論文の内容の要旨

Impact of glacial ice sheets on the Atlantic meridional overturning circulation and climate

(氷期氷床が大西洋子午面循環と気候に与える影響に関する研究)

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During glacial periods, the North American and Eurasian ice sheets grew across the continents (hereafter referred to as glacial ice sheets). These glacial ice sheets are suggested to have an impact on the Atlantic meridional overturning circulation (AMOC), which played a role in affecting the mean climate and inducing frequent climate changes (Dansgaard-Oeschger cycles; DO cycles) during glacial periods. However, the impact of glacial ice sheets on the AMOC is not fully understood. In particular, (i) processes by which the glacial ice sheets modify the AMOC (surface winds, surface cooling and atmospheric freshwater flux), (ii) the impact of glacial ice sheets on the DO cycles, for example, the duration of stadials, and (iii) the reason why the impact of glacial ice sheets on the AMOC depends on background climate (CO2) should be clarified. The objective of this study is to improve the understandings of the impact of

glacial ice sheets on the AMOC and glacial climate using a general circulation model with different configurations.

In Chapter 2, the effect of wind change due to glacial ice sheets on the AMOC and the crucial region where the wind modifies the AMOC is explored. For this purpose, numerical simulations with an atmospheric general circulation model (AGCM) and an ocean general circulation model (OGCM) are conducted. First, from AGCM experiments, the effect of glacial ice sheets on the surface wind is evaluated. Second, from OGCM experiments, the influence of the wind stress change on the AMOC is evaluated by applying wind stress anomalies regionally or at different magnitudes as a boundary condition. These experiments demonstrate that glacial ice sheets intensify the AMOC through an increase in the wind stress at the North Atlantic mid-latitudes, which is induced by the North American ice sheet. This intensification of the AMOC is caused by the increased oceanic horizontal and vertical transport of salt. Changes in winds by the Eurasian ice sheet also appear to have an impact on the AMOC, though its effect is smaller compared to the North American ice sheet.

In Chapter 3, I investigate the impact of glacial ice sheets on the duration of stadials during mid-glacial. For this purpose, freshwater hosing experiments are conducted with an atmosphere-ocean coupled general circulation model (AOGCM) under several ice sheet configurations. I find that the expansion of glacial ice sheets during mid-glacial shortens the duration of stadials (recovery time of the AMOC). In order to explore the reason why glacial ice sheets modify the recovery time, partial decoupled experiments are conducted. In these experiments, atmospheric conditions that force the ocean model are replaced to different forcing. Thus the role of changes in surface winds, surface cooling and atmospheric freshwater flux by the glacial ice sheets on the recovery time can be estimated. These experiments show that differences in the surface wind is important in causing the shorter recovery under larger ice sheets, while differences in the surface cooling has an opposite effect. The impact of atmospheric freshwater flux appeared to be small. The wind shortens the recovery time through

mainly increasing the surface salinity at the deepwater formation region, while surface cooling increased the recovery time through increasing the sea ice at the deepwater formation region. Thus these results show that differences in the surface wind induced by the glacial ice sheets play an important role in causing frequent DO cycles during mid-glacial through shortening the duration of stadials.

In Chapter 4, I explore the role of sea ice in modifying the impact of glacial ice sheets on the AMOC. For this purpose, results of AOGCM simulations are analyzed and numerical experiments are conducted using an AGCM and an AOGCM. It is shown that the expansion of sea ice over the northern North Atlantic weakens the surface wind. This is associated with a suppression of oceanic sensible heat flux due to the sea ice, which drastically increased the static stability of the air column. As a result, the surface wind cannot become strong even under the existence of glacial ice sheets and hence the wind effect of the ice sheet weakens. This modifies the relative strength of the wind effect and cooling effect of the glacial ice sheet. As a result, the cooling effect becomes stronger and thus the glacial ice sheet weakens the AMOC.

Together all, this study clarifies that the impact of glacial ice sheets on the AMOC is controlled by the relative strength of the surface winds and surface cooling. The relative strength of these effects depends on sea ice. Under warm climate and less sea ice condition, the glacial ice sheets can intensify the surface winds and the AMOC. However, under cold climate, sea ice expands and suppresses the atmosphere-ocean heat exchange. As a result, the surface winds cannot become vigorous even under the existence of the glacial ice sheets. Thus, the relative strength of wind and cooling effects changes. Since the strength of each effect depends on models, differences in the relative strength of the wind and cooling effects among models can cause a large difference in the AMOC among them. In addition, this study also suggests an important role of the glacial ice sheet on the frequent DO cycles during glacial periods. According to ice core data, the duration of the stadial is shortest during the mid-glacial period compared to the full glacial and earlier glacial periods. Over the early glacial to mid-glacial

periods, the expansion of glacial ice sheet can reduce the duration of the stadials through strengthening the surface winds since the climate is relatively warm and there is less sea ice over the North Atlantic. Over the mid-glacial to full glacial periods, the North Atlantic is widely covered by sea ice due to the cold climate. As a result, the expansion of glacial ice sheet during this period can increase the duration of stadials through the cooling effect. Thus, this study suggests that the glacial ice sheet plays an important role in causing frequent DO cycles during mid-glacial period through modifying the duration of stadials.