it is pointed out that 'dimming and brightening' associated with aerosol changes affect regional and global climate changes [11]. Decrease in anthropogenic aerosols induces brightening over Europe, which resulting in an increase in evaporation. The increase in evaporation contributed to the increase in precipitation via the water budget relationship.

Here, we investigate the impact of changes in GHGs and aerosols on precipitation over the Eurasian continent in the late 20th century using historical simulations performed by a coupled general circulation model generally known as the medium-resolution version of the Model for Interdisciplinary Research On Climate (MIROC). The atmospheric component of MIROC includes an explicit representation of the first and second kinds of indirect effects induced by soluble aerosols as well as the direct effects of all aerosols. We look into the relative contribution of individual anthropogenic forcing factors by analyzing datasets of several experiments forced with different combinations of external climate forcing factors [12]. We focus on the changes in surface radiation and heat budgets which affect the evaporation and precipitation statically.

The historical simulation by MIROC can simulate the observed precipitation trend over high-latitudinal area in the late 20th century. Significant increase in precipitation was observed and simulated during spring. Moistening trends are significant over the western part of Eurasia (Europe) during all season. According to an analysis using an approximated atmospheric moisture budget equation, we find that the increase in precipitation is caused by the increase in evaporation over the western parts of Eurasian continent. The change in evaporation is thought to be related to the surface radiation changes. So, we investigate the changes in surface radiation, and found that change in net surface shortwave radiation (SSR) controlled the changes in net radiation. The downward SSR shows an increase over Europe (Fig. 4 left). In contrast, the upward SSR shows a decrease, which means the increase in net radiation at the surface, over the central part of Eurasia (Fig. 4 right). According to an analysis of several experiments forced with individual forcing factors, it is speculated the change in downward SSR is associated with the changes in aerosols, while the changes in upward SSR is associated with the snow cover change. The increase in downward SSR over Europe was caused by the decreases in aerosols. The decrease in upward SSR over the central part of Eurasian continent was caused by the increasing concentrations of GHGs; the decrease in upward SSR is strongly associated with the surface albedo reduction which is caused by the decrease in snow cover due to global warming.

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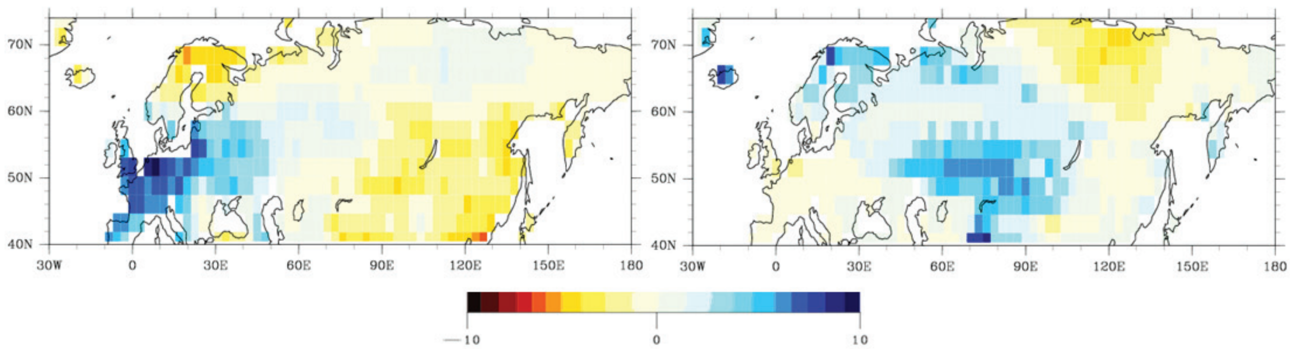

Fig. 4 Changes in surface (left) downward and (right) upward SSR [W/m^2/50years] over spring from 1959 to 2008. Note that downward flux is positive.

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全球モデルを用いた寒冷圏プロセス高度化と北極気候再現性検証による北極気候変動メカニズムの研究

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数値モデリングは気候システムを理解する上で重要な位置を占める手法である。本プロジェクトでは、全球モデル中の寒冷圏プロセスの評価と高度化に取り組んだ。

まず、MRI-CGCM3 による CMIP5 実験にみられた北部北大西洋における海氷存在域の過大傾向の原因究明に取り組んだ。海洋の表層混合過程、及び大気 - 海氷間の運動量フラックス計算法を適宜改良することにより、このバイアスは修正された。次に、海氷モデル中のサブグリッドスケール海氷厚分布スキームが海氷上熱収支に与える影響を評価した。モデル中でこのスキームを無視すると、年平均の伝導熱は 5.4 W/m^2 過小評価された。第 3 に、陸面モデル MATSIRO に積雪被覆率パラメタリゼーション SSNOWD を組み込んだ。その結果、SSNOWD を組み込むことで、気候値の空間分布だけでなく、積雪被覆率の時系列変化も改善することが示された。積雪被覆率の違いが陸面の状態量へ及ぼす影響が無視できないこともわかった。最後に、人間活動が降水量に与える影響について調査した。20 世紀後半以降に観測されたユーラシア大陸中西部における春季平均した降水量の増加には、人間活動が少なからず影響していることが示唆された。ヨーロッパ域ではエアロゾル排出の減少が、ユーラシア大陸中部では GHG 増加に起因する積雪面積の減少が、それぞれ寄与していると考えられた。

キーワード : 北部北大西洋域の海氷分布 , サブグリッドスケール海氷厚分布 , サブグリッド積雪被覆 , 人間活動の影響