ABSTRACT

The dynamics of the atmospheric circulation change over the midlatitude North Pacific under the boundary conditions during the last glacial maximum (LGM) have been studied by atmospheric general circulation models (GCMs) with different ocean feedbacks. Three boundary conditions in the LGM were different from those of the present day (PD): ice sheet with elevated topography and high albedo, atmospheric CO$_2$ concentration, and insolation. The ocean component was treated as follows: a full-circulation ocean with dynamical and thermal ocean feedback [coupled general circulation model (CGCM)]; a slab ocean only with thermal feedback used to calculate the surface heat balance [slab ocean GCM (SGCM)]; and no ocean feedback by fixing sea surface temperature (SST) with pure atmospheric dynamics (AGCM). Both CGCM and SGCM simulated a weakened Pacific high pressure system in boreal summer during the LGM compared to the PD and an intensified Aleutian low pressure system in winter. Both in summer and winter, therefore, the lower-tropospheric circulation during the LGM showed midlatitude North Pacific cyclonic anomalies (NPCAs).

To understand the dynamics determining the NPCAs, the sensitivity of the atmospheric response to the three boundary conditions were examined using the SGCM. It was shown that the high albedo of the ice sheet over North America was the dominant factor behind the NPCAs in both summer and winter. The ocean thermal feedback in winter played an essential role in the formation of the NPCA through SST change, while the ocean thermal feedback in summer and ocean dynamical feedback played secondary roles in the intensification of the NPCA. Possible mechanisms were inferred from the common features related to the NPCA formation in the experiments. In summer, the midlatitude NPCA was associated with the reduced land-ocean contrast of diabatic heating between the North Pacific and North America, which is consistent with theoretical studies on the mechanism for formation of subtropical high pressure systems. In winter, on the other hand, the anomaly of the SST gradient at midlatitude is thought to result in the NPCA through the modulation of heat and momentum transport in the storm track.

The small (large) sensitivity of the NPCA formation to the ocean feedbacks in summer (winter) explains the strong (weak) consistency among the previous GCM experiments. Since the NPCAs are consistent with some geological records, the present study should be informative in understanding the actual dynamics of the LGM climate change.

1. Introduction

The earth’s climate has fluctuated between glacial and interglacial states with an approximately 100 000-year cycle because of orbital forcing with climate system feedbacks. The last glacial maximum (LGM), ~21 000 years before present, has been studied extensively because of the magnitude of the climate changes and the availability of geological records (e.g., COHMAP Members 1988; Pinot et al. 1999; Kohfeld and Harrison 2000). During the LGM, large ice sheets with heights of a few kilometers covered high-latitude North America and Europe (Fig. 1b), and the concentrations of greenhouse gases, including CO$_2$, were reduced. Under such boundary conditions, the earth’s surface temperature was reduced by several degrees Celsius during the LGM. Furthermore, detailed spatial mapping of geological records have revealed regional climate change during the LGM, such as drier climate over East Asia and more humid climate over western North America (Kohfeld and Harrison 2000; Yu et al. 2000). It is of interest whether the climate...
changes during the LGM were merely due to the response to the global cooling or to regional forcing sources. GCMs have been used to investigate regional structures and dynamics of the LGM climate; for example, several GCMs simulated significant atmospheric change around the ice sheet over North America during the LGM (Kutzbach and Wright 1985; Broccoli and Manabe 1987); regional analysis of Europe using GCM has contributed to improved knowledge on the processes of climate system and paleoclimate reconstructions (Ramstein et al. 2007). Early numerical studies on the LGM used AGCMs with no ocean feedback calculation or slab ocean GCMs (SGCMs) with ocean thermal feedback by considering ocean surface heat budget without explicit circulation. During the past decade, more realistic LGM simulations have become possible using coupled general circulation models (CGCMs), which calculate the full circulation dynamics of the ocean (Bush and Philander 1999; Kitoh and Murakami 2001; Hewitt et al. 2003; Kim et al. 2003; Shin et al. 2003). In particular, the Paleoclimate Modeling Intercomparison Project Phase 2 (PMIP2) organized several LGM simulations using different CGCMs under the same boundary conditions (Kageyama et al. 2006; Masson-Delomte et al. 2006; Otto-Bliesner et al. 2006; Braconnot et al. 2007).

Using the PMIP2 simulation outputs, Yanase and Abe-Ouchi (2007) analyzed the atmospheric circulation around the midlatitude North Pacific. In the climatological field of the Japanese 25-Year (1979–2004) Reanalysis (JRA-25; Onogi et al. 2007), this region is characterized by the Pacific high pressure system in boreal summer and the Aleutian low pressure system in boreal winter (Figs. 2a,b). Most of the five LGM simulations in PMIP2 showed a weakened high pressure system in summer and an intensified low pressure system in winter. As an example, one of the CGCM [Model for Interdisciplinary Research on Climate 3.2 (MIROC3.2)] results is shown in Figs. 2c,d for the present day (PD) and Figs. 3a,b for the LGM anomaly. Therefore, both in summer and in winter, the lower-tropospheric circulations during the LGM showed midlatitude North Pacific cyclonic anomalies (NPCAs). Yanase and Abe-Ouchi (2007) pointed out that the NPCA and related climate response were consistent with some geological records including dust transport, pollen, and foraminifera. The NPCAs, although not always discussed, can be seen in previous AGCM, SGCM, and CGCM studies. The NPCA in summer was simulated robustly in most of the AGCMs (Kutzbach and Wright 1985; Rind 1987; Hall et al. 1996; Dong and Valdes 1998; Vettoretti et al. 2000), SGCMs (Dong and Valdes 1998; Vettoretti et al. 2000), and CGCMs (Shin et al. 2003; Laïne et al. 2009). The NPCA in winter was also simulated in many GCMs including AGCMs (Kutzbach and Wright 1985; Rind 1987; Hall et al. 1996; Dong and Valdes 1998; Vettoretti et al. 2000), SGCMs (Vettoretti et al. 2000), and CGCMs (Shin et al. 2003), although there are a few exceptions in SGCMs (Broccoli and Manabe 1987; Dong and Valdes 1998). The detailed mechanism of NPCAs has not been clarified.

To understand the various characteristics of LGM climate, some scientists used sensitivity experiments
Rind 1987; Broccoli and Manabe 1987; Justino et al. 2005), which examine the individual influence of different boundary conditions separately. For example, they pointed out that the topographic effect of the ice sheet over North America on the westerly flow caused an upstream (downstream) anticyclonic (cycloonic) anomaly in the high-latitude in winter. This result is consistent with the theoretical mechanism of stationary wave formation (Cook and Held 1988). It should be clarified as to why the winter NPCA can be formed in the midlatitude despite the opposite tendency in the high-latitude because of the ice sheet topography.

FIG. 2. Zonally varying component of geopotential height at 850 hPa in (left) boreal summer and (right) boreal winter at the PD. (a),(b) JRA-25; (c),(d) CGCM simulation; (e),(f) SGCM simulation. Contour intervals are 10 gpm. Red (blue) shading indicates positive (negative) or anticyclonic (cycloonic) geopotential height.
The purpose of the present study is to understand the dynamics determining the midlatitude NPCA during the LGM using sensitivity experiments with a CGCM, an SGCM, and an AGCM. These GCM experiments examined 1) the influences of the ice sheet with elevated topography and high albedo, atmospheric CO$_2$ concentration, and insolation; and 2) the roles of dynamical and thermal feedbacks of the ocean. The GCM used in the present study is MIROC3.2, which is considered to simulate the PD and LGM climates to an adequate degree for the following reasons. Since MIROC3.2 was one of the CGCMs used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), its ability to simulate the PD climate has been evaluated from various aspects (Solomon et al. 2007; Hori and Ueda 2006). In fact, both CGCM and SGCM of MIROC3.2 reproduced realistic midlatitude planetary-scale circulation including the Pacific high pressure system in summer and the Aleutian low pressure system in winter (Fig. 2).

Simulations of the LGM climate using the MIROC3.2 CGCM have been compared with geological records and other CGCMs by the PMIP2 group (Kageyama et al. 2006; Yanase and Abe-Ouchi 2007; Laïne et al. 2009). The model resolution of 2.8° x 2.8° employed in the present study can resolve the heat and momentum transport in the midlatitude storm track more realistically than the previous sensitivity simulations (more than 4.5° in Broccoli and Manabe 1987; Rind 1987; Justino et al. 2005).

Our paper is organized as follows: section 2 describes the GCM used in this study and the design of sensitivity experiments. Section 3 first compares the NPCAs simulated by the CGCM and SGCM and then examines the important boundary condition for the NPCA formation using the SGCM sensitivity experiments. The roles of the ocean feedbacks are also shown. Section 4 discusses the dynamics of the NPCA based on the result of our experiments and of other studies. Section 5 summarizes the conclusion of the present study.

**FIG. 3.** Anomalies of the zonally varying component of geopotential height at 850 hPa in (left) boreal summer and (right) boreal winter between the LGM and the PD. (a),(b) CGCM simulation; (c),(d) SGCM simulation. Contour intervals are 5 gpm. Red (blue) shading indicates positive (negative) or anticyclonic (cyclonic) geopotential height. The dotted areas correspond to differences in the anomaly at $p < 0.1$ using Student’s t-test.
2. Methodology

a. Model description

The MIROC3.2 GCM used in the present study was developed at the following Japanese institutes: Center for Climate System Research (CCSR), National Institute of Environmental Studies (NIES), and Frontier Research Center of Global Change (FRCGC). The atmospheric dynamical part solves the primitive equations on a sphere using a spectral transform method with the $\sigma$-pressure hybrid coordinate. The atmospheric physical schemes include radiation, cumulus convection, large-scale condensation, and vertical diffusion. Detailed information is given in the technical report by Hasumi and Emori (2004). The horizontal resolution is T42 (about $2.8 \times 2.8^\circ$), and there are 20 vertical levels.

To save on the computational costs for obtaining an equilibrium conditions for a number of sensitivity experiments, we mainly used an SGCM rather than a CGCM. The slab ocean model simply calculates sea surface temperature (SST) assuming a 50-m-deep well-mixed ocean layer, which exchanges heat through the atmosphere–ocean surface. Sea ice in the polar region sets in when the SST is lower than the freezing point. The effect of heat transport by ocean circulation was artificially prescribed by specifying heat convergence at each grid point to maintain a realistic distribution (so-called q-flux method). To simply examine the ocean thermal feedback through SST change, the heat transport effect was the same among all the SGCM experiments. In addition, the CGCM was also used for the PD and the LGM experiments to investigate the dynamical effect of the ocean circulation on the heat transport. The atmospheric component of the CGCM is the same as that of the SGCM. A detailed description of the CGCM experiment using the MIROC3.2 model is given in Yanase and Abe-Ouchi (2007).

b. Experimental design

Three boundary conditions in our PD experiment were changed in the LGM experiment: ice sheet distribution, insolation, and greenhouse gas concentrations including CO$_2$. The experimental design is based on the PMIP2 project (Masson-Delomotte et al. 2006; Kageyama et al. 2006; Braconnot et al. 2007; Yanase and Abe-Ouchi 2007) except that an SGCM was used in the sensitivity experiment instead of a CGCM. Large ice sheets were prescribed over North America (the Laurentide ice sheet) and northern Europe (the Fennoscandia ice sheet) in the LGM experiment (Fig. 1b) based on the ICE-5G reconstruction dataset (Peltier 2004). In the ice sheet regions, the boundary conditions of note are high albedo of ice surface at temperatures below freezing point and elevated topography. The concentrations of atmospheric greenhouse gasses (CO$_2$, CH$_4$, and N$_2$O) were reduced in the LGM experiments. The concentration of CO$_2$, which is the most dominant greenhouse gas, was only 185 ppm during the LGM compared with the PD (preindustrial) value of 280 ppm. The estimated insolation during the LGM was based on the earth’s orbital parameters (Berger 1978).

To understand which boundary condition was the dominant cause of the NPCA in summer and winter during the LGM, three groups of sensitivity experiments were performed. The experiments in group A examined the role of the ice sheets, atmospheric CO$_2$ (and the other greenhouse gases) concentration, and insolation using the SGCM. Table 1a summarizes the name and design of the experiments in group A, while Table 1b shows the effects of boundary conditions by comparing two different experiments. For example, experiment LCO2INS employed the atmospheric CO$_2$ concentration and insolation of the LGM and the ice sheet distribution of the PD, while experiment LGM used all of the LGM boundary conditions. By comparing experiments LGM and LCO2INS, therefore, the effect of the ice sheets can be discussed. To further investigate the dynamics of atmospheric circulation change, additional experiments were also performed. The experiments in group B using the SGCM compare the detailed roles of the ice sheet including high albedo of ice surface, elevated topography, and locations (Table 2). The experiments in group C using the AGCM examine the role of thermal feedback from the slab ocean (Table 3). The purposes of experiments in groups B and C are to be explained in detail in section 3.

Each experiment using the SGCM and the AGCM was integrated for 50 years. Since the atmosphere–ocean
system almost reached a state of equilibrium during the first 20 years, the average of the last 30 years was used for the analysis. The boreal summer field was defined by the mean of June, July, and August (JJA), while the boreal winter field was defined by the mean of December, January, and February (DJF).

3. Results

a. LGM anomalies in the CGCM and SGCM experiments

First, we confirm whether the response of the SGCM with simplified ocean thermal feedback was similar to that of the CGCM and examine how the ocean dynamical feedback affected the atmospheric response over the midlatitude North Pacific. Figures 3a and 3b show the LGM anomalies of the zonally varying components of geopotential height at 850 hPa in boreal summer and winter, respectively, simulated by the CGCM, while Figs. 3c,d show those by the SGCM. In boreal summer (Figs. 3a,c), the SGCM simulated a distinct NPCA with the amplitude 71% of that in the CGCM experiment (see also Table 4). This means that the ocean dynamical feedback in summer only played a secondary role in intensifying the NPCA. Thus, the SGCM also has the properties necessary to produce the NPCA in summer.

In winter (Figs. 3b,d), on the other hand, the amplitude of the NPCA simulated by the SGCM was only 28% of that simulated by the CGCM. The ocean dynamical feedback in winter appeared to play a more important role in intensifying the NPCA than in summer. However, since the SGCM still simulated significant (p < 0.1) midlatitude NPCA even in winter, the sensitivity experiments using the SGCM seems to provide some clues to the winter NPCA mechanism. It should be noted that the anticyclonic anomaly over the “high latitude” North Pacific both in the CGCM and in the SGCM also agrees with the result in Justino et al. (2005). The relation between the midlatitude and high-latitude atmospheric responses is discussed in section 4a.

b. Effects of the ice sheets, atmospheric CO₂ concentration, and insolation

Since the SGCM simulated the NPCA both in summer and winter, we proceeded with the sensitivity experiments in group A (Table 1), which separates the influence of the ice sheets, atmospheric CO₂ concentration, and insolation. Figure 4 shows the zonally varying component of geopotential height anomaly at 850 hPa due to the effect of the three boundary conditions. In summer (left column in Fig. 4), a significant NPCA appeared only when the ice sheet distribution was changed (Fig. 4a). The influences of the atmospheric CO₂ concentration and insolation (Figs. 4d,f) seem to reduce the NPCA anomaly in experiment LGM (Fig. 3d). Taken together, these results clearly suggest that the change in ice sheet distribution caused the NPCA both in summer and winter.

### Table 2

<table>
<thead>
<tr>
<th>Expt name</th>
<th>Albedo</th>
<th>Topography</th>
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<tbody>
<tr>
<td>CTL</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>ALB</td>
<td>L</td>
<td>P</td>
</tr>
<tr>
<td>TOPO</td>
<td>P</td>
<td>L</td>
</tr>
<tr>
<td>ALBNA</td>
<td>L (NA)</td>
<td>P</td>
</tr>
<tr>
<td>ALBNE</td>
<td>L (NE)</td>
<td>P</td>
</tr>
</tbody>
</table>

(a) Experiment names and designs in group B. The letters “P” and “L” indicate that the ice sheet factors of PD and LGM, respectively, were given in the experiments. The letters “NA” and “NE” in the parentheses mean that the boundary conditions were only changed over North America and northern Europe, respectively. (b) Relation between the experiments and the boundary conditions.

### Table 3

<table>
<thead>
<tr>
<th>Expt name</th>
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</thead>
<tbody>
<tr>
<td>A-CTL</td>
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<td>CTL</td>
</tr>
<tr>
<td>A-ALBNA</td>
<td>ALBNA</td>
<td>CTL</td>
</tr>
<tr>
<td>A-SST</td>
<td>CTL</td>
<td>ALBNA</td>
</tr>
</tbody>
</table>

(a) Experiment names and designs in group C. The letters “CTL” and “ALBNA” indicate that the boundary condition of the expt CTL and expt ALBNA, respectively, in group B were given in the AGCM experiments. (b) Relation between the experiments and the boundary conditions.

(b) Boundary condition Difference between two expt

<table>
<thead>
<tr>
<th>Boundary condition</th>
<th>Difference between two expts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo over North America</td>
<td>Expt A-ALBNA minus expt A-CTL</td>
</tr>
<tr>
<td>Ocean thermal feedback</td>
<td>Expt A-SST minus expt A-CTL</td>
</tr>
</tbody>
</table>
TABLE 4. Summary of the sensitivity experiments. The NPCA in the midlatitude North Pacific is defined here by the areal average (30°–50°N, 160°E–160°W) of the zonally varying component of geopotential height anomalies at 850 hPa (the unit is gpm). The extent of the influence of boundary conditions was estimated in the SGCM experiments, unless "CGCM" or "AGCM" are specified in brackets. Bold characters highlight the dominant boundary conditions for the NPCA.

<table>
<thead>
<tr>
<th>Boundary condition</th>
<th>JJA</th>
<th>DJF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full LGM factors (CGCM)</td>
<td>−39.6</td>
<td>−26.8</td>
</tr>
<tr>
<td>Full LGM factors</td>
<td>−28.0</td>
<td>−7.9</td>
</tr>
<tr>
<td>Atmospheric CO₂</td>
<td>4.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Insolation</td>
<td>−4.2</td>
<td>10.2</td>
</tr>
<tr>
<td>Ice sheet</td>
<td>−26.8</td>
<td>−16.7</td>
</tr>
<tr>
<td>Topography</td>
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<td>15.8</td>
</tr>
<tr>
<td>Ice albedo</td>
<td>−32.9</td>
<td>−19.3</td>
</tr>
<tr>
<td>Northern Europe</td>
<td>0.1</td>
<td>−4.4</td>
</tr>
<tr>
<td>North America</td>
<td>−33.5</td>
<td>−19.5</td>
</tr>
<tr>
<td>Direct atmospheric response (AGCM)</td>
<td>−18.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Ocean thermal feedback (AGCM)</td>
<td>−13.9</td>
<td>−19.1</td>
</tr>
</tbody>
</table>

c. Dynamical, thermodynamical, and regional effects of the ice sheets

Now that we have confirmed the dominant role of the ice sheet among the three boundary conditions, we attempt to determine the mechanism by which the ice sheets modify the atmospheric circulation. We consider two different mechanisms: deformation and obstruction of the atmospheric flow by the elevated topography of ice sheets (dynamical effect) and reduction of lower-tropospheric temperature due to large reflection of insolation caused by the high albedo of the ice surface (thermodynamical effect). To separate the dynamical and thermodynamical effects of the ice sheets, we performed the sensitivity experiments in group B (Table 2) using the SGCM. We will also compare the influences of the ice sheet over North America and that over northern Europe.

Figure 5 shows the zonally varying component of geopotential height anomaly at 850 hPa due to the different ice sheet effects. In summer, the ice albedo apparently caused the NPCA (Fig. 5a), while the effect of ice sheet topography resulted in an opposite tendency of that of the NPCA (Fig. 5c). Therefore, only the effect of ice albedo can explain the NPCA in summer. The anticyclonic anomaly around the ice sheet over North America and northern Europe in Fig. 5a seems to result from the increased density of the local atmosphere due to the direct cooling over the ice surface. It should be noted that the effects of the ice albedo and topography cannot be combined linearly (i.e., the pattern of Fig. 5a plus Fig. 5c is not equal to that of Fig. 4a), because the atmospheric response to the forcing sources of the boundary conditions is nonlinear. The ice albedo over North America rather than that over northern Europe played a dominant role in the formation of the NPCA (Figs. 5e,g).

In winter, a cyclonic anomaly over the North Pacific was also caused by the ice albedo effect (Fig. 5b). The ice sheet topographic effect (Fig. 5d) resulted in an anticyclonic anomaly over the high–midlatitude North Pacific and a cyclonic anomaly over the western subtropical North Pacific only. Note that, over the North Atlantic, the ice sheet topography caused a remarkable cyclonic anomaly on the lee side of the North American ice sheet. These are consistent with the theoretical study on anticyclonic (cyclonic) circulation formation upstream (downstream) of a high topography in a westerly flow (Cook and Held 1988). Again, the ice albedo over North America was the dominant cause of the NPCA (Fig. 5f), while that over northern Europe had little influence on the atmospheric circulation over the North Pacific (Fig. 5h). Thus, it is the ice albedo over North America that resulted in the NPCA both in summer and winter.

d. Thermal feedback of the slab ocean

In the previous subsection, we have seen that the ice albedo over North America resulted in the NPCA during the LGM, both in summer and winter. However, one might think that the ice albedo hardly influences the atmospheric thermodynamics in winter, because the insolation itself is weak during the season. Thus, it is not obvious whether the ice albedo modifies the atmospheric circulation in the same manner in winter as in summer. In the SGCM experiments, the atmospheric circulation could also be affected by the thermal feedback of the slab ocean in which changes in SST and sea ice modify the amount of atmosphere–ocean heat fluxes. In this subsection, we will focus on the “direct effect” (i.e., in the absence of ocean feedback) of ice albedo over North America and the thermal feedback effect of the slab ocean.

Using the AGCM with prescribed SST and sea ice as boundary conditions, we performed the three experiments in group C (Table 3). The designs of experiments A-CTL and A-ALBNA are almost the same as those of experiments CTL and ALBNA in group B using the SGCM, respectively, except that the SST and sea ice were fixed to those of experiment CTL in group B for both experiments. Therefore, by comparing experiments A-CTL and A-ALBNA, we can examine the direct atmospheric response to the ice albedo over North America without the ocean thermal feedback. The design of experiment A-SST is almost the same as that of experiment A-CTL except that the SST and sea ice were prescribed using the result of experiment ALBNA in group B. Therefore, by comparing experiments A-CTL and A-SST, we can examine the effect of SST change caused by the ice albedo over North America in the SGCM experiments.
Figure 6 shows the zonally varying component of geopotential height anomaly at 850 hPa due to the “direct effect” of ice albedo over North America and due to the thermal feedback effect of the slab ocean. In summer, the direct effect of ice albedo alone was clearly responsible for the formation of the NPCA (Fig. 6a). Furthermore, the SST change resulted in a NPCA, particularly over the central and western North Pacific including the subtropical region (Fig. 6c), which means the ocean thermal feedback intensified the NPCA and extended it westward and southward in summer. In winter, on the other hand, the direct effect of ice albedo failed to produce an NPCA (Fig. 6b), while the SST change resulted in a distinct NPCA (Fig. 6d). Thus, the ocean thermal feedback was indispensable for NPCA formation in winter.

FIG. 4. Same as in Fig. 3 except for the experiments in group A. (a),(b) The effect of the LGM ice sheets; (c),(d) the effect of reduced atmospheric CO₂ concentration; (e),(f) the effect of LGM insolation.
FIG. 5. Same as in Fig. 3 except for the experiments in group B. (a),(b) The effect of ice sheet albedo; (c),(d) the effect of ice sheet topography; (e),(f) the effect of ice sheet albedo over North America; (g),(h) the effect of ice sheet albedo over northern Europe.
4. Discussion

a. Dominant boundary condition responsible for the NPCA

The relation between the NPCA and the boundary conditions during the LGM obtained by the sensitivity experiments in section 3 is summarized in Table 4. In the SGCM experiments, the effect of ice albedo over North America resulted in the midlatitude NPCA both in boreal summer and in winter. In winter, however, the ocean thermal feedback was indispensable for the NPCA formation. The ocean thermal feedback in summer and ocean dynamical feedback played secondary roles in intensifying the NPCA.

These results help us to comprehensively understand previous numerical studies using AGCMs, SGCMs, and CGCMs. In summer, the direct effect of the ice albedo over North America produced an NPCA even in the absence of thermal and dynamical ocean feedbacks. This explains why a robust NPCA in summer was simulated in most of the AGCMs (e.g., Kutzbach and Wright 1985; Rind 1987; Hall et al. 1996; Dong and Valdes 1998; Vettoretti et al. 2000), SGCMs (e.g., Dong and Valdes 1998; Vettoretti et al. 2000), and CGCMs (e.g., Shin et al. 2003; Yanase and Abe-Ouchi 2007). In winter, on the other hand, the NPCA was sensitive to the ocean feedbacks in our experiments. This could explain why there has been a minor inconsistency among the previous studies: the winter NPCA was simulated in AGCM experiments with prescribed SST (e.g., Kutzbach and Wright 1985; Rind 1987; Hall et al. 1996; Dong and Valdes 1998; Vettoretti et al. 2000), in SGCM experiments (e.g., Vettoretti et al. 2000), and in CGCM experiments (e.g., Shin et al. 2003; Yanase and Abe-Ouchi 2007; Laine et al. 2009), while an opposite tendency was simulated in some other SGCM experiments (e.g., Broccoli and Manabe 1987; Dong and Valdes 1998). Since the q flux used to calculate the SST distribution during the LGM were different in each of the SGCM experiments, the inconsistency among the models might be largest in these experiments. The SST distributions prescribed in AGCMs based on paleoclimate reconstruction and those simulated by CGCMs are
considered to be consistent in producing a distinct NPCA in winter. This is to be discussed in section 4c.

Another reason for the inconsistency in the winter NPCA among the GCMs might be the effect of ice sheet topography, which causes an anticyclonic anomaly over the North Pacific at high latitudes and partly at mid-latitudes (Fig. 5d). This mechanism was pointed out in the sensitivity studies by Broccoli and Manabe (1987) and Justino et al. (2005) and in the theoretical studies using a linearized atmospheric model by Cook and Held (1988). In fact, Otto-Bliesner et al. (2006) demonstrated that the difference in ice sheet height over North America resulted in a quantitatively different atmospheric response. When the effect of ice albedo was added to this (Fig. 4b), however, most of the anticyclonic anomaly over the midlatitude North Pacific turned into cyclonic, presumably because of the ocean thermal feedback. Therefore, simulation of the winter NPCA in a GCM seems to depend on the delicate balance between the albedo effect, topographic effect, and the ocean feedbacks.

b. Mechanism of the NPCA in boreal summer

The sensitivity experiments have demonstrated that the direct effect of the ice albedo over North America alone resulted in the NPCA in summer (Fig. 6a) and that the ocean thermal feedback merely intensified it (Fig. 6c). Here, we discuss the mechanism by which the ice albedo over North America gives rise to the NPCA. Since the subtropical high pressure system dominates the North Pacific even at midlatitudes during the climatological summers of the PD (Fig. 2a), a cyclonic anomaly during the LGM means that the subtropical high pressure system was weakened. Therefore, the theoretical studies on the subtropical high pressure system might help us to understand the NPCA dynamics in summer.

Hoskins (1996) suggested that the zonally localized distribution of the subtropical high pressure system in summer cannot be explained simply by the mechanism related to the zonally uniform descending belt of the Hadley cell. Hoskins (1996), Rodwell and Hoskins (1996), and Rodwell and Hoskins (2001) showed the anticyclonic circulation formation due to the westward response of the atmospheric circulation to the convective heating over the summertime continent. Miyasaka and Nakamura (2005) also suggested the westward response of the atmospheric circulation to the forcing over the land surface rather than the convective heating. On the other hand, Chen et al. (2001) suggested that the heating over the Asian continent influenced the anticyclonic circulation over the North Pacific (i.e., eastward response of the atmosphere to the forcing). Liu et al. (2004) suggested that the sensible heat flux over the land was more important than the convective heating, although they did not show which continent had the largest influences on the North Pacific. In addition, some studies have pointed out that other factors such as cloud radiation and ocean response have positive feedbacks that intensify the subtropical high pressure system (e.g., Hoskins 1996; Miyasaka and Nakamura 2005).

Since the ice albedo over North America caused the NPCA in our experiments, the NPCA dynamics seems to be explained by the westward response of the atmosphere to the diabatic forcing over the continent including the surface sensible heat flux and condensational heating. Figures 7 and 8 show the zonal distribution of surface sensible heat flux and precipitation, respectively, at the midlatitudes in boreal summer. Here, the precipitation is assumed to approximate the vertically integrated condensational heating. The sensible heat flux in experiment CTL (Fig. 7a; not anomaly) was significantly larger over the continents than over the oceans, while the precipitation was largest around the eastern coasts of the continents (Fig. 8a). The effect of total ice sheet (Figs. 7b and 8b), ice albedo (Figs. 7c and 8c), and ice albedo over North America (Figs. 7d and 8d, respectively) reduced the tendency of surface sensible heat flux over North America and precipitation around the eastern coast of North America, because the high albedo of the ice prevented the insolation from raising the land surface temperature. As has been seen in section 3c, all of these experiments resulted in the NPCA in summer (Figs. 4a and 5a,e). On the other hand, the effect of the topography, which caused the anticyclonic anomaly over the North Pacific (Fig. 5c) increased the tendency of surface sensible heat flux and precipitation around North America (Figs. 7d and 8d, respectively). The effect of albedo over northern Europe, which resulted in only a small circulation anomaly over the North Pacific (Fig. 5g), shows negligible anomalies (Figs. 7f and 8f). Thus, the anomalies of surface sensible heat flux over North America and precipitation around eastern coast of North America were positively correlated with the anomaly of geopotential height over the North Pacific. This result is consistent with the theory that the diabatic heating over a continent causes westward atmospheric circulation response over the ocean (Hoskins 1996; Rodwell and Hoskins 1996, 2001; Miyasaka and Nakamura 2005), although it is difficult to separate the influences of surface sensible heat flux and condensational heating. It should be noted that the subsidence just to the west of the diabatic heating over the continent in experiment CTL and its tendency in the sensitivity experiments were also consistent with theoretical studies (not shown).
c. Mechanism of the NPCA in boreal winter

As has been shown in section 3d, the direct effect of the ice albedo over North America did not cause the midlatitude NPCA in boreal winter. Since the insolation in winter itself was small, the ice albedo had little influence on the surface heat budget including surface sensible heat flux (not shown). In the SGCM experiment, the winter SST can be modified by the atmosphere–ocean interaction not only in winter itself but also by that during the other season, because the large heat capacity preserves the ocean's memory beyond several seasons. The anomalies of local or remote SST, in turn, can affect the midlatitude atmospheric circulation in winter. Since no stationary wave propagation signal from remote regions, including the tropics to the midlatitude North Pacific, was consistent with the NPCA formation (not shown), the local midlatitude SST was more likely to produce the NPCA. One

![Graphs showing zonal distribution of surface sensible heat flux](https://example.com/graphs.png)
possible mechanism as to how the SST anomaly in the midlatitude North Pacific modifies the local atmospheric circulation in winter was suggested in a study on decadal variability dynamics by Nakamura et al. (2004): in response to changes in near-surface baroclinicity due to cool SST anomaly in the midlatitudes, the storm track with heat and momentum transports is displaced southward, which in turn forms a cyclonic circulation.

To examine whether the dynamics in Nakamura et al. (2004) was consistent with the NPCA formation, the anomalies of SST and storm track were analyzed in several experiments. Figure 9 shows surface temperature anomalies in four experiments in which the midlatitude NPCA formed in winter: the effect of full LGM factors in the CGCM experiment (see Figs. 3b and 9a), that of full LGM factors in the SGCM experiment (Figs. 3d and 9b), that of total ice sheet (Figs. 4b and 9c), and that of ice albedo over North America (Figs. 5f and 9d). All of these experiments show increased meridional SST gradient in the midlatitudes: the entire North Pacific
Fig. 9. Anomalies of surface temperature (shaded) in boreal winter in the experiments. (a) The effect of full LGM factors in the CGCM experiments, (b) the effect of full LGM factors in the SGCM experiments, (c) the effect of total ice sheet in the group A experiment, and (d) the effect of albedo over North America in the group C experiment. Sea ice fraction was changed from white to red lines because of each effect.

(Fig. 9d), western-central North Pacific (Fig. 9b), or to the south of SST anomaly minimum in the western-central North Pacific (Figs. 9a,c). Figure 10 shows the Eady growth rate and the vertical component of Eliassen–Palm (EP) flux at 850 hPa in experiments CTL and ALBNA in group B. The former represents baroclinic instability in the environmental atmosphere (Hoskins and Valdes 1990), while the latter indicates the storm-track activity measured by poleward heat flux associated with 2–8-day filtered eddies (Nakamura et al. 2004). In experiment CTL, the baroclinic instability was dominant over the midlatitude North Pacific and North Atlantic (Fig. 10a), which caused intense storm activity in these regions (Fig. 10c). The effect of the ice albedo over North America intensified both the baroclinic instability (Fig. 10b) and storm activity (Fig. 10d) over the North Pacific, particularly on the southern side of the maximum in experiment CTL (i.e., southward shift of the maximum). The relation between the intensified SST gradient in the midlatitudes (Fig. 9d), southward shift of the storm track (Figs. 10b,d), and cyclonic circulation anomaly (Fig. 5e) over the North Pacific is consistent with the dynamics of Nakamura et al. (2004). Future studies should clarify what causes the SST anomaly, which is favorable for NPCA formation in winter.

The anomalies of SST and storm track mentioned above were also supported by the previous CGCM studies. The increased meridional gradient of SST in the midlatitude North Pacific was simulated in most CGCMs of the PMIP2 project (Yanase and Abe-Ouchi 2007; Solomon et al. 2007). Laïne et al. (2009) showed that the atmospheric baroclinicity and storm tracks shifted southward over the North Pacific, and eddy momentum transport tended to form a cyclonic anomaly in most CGCMs of the PMIP2 project. Furthermore, the paleoclimatic reconstruction also showed strong SST reduction in the midlatitude of the western North Pacific (Oba and Murayama 2004). These results support the mechanism whereby the anomaly of the midlatitude SST gradient causes the winter NPCA in a manner consistent with Nakamura et al. (2004).
It should also be noted that sea ice extent (white and red lines in Fig. 9) does not seem to explain the midlatitude atmospheric response in most of the experiments, which is consistent with the result of Laïne et al. (2009).

5. Summary

The atmospheric circulation over the midlatitude North Pacific during the LGM was examined by using an AGCM, SGCM, and CGCM. In both CGCM and SGCM experiments, the Pacific high pressure system in boreal summer weakened during the LGM, while the Aleutian low pressure system in winter intensified. Thus, both in summer and winter, the lower-tropospheric circulation exhibited a cyclonic anomaly over the midlatitude North Pacific during the LGM (NPCA), although the anomaly in winter was somewhat weak in the SGCM experiment.

To understand the NPCA dynamics, the sensitivities of the atmospheric circulation to the following three boundary conditions were examined using an SGCM: ice sheet with elevated topography and high albedo, atmospheric CO₂ concentration, and insolation. The effect of high albedo of the ice sheet over North America was the main cause of the NPCAs, both in summer and winter. By comparing the CGCM, SGCM, and AGCM experiments, the roles of dynamical and thermal feedbacks of the ocean were discussed. The ocean thermal feedback in winter played an essential role in forming the NPCAs, while that in summer and ocean dynamical feedback played secondary roles in intensifying the NPCAs.

The NPCA in summer was associated with a reduction in sensible heat flux and condensational heating around North America due to the cold ice surface. This result is consistent with the theoretical studies describing the
mechanism of the subtropical high pressure system (Hoskins 1996; Miyasaka and Nakamura 2005). Since ocean feedbacks only played secondary roles, the previous GCMs simulated a robust NPCA in summer through the direct influence of the ice albedo on the atmospheric circulation. In winter, on the other hand, the SST anomaly due to ocean thermal feedback produced an NPCA, while the direct effect of the ice albedo over North America was negligible. The mechanism similar to that of the Pacific interdecadal oscillation (Nakamura et al. 2004) may apply: the anomaly of the midlatitude SST gradient seems to modify the heat and momentum transport in the storm track, which in turn changes the planetary-scale circulation over the North Pacific. Future studies should clarify what causes the SST anomaly, which is favorable for NPCA formation in winter. The large sensitivity of the atmospheric response to ocean feedbacks seems to result in a minor inconsistency among the previous LGM simulations.

Finally, as suggested by Yanase and Abe-Ouchi (2007), climate changes related to the NPCA seem to explain many LGM characteristics reconstructed from geological records. Yanase and Abe-Ouchi (2007) demonstrated that the weakened Pacific high pressure system in summer during the LGM reduced water vapor transport over East Asia, which can explain the drier climate there. The cooling of sea surface in the midlatitude Pacific was also observed in oxygen isotope records of foraminifera (Oba and Murayama 2004). The intensified wintertime Aleutian low during the LGM is consistent with the dust transport record, which shows intensification of East Asian winter monsoon and southward shift of the upper-tropospheric westerly jet (Donghuai 2004). More quantitative and direct comparison between simulations and geological records is expected to be possible by using upcoming geological records such as the dust records in the Sea of Japan (Nagashima et al. 2007; K. Nagashima 2007, personal communication) and using more realistic GCMs (Takemura et al. 2009).

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